DNAPL Remediation: Selected Projects Where Regulatory Closure Goals Have Been Achieved

STATUS UPDATE

144052

Section **Page**

1.0 PURPOSE 1
2.0 OVERVIEW...2
3.0 CHALLENGES OF DNAPL CHARACTERIZATION AND REMEDIATION 8
4.0 OVERVIEW OF DNAPL REMEDIATION TECHNOLOGIES 9
5.0 DNAPL REMEDIATION PROJECTS 13
6.0 SUMMARY OF FINDINGS 13
REFERENCES 16
NOTICE AND DISCLAIMER.............................19
Appendix A: DNAPL Remediation Project Profiles..20
Appendix B: Suspected DNAPL Threshholds Based on Solubility Relative to One Percent of Aqueous Solubility 49
Appendix C: Acronyms and Abbreviations........51

1.0 PURPOSE

The purpose of this paper is to highlight sites where dense nonaqueous phase liquid (DNAPL) source reduction has been demonstrated as an aid in meeting regulatory cleanup goals.[1] The presence of DNAPL in the subsurface can serve as a long-term source of dissolved contaminant plumes in groundwater, making it more difficult to reach regulatory closure. However, once the DNAPL source is addressed, residual groundwater plumes may be more amenable to treatment, including less aggressive techniques such as monitored natural attenuation (MNA) or bioremediation (U.S. Environmental Protection Agency [EPA] 1999b).

This paper updates the document, *DNAPL Remediation: Selected Projects Approaching Regulatory Closure*, prepared in 2004 (EPA 2004a) by providing more recent information on technologies and on five additional selected sites at which DNAPL source reduction technologies were applied.

The sites were identified by reviewing project summaries found on various state and federal Web sites and selecting those that met the criteria for inclusion. The sources also included published and nonpublished reports, commercial websites, and interviews with regulatory staff. The review was not statistically based, and the sites are presented for illustrative purposes only.

Ten of the 13 sites summarized in Table 1 and fully profiled in Appendix A have reached regulatory closure (i.e., a no further action [NFA] determination has been made). NFA is defined in this document as (1) no further active intervention will be required, (2) there is currently no active remedial activity taking place, and (3) the site is sufficiently clean that long term monitoring is not required or will not be required after some specified time. At two sites (the confidential chemical manufacturing plant in Portland, Indiana, and the Avery Dennison site in Waukgan, Illinois) the remediation

---

[1] A few of the projects documented in this report are still undergoing verification groundwater-monitoring to confirm no rebound.

United States
Environmental Protection
Agency

Solid Waste and
Emergency Response
(5203P)

EPA 542/R-09/008
August 2009
www.CLUIN.org

was aimed at soil and they have met cleanup goals and institutional controls are in place to prevent use of groundwater. The King's Bay site is in a MNA mode with MCLs being met at the property line. Since the site is naturally anaerobic, it is anticipated that monitoring will end soon. Most of the sites were addressed under state cleanup programs, but four were addressed under Superfund (31%), and one was addressed as a state led RCRA corrective action (8%).

The sites profiled illustrate that addressing DNAPL source areas can lead to regulatory closure and, as is the case in six sites, unrestricted use. As discussed in Section 3.0, the benefits of DNAPL source reduction, and especially partial source removal, are still being debated. Although this paper does not attempt to resolve this issue, it does provide information that illustrates instances where source reduction has contributed to a site meeting cleanup goals (groundwater maximum contaminant limits [MCLs] were achieved at five sites). This paper helps, in part, to satisfy the recommendation of EPA’s Ground Water Task Force to better assess and document results achieved by DNAPL source reduction. The information provided is also part of a national effort to better understand current technology capabilities and to illustrate the use of different cleanup criteria.

This paper is targeted toward project managers, federal and state regulatory staff, site owners, consultants, and technology providers with a basic understanding of site remediation approaches and terminology. References and available Web links are cited for those seeking further information about specific remedial technologies in the Reference section (page 16).

2.0 OVERVIEW

The presence of DNAPLs in soil and groundwater presents unique challenges to site remediation. DNAPLs have a specific gravity greater than water, a relatively low solubility, and a tendency to diffuse into fine-grained materials in an aquifer. These properties make DNAPL masses and residuals difficult to locate and characterize in the subsurface, and they can prolong the process of conventional remedial technologies, such as groundwater pump-and-treat (P&T).

Due to their specific gravity, DNAPLs tend to sink in the subsurface. Their migration pathways tend to be complex and hard to predict due to the heterogeneous nature of the underlying soil and fractured bedrock. As a result, a complicated DNAPL architecture (shape and size) can develop that is made up of pools, ganglia, and globules in multiple soil layers and bedrock fracture zones. And because of their low solubility, tendency to displace water from larger soil pores, and tendency to diffuse into silt and clay, DNAPLs can release dissolved constituents for long periods of time forming large groundwater plumes. Constituents in the migrating plume can diffuse into aquifer materials under certain conditions only to back diffuse out at a later time.

DNAPLs often are present at electronics manufacturers, metal plating facilities, drycleaners, solvent recyclers, and other sites that have used chlorinated solvents. They also are found at wood treatment facilities that used creosote and at former manufactured gas plants (MGPs) that produced coal tar wastes. Chlorinated solvents, such as tetrachloroethene (PCE) and trichloroethene (TCE), are the most common types of organic soil and groundwater contaminants at Superfund and other hazardous waste sites.

Site owners will likely spend billions of dollars over the next several decades cleaning up DNAPL-impacted sites (EPA 2000).

The following sections present some of the challenges to characterizing and remediating sites with DNAPL contamination and summarize the many technologies that have been used to treat the DNAPL source zone. The 13 examples of sites that have successfully addressed the source zone to meet regulatory requirements are also summarized, including information about the extent of contamination, the cleanup goals, and the treatment approach. These sites are further detailed in the profiles contained in Appendix A. For quick reference to these sites, see Table 1.

***For more information*:** The DNAPL focus area on EPA's CLU-IN website further explains their chemistry and behavior as well as characterization and remediation approaches:

http://www.cluin.org/contaminantfocus/default.focus/sec/Dense_Nonaqueous_Phase_Liquids_(DNAPLs)/cat/Overview/

Table 1. Summary of Selected DNAPL Remediation Projects

(A List of Acronyms is Found at the End of the Table)

Site Name, Location	**Technology, Period of Operation**	**Media, Quantity Treated**	**Project Goals, Program (mg/kg= soil or sediment µg/L= groundwater)**	**Contaminant Concentrations (Before Treatment) (mg/kg= soil or sediment µg/L= groundwater)**	**Contaminant Concentrations (After Treatment) (mg/kg= soil or sediment µg/L= groundwater)**	**Project Status, Comments**
IN SITU THERMAL TREATMENT PROJECTS						
Confidential Chemical Manufacturing Facility, Portland, IN	In situ conductive heating (145 heater/vacuum wells) 7/97 to 12/97	Soil, one area 7,500 ft^2 by 18 ft deep and a second area 600 ft^2 by 11 ft deep	PCE – 8 mg/kg, TCE – 25 mg/kg, 1,1-DCE – 0.08 mg/kg (IDEM Tier II, Industrial Land Use), State Voluntary Cleanup Program	PCE – 3,500 mg/kg, TCE – 79 mg/kg, 1,1-DCE – 0.65 mg/kg, Suspected DNAPL	PCE – 0.53 mg/kg, TCE – 0.02 mg/kg (average in soil) 1,1-DCE – not available	IDEM NFA letter (Date not provided)
Avery Dennison Site, Waukegan, IL	ERH (95 electrodes/ 34 recovery wells) 12/99 to 11/00	Saturated and unsaturated soil, 16,000 yd^3	MC – 24 mg/kg (IEPA TACO), State Voluntary Cleanup Program	MC – 50,000 mg/kg (maximum in soil), MC – 1,900 mg/kg (average in soil), Suspected DNAPL	MC – 2.51 mg/kg (average in soil)	IEPA NFR letter (4/01) required institutional controls
Camelot Cleaners, West Fargo, ND (Superfund Removal Program)	ERH (56 multi-zone electrode vents, array of horizontal vapor extraction wells, and dual vacuum extraction wells) 2/05 to 1/06	Cleanup footprint was 10,300 ft^2 and up to 56 ft deep, GW occurs 3-5 ft bgs and tends to be perched	Reduce VOC levels to less than 3 mg/kg in soil and 1 mg/L in GW, EPA Superfund Removal Program	Maximum PCE concentrations detected in soil 2,200 mg/kg and in water 89 mg/L, Suspected DNAPL	One small area above 3 mg/kg; the rest were below. All GW samples total VOCs under 1 mg/L	Unconditional no further action, extraction and monitoring wells were removed
Former MGP Gasholder, North Adams, MA	In situ conductive heating (25 thermal wells on 12-ft centers) 8/03 to 6/05	About 2,000 yd^3 of soil, debris, and coal tar. Depth of 18 ft bgs.	Cleanup goals were to reduce B(a)P levels to 300 mg/kg, naphthalene to 10,000 mg/kg and TPH to 10,000 mg/kg, MADEP	Maximum detected B(a)P 650 mg/kg, naphthalene 14,000 mg/kg, and TPH 230,000 mg/kg, Observed DNAPL	16,000 gallons of coal tar recovered; final concentration averages were B(a)P 0.33 mg/kg, naphthalene 5.7 mg/kg, and TPH 43.15 mg/kg	Site owner filed for an Activity and Use Limitation to the MADEP due to other unrelated site problems
Former Wood Treatment Area, Alhambra, CA	ISTD (131 heater-vacuum wells and 654 heater-only wells 6/03 to 9/05 (actual heating)	Soil –16,500 yd^3 (Average depth 20 ft bgs; maximum	Total PAHs – 0.065 mg/kg (B(a)P-eq), PCP – 2.5 mg/kg, dioxins – 0.001 mg/kg expressed as 2,3,7,8-TCDD TEQ	Maximum concentrations: Total PAHs – 35,000 mg/kg, PCP – 58 mg/kg, dioxins – 0.184 mg/kg as 2,3,7,-TCDD, Suspected DNAPL	All contaminant concentrations were below project goals.	Certificate of completion issued 2/08/07

Site Name, Location	Technology, Period of Operation	Media, Quantity Treated	Project Goals, Program (mg/kg= soil or sediment µg/L= groundwater)	Contaminant Concentrations (Before Treatment) (mg/kg= soil or sediment µg/L= groundwater)	Contaminant Concentrations (After Treatment) (mg/kg= soil or sediment µg/L= groundwater)	Project Status, Comments
		depth greater than 100 ft bgs	California Expedited Remedial Action Program			
Southern California Edison Company Visalia Pole Yard, Visalia, CA (Superfund NPL)	ISTD (11 injection and 8 extraction wells) 5/97 to 6/00	Soil and groundwater (Maximum depth 145 ft bgs)	Pentachlorophenol 17 mg/kg and 1 µg/L ; Benzo(a)pyrene 0.39 mg/kg and 0.2 µg/L ; and TCDD equivalent 0.001 mg/kg and 30 pg/L Superfund NPL with state lead	DNAPL (Creosote) and LNAPL (diesel with pentachlorophenol) pools present	All contaminant concentrations were below project goals.	Final Remediation Action Completion Report approved by state 12/4/08 IC in place commercial and/or industrial redevelopment only
Ex Situ Thermal						
Southern Maryland Wood Treating Hollywood, MD (Superfund NPL)	Excavation and ex situ thermal desorption, P&T	Soil, sediment 270,000 tons of soil	Surface soil: Total PAHs – 0.1 mg/kg B(a)P-eq Subsurface soil: Total PAHs – 1.0 mg/kg B(a)P-eq Sediment: PCP – 0.4 mg/kg PCP, low molecular wt. PAHs – 3.2 mg/kg, high molecular wt. PAHs – 9.6 mg/kg EPA Superfund NPL	Maximum concentration of PAHs in surface soil and sediment 4,120 mg/kg and 41 µg/kg, respectively, Observed DNAPL	All cleanup goals were met.	Ready for Reuse determination issued by EPA on 11/18/04. Unrestricted use of site
ISCO PROJECTS						
Former Southern California Edison MGP Site, Long Beach, CA	In situ ozonation and excavation 1998 to 2001	Soil and GW, 340 ft by 230 ft	B(a)P-eq – 1.75 mg/kg (Site-specific risk-based cleanup level), California DTSC	Total PAH – 2,484 mg/kg >100 mg/kg B(a)P-eq (maximum in soil), Suspected DNAPL	B(a)P-eq – 1.4 mg/kg (average in soil), PAH concentrations in GW reduced to ND	California DTSC will issue a Certificate of Completion once deed restrictions are recorded
Former Cowboy Cleaners Site, Broomfield, CO	Potassium permanganate 9/01 to 8/02	Soil and GW, 65,340 ft^2 (1.5 acre) plume	Project goals not identified; State Voluntary Cleanup Program	PCE – 1,900 µg/L (maximum in GW), Suspected DNAPL	PCE – 48 µg/L (source area)	NFA letter issued by State of Colorado (2/03) requires commercial use

Site Name, Location	**Technology, Period of Operation**	**Media, Quantity Treated**	**Project Goals, Program (mg/kg= soil or sediment µg/L= groundwater)**	**Contaminant Concentrations (Before Treatment) (mg/kg= soil or sediment µg/L= groundwater)**	**Contaminant Concentrations (After Treatment) (mg/kg= soil or sediment µg/L= groundwater)**	**Project Status, Comments**
Dry Clean USA #11502, Orlando, FL	SVE: 4/99 to 12/00, P&T: 4/99 to 1/01 and 2/01 to 11/02, Hydrogen peroxide: 10/05	Full-scale deepest contamination was 68 ft bgs, plume was 800 ft long and 300 ft wide	Meet contaminant target cleanup goals: 3 µg/L PCE, 30 µg/kg PCE, 30 µg/kg TCE, 400 µg/kg *cis*-DCE, 700 µg/kg trans DCE, and 7 µg/kg vinyl chloride, State Drycleaner Program	PCE – 27,300 µg/L in GW and 3.9 mg/kg detected in soil, Suspected DNAPL	10/05 to 10/06 PCE ranged between 1.7 and 3 µg/L	State Rehabilitation Order (NFA) issued 2/16/07
Naval Submarine Base Kings Bay, Site 11, Camden County, GA	P&T: 1993 to 1999 Fenton's reagent: 6/99 to 11/01 Biostimulation, MNA: ongoing	GW plume estimated to be 700 ft by 200 ft and 30 to 40 ft deep	Georgia DNR MCLs, RCRA Corrective Action	Total chlorinated hydrocarbons – nearly 200,000 µg/L, Suspected DNAPL	Total chlorinated hydrocarbons –< 1 to 13.9 µg/L	Awaiting status of monitoring and MNA
Former Sta-Lube Site Rancho Dominguez, CA	P&T: 1997-2003 SVE: 2000-2001 Excavation: 2003 Catalyzed hydrogen peroxide and sodium persulfate: 06/05 to 06/08	Soil and GW, GW plume estimated at 200 ft by 80 ft	50 µg/L MC, California RWQCB Los Angeles Region	MC – as high as 2,600,000 µg/L, Suspected DNAPL	MC – <50 µg/L	Final closure granted 06/08
OTHER						
Pasley Solvents and Chemicals, Inc., Hempstead, NY (Superfund NPL)	SVE/AS 11/97 to 10/02	Surface soil and subsurface soil, and GW, Site is about 75-ft wide by 275-ft long with a 60-ft wide and 400-ft long contaminant plume	Clean up site to residential risk levels and contaminant MCLs, EPA Superfund NPL	Maximum detected concentrations were: Surface soil: total VOCs – 603 mg/kg, total SVOCs – 204 mg/kg Groundwater: Total VOCs – 37 mg/L, TCE – 320 µg/L, Suspected DNAPL	All contaminants of concern under 1 mg/kg in soil and GW concentrations ranged from ND to 4 µg/L	2006 NFA with discontinuing of GW monitoring activity, No institutional control restrictions

Source: Project profiles in Appendix A

Notes:

µg/L	micrograms per liter
bgs	below ground surface
B(a)P	benzo(a)pyrene
B(a)P-eq	benzo(a)pyrene equivalent
DCE	dichloroethene
DNAPL	dense non-aqueous phase liquid
DTSC	Department of Toxic Substances Control
EPA	U.S. Environmental Protection Agency
ERH	electrical resistive heating
ft	foot or feet
ft^2	square foot or feet
ft^3	cubic foot or feet
GW	groundwater
HRC®	Hydrogen Release Compound
IC	institutional controls
IDEM	Indiana Department of Environmental Management
IEPA	Illinois Environmental Protection Agency
ISTD	in situ thermal desorption
MADEP	Massachusetts Department of Environmental Protection
MC	methylene chloride
MCL	maximum contaminant level (EPA)
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MGP	manufactured gas plant
MNA	monitored natural attenuation
ND	non-detectable
NFA	no further action
NFR	no further remediation
NPL	National Priorities List
P&T	pump and treat
PAH	polycyclic aromatic hydrocarbon
PCE	tetrachloroethene
RBEL	risk-based exposure level
RCRA	Resource Conservation and Recovery Act
SCE	Southern California Edison
SVE	soil vapor extraction
SVOC	semivolatile organic compound
TACO	tiered approach to correction action objectives
TCA	trichloroethane
TCDD	2,3,7,8 tetrachlorodibenzodioxin
TCE	trichloroethene
TCEQ	Texas Commission on Environmental Quality
TPH	total petroleum hydrocarbons
TRRP	Texas Risk Reduction Program
VC	vinyl chloride
VOC	volatile organic compound
yd^3	cubic yard

3.0 CHALLENGES OF DNAPL CHARACTERIZATION AND REMEDIATION

As noted above, the physical and chemical properties of DNAPLs hinder their characterization and remediation. This section further explains some of the challenges.[2]

Locating and Verifying the Presence of DNAPLs

DNAPLs tend to migrate along the path of least resistance in the subsurface. Because of difficulties characterizing a heterogeneous subsurface, DNAPL source zones are often difficult to locate, and their size and spatial distribution difficult to define. Techniques that can be effective in locating and characterizing DNAPLs include membrane interface probes, ribbon NAPL samplers (e.g., the FLUTe™ membrane system), partition interwell tracer testing, and direct push vadose zone and groundwater profiling. In addition, cone penetrometers can be equipped with fluorescence detection systems to help locate creosote and coal tar; Raman spectroscopy to identify contaminants and DNAPL in situ; or GeoVIS to help visually identify NAPL through downhole video imaging.

It is usually difficult to verify the presence of DNAPLs through direct observation, even with downhole video imaging. However, dyes that change color when they encounter a DNAPL mass or partition into them (e.g., Sudan IV) have been used to help identify the presence of clear DNAPLs. Dyes can be used during continuous soil coring with a direct push rig in order to pinpoint DNAPL masses. The FLUTe™ system, which involves deploying a fabric dye-treated tube down a borehole, may be used, both in soil and bedrock, to provide information on the presence and location of the DNAPL.

The presence of a DNAPL can sometimes be inferred based on groundwater concentration data and the "1% of solubility" rule of thumb (EPA 1992). Under this approach, DNAPL is suspected to be present when the concentration of a chemical in groundwater is greater than 1% of its pure-phase solubility. For example, when the dissolved phase of PCE is greater than 1,500 micrograms per liter (μg/L)─which is 1% of its pure-phase solubility of 150,000 μg/L─PCE is inferred to be present as a DNAPL. This is a very conservative estimate since many DNAPL residual architectures produce plumes with thin, highly concentrated cores that can be diluted by conventional monitoring well construction and sampling techniques. Appendix B lists the values of 1% solubility concentrations for several DNAPLs. Note that for chemical mixtures the solubility of an individual chemical may be lower than its pure phase solubility.

For more information: The Interstate Technology and Regulatory Council's (ITRC) report, Technology Overview: An Introduction to Characterizing Sites Contaminated with DNAPLs (ITRC 2003a), discusses characterization approaches, data collection techniques, and investigation methods for sites contaminated with DNAPLs. EPA's report, *Site Characterization Technologies for DNAPL Investigations* (EPA 2004b), describes geophysical and non-geophysical technologies that are useful in locating, quantifying, and verifying the presence of DNAPLs.

DNAPL as a Continuing Contaminant Source and Dissolved Plume Management

Because DNAPLs slowly dissolve as they migrate and diffuse into silt and clay, they can act as continuing sources of groundwater contamination. The combination of DNAPL migration and slow dissolution into groundwater, make DNAPLs difficult to

---

[2] Mention of trade names or commercial products in this report does not constitute endorsement or recommendation for use.

eliminate using pump and treat extraction technologies. Although P&T and other methods may contain and recover or treat the dissolved fraction of the contaminant mass, this fraction can be very small compared to the amount of DNAPL sorbed to soil or pooled in the source area. It can take many years or decades for the majority of the contamination to be recovered by conventional means; thus, cleanup goals can be difficult to attain when even small amounts of DNAPL are present at a site.

Debate Over Effectiveness of Partial Source Removal

DNAPL source zones are hard to locate and verify; thus, DNAPL source reduction may achieve only a partial removal of the source mass. There is an ongoing debate within the remediation community regarding the utility of partial source removal or reduction, where some, but not all, of the DNAPL source is removed or destroyed. Recent reports have emphasized the need for historical performance data to better predict the effectiveness of DNAPL remediation efforts. For example, EPA convened an expert panel to examine four issues regarding DNAPL source zone management and treatment. In its report, *The DNAPL Remediation Challenge: Is There a Case for Source Depletion?* (EPA, 2003), the expert panel concluded that partial mass depletion from DNAPL source zones has been a viable strategy at certain sites and is likely to provide benefits at a number of other sites. However, barriers to more widespread use of DNAPL source-zone technologies persist. Additional theoretical analysis and assessment tools, improved monitoring techniques (site characterization; performance assessment), and field-scale demonstrations that elucidate benefits of partial source depletion are needed to provide a more informed basis for decision-making on whether to undertake DNAPL source-zone depletion at both sites with a containment remedy in place and at new DNAPL sites.

Variation in Cleanup Levels and Closure Criteria

Cleanup levels and closure criteria vary at sites contaminated with DNAPL. These criteria include a wide range of quantitative goals as well as goals that specify qualitative objectives. Examples of remedial action objectives established as qualitative criteria include: "Clean up groundwater to the extent practicable for the source area;" "Clean up the source area to the extent practicable;" and "Remove the source area, then conduct monitored natural attenuation."

Some state agencies, such as the Illinois EPA (IEPA), follow a tiered approach to developing remediation objectives for contaminated soil and groundwater. IEPA's remediation objectives emphasize the protection of human health, but also take into account site-specific conditions and land use to provide flexibility to site owners and operators in developing site-specific remediation objectives. Each successive tier of the three-tiered approach is more involved than the previous tier, with Tier III conducted at sites where remediation possibilities are limited due to physical barriers or at complex sites requiring full-scale risk assessments or alternative modeling.

4.0 OVERVIEW OF DNAPL REMEDIATION TECHNOLOGIES

In situ technologies being used to remediate DNAPL sources include:

- In situ thermal technologies,
- In situ chemical oxidation,
- Surfactant/co-solvent flushing,
- In situ bioremediation, and
- Zero valent iron.

Other technologies that have been used to treat DNAPL sources include direct pumping of DNAPL, dual-phase extraction, excavation, soil vapor extraction (SVE)/air sparging, containment (e.g., engineered slurry walls and permeable reactive zones), and stabilization/solidification. P&T may be successful in treating small residual DNAPL source zones in very permeable soil, but is not generally cost-effective for treating larger pools of DNAPL, or large or hard-to-reach areas of residual DNAPL contamination because of the long time frames involved.

In general, successful source remediation depends largely on the location and architecture of the DNAPL. For example, large deep pools of DNAPL or discharges of DNAPL to bedrock are especially difficult to address due to limited accessibility to treatment. However, small, shallow areas of residual DNAPL are relatively easy to remediate by excavation, SVE, or even—as mentioned above—P&T. The time to reach an NFA decision can be greatly reduced if the source area and associated highly contaminated pore water are treated directly, rather than addressing the dissolved plume only. While there may be some dispute over the value of treating a complex source zone, especially if the goal is to reach maximum contaminant levels (MCLs), there is general agreement that targeting the source zone usually can help clean up a site in a shorter time frame. Cleanups of the some of the sites profiled in this report, for example, the Dry Clean USA, Former Southern California Edison MGP, Pasley Solvents and Chemicals sites, were able to achieve MCLs onsite. Others, such as the Former Cowboy Cleaners and Naval Submarine Base Kings Bay Site 11, obtained MCLs at a point of compliance.

This section provides an overview of selected technologies that have been used to treat DNAPL sources, including the use of combined remedies. The project profiles in Appendix A illustrate the use of several of these technologies to achieve site cleanup goals.[3]

***For more information*:** More information about in situ treatment is available in *In Situ Treatment Technologies for Contaminated Soil* (EPA 2006) and the FRTR's compilation of remediation technology assessment reports (http://www.frtr.gov/multisitereports.htm). Also, the DNAPL focus area on EPA's CLU-IN website contains information. http://www.cluin.org/contaminantfocus/default.focus/sec/Dense_Nonaqueous_Phase_Liquids_(DNAPLs)/cat/Treatment_Technologies/

In situ thermal treatment technologies employ heat in the source zone to volatilize or sometimes decrease the viscosity of DNAPLs to increase their mobility toward vapor and groundwater extraction wells. In some applications, such as methylene chloride contamination, high temperature conditions may destroy DNAPLs through pyrolysis or enhanced hydrolysis; however, the emphasis of thermal remediation is to recover the contaminants from the subsurface for subsequent destruction , not to try to destory them in place.

Various thermal approaches can be used, including:

- Injection of steam (also referred to as "steam-enhanced extraction"), or hot water to heat the source area.
- Three-phase and six-phase electrical resistive heating (ERH), which applies an electrical current via electrodes to heat the source area.
- Thermal conduction (also referred to as "in situ thermal desorption"), which supplies heat to the soil through steel wells in the case of deep contamination or with a blanket that covers the ground surface in the case of shallow contamination.

***For more information*:** In situ thermal treatment technologies are described in more detail in *In Situ Thermal Treatment of Chlo-*

---

[3] Mention of trade names or commercial products in this report does not constitute endorsement or recommendation for use.

rinated Solvents: Fundamentals and Field Applications (EPA 2004c).

In situ chemical oxidation (ISCO) technologies typically inject chemical oxidants and some times other amendments directly into the source area where they react with the contaminants at the dissolved-phase/ liquid-phase interface. This reaction destroys the dissolved-phase DNAPL constituents and speeds up the dissolution of the DNAPL at the water/NAPL interface by keeping the concentration of the dissolved phase below the DNAPL solubility limit. Although injection of oxidants is the most common delivery method, certain circumstances such as subsurface heterogeneity, deep contamination, or low hydraulic gradient may require other methods to enhance the delivery of oxidants to the contaminant. These methods include recirculation, deep soil mixing, or soil fracturing. Oxidants that are delivered in the dissolved phase to the contaminant will not attack the DNAPL directly.

Four of the more common chemical oxidants used for DNAPL treatment are sodium and potassium permanganate, hydrogen peroxide (when used with iron catalysts, this is generally referred to as Fenton's chemistry or Fenton's reagent), ozone, and persulfate (activated with either iron, hydroxide, or heat). The oxidants react with the dissolved-phase contaminant, breaking chemical bonds and yielding degradation products, such as carbon dioxide, water, and chloride ion, when the DNAPL is chlorinated.

Surfactant-enhanced ISCO (S-ISCO™) uses a proprietary nonionic surfactant to help solubilize DNAPL thus enhancing oxidation.

***For more information*:** ISCO is described in greater detail in *Engineering Issue: In Situ Chemical Oxidation* (EPA 2006) and *Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater* (ITRC 2001). In addition, the Environmental Security Technology Certification Program and Strategic Environmental Research & Development Program are funding a number of bench- and field-scale studies related to ISCO, as well as funding development of a technology practices manual. Summaries of these projects can be found at http://www.serdp-estcp.org/ISCO.cfm.

Surfactant and co-solvent flushing technologies enhance DNAPL removal through injection and subsequent extraction of chemicals to solubilize and/or mobilize DNAPL constituents. Typically, the chemicals used are aqueous surfactant solutions, which may include electrolytes that aid in contaminant solubilization or co-solvents (including alcohols, such as ethanol or isopropanol) that lower the interfacial tension. The chemicals are injected into a system of wells designed to flood the DNAPL zone within the aquifer. The chemical "flood" and the solubilized or mobilized DNAPL are extracted from the subsurface and separated and treated above ground. S-ISCO™ combines elements of flushing technology with ISCO. As noted above, S-ISCO™ may enhance chemical oxidation through use of a proprietary surfactant, which helps solubilize the DNAPL.

Surfactant/co-solvent flushing technology is described in greater detail in *Technical and Regulatory Guidance for Surfactant/Co-Solvent Flushing of DNAPL Source Zones* (ITRC 2003b).

In situ bioremediation technologies engineer subsurface conditions to enhance the biological activity of subsurface microbial populations. Typically, electron donor substrates, such as lactate or molasses, are introduced into the subsurface using injection-only or recirculation configurations. The substrates provide a carbon source which creates anaerobic conditions that stimulate native microbes to degrade chlorinated contaminants through the process of reductive dechlorination. Advances are being made in designing longer-lived substrates (e.g., emulsified vegetable oil) that may be more effective in higher-concentration source zones. Where sufficient populations of the necessary bacteria are lacking, non-indigenous microbes can be introduced into the subsurface (referred to as "bioaugmentation").

Although more commonly applied to dissolved-phase plumes, in situ bioremediation has been used at sites to treat DNAPL sources.

For more information: In situ bioremediation is described in greater detail in *Engineered Approaches to In Situ Bioremediation of Chlorinated Solvents: Fundamentals and Field Applications* (EPA 2000) and *Overview of In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones* (ITRC 2005). Additional detail on design, operation, and performance monitoring is contained in *In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones* (ITRC 2008).

Zero valent iron technologies deliver nano or micro scale ZVI suspended in a carrier fluid or as a powder into the subsurface so they can make contact with the contaminant of concern. Fluids are usually injected, while powders are mixed in the soil by augering or by direct placement in a trench below the water table. Pneumatic and hydraulic fracturing is sometimes used to improve delivery and distribution of suspended ZVI. Introduction of ZVI into the subsurface promotes the chemical reduction of many chlorinated solvents. Use of ZVI to reduce chlorinated solvents has been studied in permeable reactive zones that treat the dissolved-phase contaminants present in the groundwater plume. An innovative variant of ZVI technology developed by the National Aeronautics and Space Administration emulsifies the ZVI in vegetable oil. The vegetable oil is miscible with the DNAPL source and attacks it directly while forming a coating that prevents it from dissolving without first going through the oil with its reactant iron.

For more information: More information on the use of ZVI to treat source zones can be found on the DNAPL focus area of EPA's CLU-IN website at http://www.clu-in.org/contaminantfocus/default.focus/sec/Dense_Nonaqueous_Phase_Liquids_(DNAPLs)/cat/Treatment_Technologies/p/6. A fact sheet on nanotechnology is also available at http://www.clu-in.org/542f08009.

A combined remedy is a combination of treatment technologies used simultaneously or in sequence (also known as a "treatment train"). There is increasing evidence that combined remedies can be useful in cleaning up a site in a much shorter time frame than traditional methods alone. For example, SVE plus thermal remediation is more effective in low-permeability formations than SVE alone and may eliminate back diffusion rebound that is often associated with the remediation of contaminated silts and clays.

A combined remedy approach is also useful for sites with operating cleanup systems because one part of the approach is to continually evaluate if an existing system is still suited to the site conditions and whether a more efficient system is available. System optimization and continuous evaluation should be an integral part of any operation and maintenance program.

For more information: A discussion of combined remedies can be found in *Guidance for Optimizing Remedy Evaluation, Selection, and Design* (NAVFAC 2004).

EPA is interested in identifying additional sites where DNAPLs are present, a remedial technology has been used, and the site has since reached regulatory closure or is approaching closure. Please contact Linda Fiedler at EPA's Office of Superfund Remediation and Technology Innovation to discuss further, at (703)-603-7194, or e-mail fiedler.linda@epa.gov.

5.0 DNAPL REMEDIATION PROJECTS

Thirteen remediation projects illustrating how treatment of the DNAPL source zone expedited attainment of cleanup goals are profiled in this report. DNAPL was reported to have been observed at 3 sites and suspected at 10 sites, based on elevated contaminant concentrations in groundwater. At each site:

- A destruction or removal technology was used to address the DNAPL source zone; and
- Regulatory closure was reached with no long-term monitoring required; or regulatory goals have been met, but groundwater monitoring is still ongoing with the intention that it will not be long term (i.e., rebound has not occurred but the regulators want to be sure before abandoning the monitoring wells).

For quick reference, Table 1 summarizes information about the remediation projects profiled in Appendix A. These projects are not necessarily representative of the range of DNAPL sites and the treatment projects being performed today.

In addition to the project profiles, the following sources provide further information about specific DNAPL-contaminated sites where aggressive in situ treatment technologies have been used:

- In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones: Case Studies. ITRC. April 2007. (http://www.itrcweb.org/Documents/bioDNPL_Docs/BioDNAPL-2.pdf)
- In Situ Treatment of Groundwater Contaminated with NAPL Contamination: Fundamentals and Case Studies. Proceedings of meeting sponsored by EPA and ITRC, December 2002. (http://cluin.org/studio/napl_121002/)
- In Situ Thermal Treatment database (http://cluin.org/products/thermal)
- In Situ Chemical Oxidation database (http://cluin.org/products/chemox)
- FRTR Cost and Performance Case Studies (http://www.frtr.gov/costperf.htm)
- State Coalition of Drycleaner Case Studies (http://www.drycleancoalition.org)

6.0 SUMMARY OF FINDINGS

The following general and technology-specific findings about DNAPL characterization and remediation are based on available information on the field technology applications highlighted in this paper.

General Findings

The 13 sites profiled in Appendix A include 3 drycleaning establishments, 4 manufacturing or chemical processing facilities, 2 MGPs, and 3 wood treatment sites, as well as 1 landfill. The majority of the sites (8) were suspected to have had chlorinated solvents (e.g., PCE, TCE, and/or methylene chloride) and, in some cases, their degradation products, in the form of DNAPL or a dissolved plume. The remaining 5 sites (the MGP and wood treatment sites) were contaminated with creosote or coal tar DNAPL and in some cases diesel range hydrocarbons used as carrier for the creosote or pentachlorophenol. .

The types of treatment used to address the DNAPL sources included:

- In situ thermal technologies (six sites)
- Ex situ thermal technologies (one site)
- In situ chemical oxidation (five sites)
- SVE and air sparging (one site)

Source removal through the excavation of contaminated soil was conducted at three sites in addition to the subsequent treatment application. The time span from commencing in situ treatment to receiving a closure letter at these sites varied from about one to eight years.

Of the 13 sites examined 7 had restrictions or conditions placed on closure. For example:

- The NFA letter for the Avery Dennison Site, Illinois, required implementation of institutional controls.
- The NFA letter for the Former Cowboy Cleaners Site, Colorado, permitted only commercial land use.
- The Certificate of Completion for the Former Southern California Edison MGP will be signed pending deed restrictions that prohibit residential use.

Of the 7 sites where groundwater contamination was treated , six had MCLs as goals and 5 achieved the MCLs. For example:

- Following oxidation treatment the former Sta-Lube site achieved methylene chloride concentrations of less than the 50 µg/L MCL goal.
- At the Dry Clean USA site PCE levels which started out with a maximum detected of 27,300 µg/L were in the ND to 3 µg/L levels (MCL 5 µg/L) following treatment.
- Using SVE and groundwater air sparging at the Pasley Solvents and Chemicals, Inc. site total VOCs and TCE were reduced from 37 mg/L and 320 µg/L respectively to between ND and 4 µg/L. The MCL for TCE is 5 µg/L.

Technology-Specific Findings

In Situ Thermal Treatment – Full-scale in situ thermal treatment was implemented at six sites: two manufacturing facilities, one drycleaner, one MGP, and two wood treatment facilities. Three of the sites were treated using thermal conduction, two with ERH, and one with steam injection. The treated soils primarily were a stratified mix of relatively low-permeability units such as silts, clays, and silty sands. One site contained coarser-grained fill material comprising sand, gravel, and cobbles. Volumes ranging from approximately 50,000 to 500,000 ft^3 were treated. The deepest contamination treated was over 145 ft below ground surface (bgs). Three sites received closure letters within less than two years of commencing thermal treatment. Overall, these projects showed that in situ thermal treatment was able to remediate sites with varying subsurface conditions in both the saturated and unsaturated zones to satisfy regulatory requirements.

- The Confidential Chemical Manufacturing Facility, Portland Indiana, used in situ thermal conduction to treat two contaminated areas comprising a total volume of about 135,000 ft^3 of saturated and unsaturated soil. The goal was to reduce TCE, PCE, and 1,1-DCE concentrations from more than 3,500 mg/kg to less than state risk-based cleanup goals for industrial land use (25 mg/kg for TCE, 8 mg/kg for PCE, and 0.08 mg/kg for 1,1-DCE) in five months. These goals were met and a NFA letter was issued by the state.
- The Avery Dennison Site, Illinois, used ERH to treat approximately 16,000 ft^3 of saturated and unsaturated soil. The goal was to reduce methylene chloride (MC) concentrations from more than 50,000 mg/kg to less than the state risk-based cleanup goal (24 mg/kg) in 11 months. While institutional controls were imposed the average soil concentration of .51 mg/kg MC met cleanup goals.
- The Camelot Cleaners Superfund site in North Dakota used an ERH system to treat approximately 370,000 ft^3 of soil and groundwater with the deepest zone targeted at 56 bgs. Cleanup goals (3 mg/kg in soil and 1 mg/L total volatiles in groundwater) were largely met with one small area having levels above 3 mg/kg. The heating and extraction system operated for 11 months.
- A Former MGP Site in Massachusetts used in situ thermal conduction to recover 16,000 gallons of coal tar and clean up about 54,000 ft^3 of contaminated soil and fill in an abandoned gasholder. The goal to clean up the soil to meet state cleanup

levels for unrestricted use was met; however, the site has institutional controls as a whole because there are other areas at the site that could not be cleaned up because of their proximity to operating equipment and pipelines. The gas holder project lasted approximately two years from initial construction to demobilization.

- In situ thermal desorption was used to treat about 450,000 ft^3 of soil at the Former Wood Treatment Area, California. The goal was to treat soil containing up to 35,000 mg/kg PAHs and 58 mg/kg PCP to levels of 0.065 mg/kg (expressed as benzo(a)pyrene equivalents [B(a)P-eq]) and 2.5 mg/kg PCP. Cleanup goals were met and the site is open for unrestricted use.
- Steam with injected air was used at the Visalia Pole Yard to treat about 300,000 pounds of contaminants. DNAPL (creosote) and LNAPL (diesel range hydrocarbons were present at the site. The cleanup goals of 17 mg/kg and 1 µg/L pentachlorophenol, 0.39 mg/kg and 0.2 µg/L benzo(a)pyrene and 0.001 mg/kg and 30 pg/L TCDD equivalent were all achieved by the end of an air sparging and bioventing polishing step following the steam application.

In Situ Chemical Oxidation – The five ISCO projects were conducted at two drycleaning facilities, a former MGP, a former chemical manufacturing plant, and a landfill. A variety of oxidants were used:

- Fenton's reagent (2 sites)
- Permanganate (1 site)
- Sodium persulfate (1)
- Hydrogen peroxide (1 site)
- Ozone (1 site)

The geology at the ISCO sites range from fine- to medium-grained sand to stiff clay. Several of the projects involved multiple (up to four) phases of chemical injection and the ozone remediation pulsed ozone and oxygen into the subsurface over a two year period . Three of the sites received closure letters, and one will receive a Certificate of Completion once deed restrictions are recorded. The landfill site has not yet received an NFA determination. Although MCLs have been met at the point of compliance (the site boundaries) and the onsite plume is approaching MCLs, groundwater monitoring is continuing at the landfill to determine when the onsite plume has met cleanup standards and ensure compliance.

- The Former MGP Site, Southern California Edison used excavation and in situ ozonation to reduce total polycyclic aromatic hydrocarbons (PAHs) concentrations in soil from 2,500 mg/kg to less than 1.75 mg/kg as B(a)P-eq (the site-specific risk-based cleanup goal) in approximately three years. Cleanup goals in groundwater and soil were met except for an inaccessible area around a highway foundation.
- The Former Cowboy Cleaners Site, Colorado, used potassium permanganate to reduce PCE concentrations in groundwater from 1,900 µg/L to 48 µg/L in approximately one year. This was sufficient for the state to issue a NFA with site uses restricted to commercial.
- Dry Clean USA #11502, Florida, used a combination of P&T, SVE, and hydrogen peroxide to treat a groundwater plume approximately 800 ft by 300 ft and up to 68 ft deep. The goal was to reduce PCE concentration in the groundwater to 3 µg/L, or less. The P&T and SVE systems operated about 3.5 years. They were followed by a one-month application of peroxide for polishing. One year PCE concentrations varied between 1.7 and 3 µg/L and the state issued an NFA with unrestricted use.
- Four injections of Fenton's reagent were conducted from 1998 to 2001 at the Naval Submarine Base Kings Bay, Site 11, Georgia. Groundwater P&T to contain the groundwater plume (700 ft by 200 ft and 30 to 40 ft deep) within the site bounda-

ries had failed, and modeling suggested that if the plume concentrations were lowered to 100 µg/L total chlorinated hydrocarbons, MNA would treat the remaining dissolved contaminants. ISCO reduced levels to the target, but made the aquifer aerobic in the injection areas and some distance downgradient. To return the now aerobic section of the aquifer to reducing conditions, subsequent injections of emulsified oil were made and these created the necessary anaerobic conditions for degradation. As of 2004, the levels have been reduced to less than 13.9 µg/L. MNA is the final corrective action for remaining groundwater contamination at the site. MCLs have been met at the site property line for all contaminants having them.

- Following large-auger excavation of the source area, persulfate catalyzed with hydrogen peroxide was injected at the Sta-Lube site, California, to treat a methylene chloride plume. Due to the presence of DNAPL, a 80-ft by 30-ft plume beneath the building was not treated by the previous SVE and P&T systems. Concentrations were reduced from a maximum of 18,000 µg/L to the cleanup goal of 50 µg/L within 5 months. Final closure was granted in June 2008.

SVE and Air Sparging – Contamination at a solvent transfer facility was cleaned up principally by SVE and air sparging.

- The Pasley Solvents and Chemicals Superfund Site in New York used SVE/AS to treat soil source zones (total VOCs up to 603 mg/kg) and a 60-ft by 400-ft-long chlorinated solvents plume (TCE up to 320 µg/L). All cleanup goals were met including Maximum Contaminant Levels (MCLs) for groundwater contaminants. A NFA letter was issued with no institutional controls requirements. The remediation took 60 months with 18 months of subsequent groundwater monitoring.

REFERENCES

General

EPA 2007. Recommendations from the EPA Ground Water Task Force. EPA 500-R-07-001.December 2007. http://gwtf.clu-in.org/docs/report/gwtf_report_coverletter.pdf

EPA. 2006. Engineering Forum Issue Paper: In Situ Treatment Technologies for Contaminated Soil, EPA 542-F-06-013. http://www.epa.gov/tio/tsp/download/542f06013.pdf

EPA. 2004a. DNAPL Remediation: Selected Projects Approaching Regulatory Closure, EPA 542-R-04-016. http://www.epa.gov/tio/download/remed/542r04016.pdf

EPA. 2004b. Site Characterization Technologies for DNAPL Investigations. EPA 542 R-04-017. http://www.clu-in.org/download/char/542r04017.pdf

EPA 2004c. In Situ Thermal Treatment of Chlorinated Solvents: Fundamentals and Field Applications. EPA 542-R-04-010. http://costperformance.org/remediation/pdf/in_situ_thermal_trtmnt.pdf

EPA. 2004d. Cleaning Up the Nation's Waste Sites: Markets and Technology Trends. EPA 542-R-04-015. http://clu-in.org/market/

EPA 2003. The DNAPL Remediation Challenge: Is There a Case for Source Depletion? EPA/600/R-03-143. http://www.clu-in.org/download/remed/600R03143.pdf

EPA. 2002. Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action. EPA 530 F-01-021.

http://www.epa.gov/correctiveaction/resource/guidance/gw/gwhandbk/gwhb041404.pdf

EPA. 1999a. Groundwater Cleanup: Overview of Operating Experience at 28 Sites. EPA 542-R-99-006. http://www.clu-in.org/download/remed/ovopex.pdf.

EPA. 1999b. Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites. OSWER Directive 9200.4-17P. http://www.epa.gov/OUST/directiv/d9200417.pdf

EPA. 1996. The Role of Cost in the Superfund Remedy Selection Process. Publication 9200.3-23FS, 8 pp. EPA 540 F-96/018. http://www.epa.gov/superfund/resources/cost_dir/cost_dir.pdf

EPA. 1993. Guidance for Evaluating the Technical Impracticability of Ground Water Restoration. OSWER Directive 9234.2-25. http://www.epa.gov/swerffrr/pdf/groundwater.pdf

EPA. 1992. Estimating Potential for Occurrence of DNAPL at Superfund Sites. OSWER Publication 9355.4-07FS. National Technical Information Service (NTIS) Order Number PB92-963338CDH. http://www.epa.gov/superfund/resources/gwdocs/non_aqu.htm

Freeze, Allan R. and David B. McWhorter. 1997. A Framework for Assessing Risk Reduction Due to DNAPL Mass Removal from Low-Permeability Soils. Ground Water. Vol. 35, No. 1, Pages 111-123.

Illinois Environmental Protection Agency (IEPA). 2004. Fact Sheet. Tiered Approach to Correction Action Objectives (TACO). http://www.epa.state.il.us/land/taco/1-introduction.html

Illinois Administrative Code. Title 35, Subtitle G, Chapter I, Subchapter f, Part 742: Tiered Approach to Corrective Action Objectives. http://www.ipcb.state.il.us/documents/dsweb/Get/Document-38408/

ITRC. 2004. Strategies for Monitoring the Performance of DNAPL Source Zone Remedies (DNAPLs-5). http://www.itrcweb.org/gd_DNAPLs.asp

ITRC. 2003a. Technology Overview: An Introduction to Characterizing Sites Contaminated with DNAPLs. http://www.itrcweb.org/gd_DNAPLs.asp

ITRC. 2000. Technology Overview: Dense Non-Aqueous Phase Liquids (DNAPLs): Review of Emerging Characterization and Remediation Technologies. http://www.itrcweb.org/Documents/DNAPLs-1.pdf

Kram, Mark L., Arturo Keller, Joseph Rossabi, and Lorne Everett. 2001. DNAPL Characterization Methods and Approaches, Part 1: Performance Comparisons. Ground Water Monitoring and Remediation. Fall. Pages 109-123. http://www.cluin.org/download/char/GWMR_Fall_109-123.pdf

NAVFAC. 2004. Guidance for Optimizing Remedy Evaluation, Selection, and Design. UG-2060-ENV. https://portal.navfac.navy.mil/portal/page/portal/navfac/navfac_ww_pp/navfac_nfesc_pp/environmental/erb/opt/ug-2060-opt.pdf

National Research Council. 2003. Environmental Cleanup at Navy Facilities: Adaptive Site Management. National Academies Press. http://www.nap.edu/catalog.php?record_id=10599

National Research Council. 1997. Innovations in Ground Water and Soil Cleanup – From Concept to Commercialization. National Academies Press. http://www.nap.edu/catalog.php?record_id=5781

Sale, Tom C. and David B. McWhorter. 2001. Steady State Mass Transfer from Single-Component Dense Nonaqueous Phase Liquids in Uniform Flow Fields. Water Resources Research. Vol. 37, No. 2. pp. 393-404.

In Situ Bioremediation

EPA. 2000. Engineered Approaches to In Situ Bioremediation of Chlorinated Solvents: Fundamentals and Field Applications. EPA 542-R-00-008. http://cluin.org/download/remed/engappinsitbio.pdf

ITRC. 2005. Overview of In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones. http://www.itrcweb.org/documents/BioDNAPL-1.pdf

ITRC. 2008. In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones. http://www.itrcweb.org/Documents/bioDNPL_Docs/BioDNAPL3.pdf

In Situ Chemical Oxidation

Environmental Security Technology Certification Program (ESTCP). 1999. Technology Status Review: In Situ Oxidation. http://www.estcp.org/documents/techdocs/ISO_Report.pdf

Huling, Scott and Bruce Pivetz. 2006. Engineering Issue: In-Situ Chemical Oxidation, EPA/600/R-06/072. http://www.epa.gov/ada/download/issue/600R06072.pdf

ITRC. 2001. Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater. http://www.itrcweb.org/Documents/ISCO-2.pdf

Watts, R., Frank Loge, and Amy Teel. 2006. Improved Understanding of Fenton-Like Reactions for the In Situ Remediation of Contaminated Groundwater Including Treatment of Sorbed Contaminants and Destruction of DNAPLs. Strategic Environmental Research and Development Program. http://docs.serdp-estcp.org/viewfile.cfm?Doc=ER_1288_FR.pdf

In Situ Surfactant/Co-Solvent Flushing

ITRC. 2003b. Technical and Regulatory Guidance for Surfactant/Co-Solvent Flushing of DNAPL Source Zones. http://www.itrcweb.org/gd_DNAPLs.asp

In Situ Thermal Treatment

EPA. 2004c. In Situ Thermal Treatment of Chlorinated Solvents - Fundamentals and Field Applications. EPA 542-R-04-010. http://cluin.org/techfocus/default.focus/sec/Thermal_Treatment:_In_Situ/cat/Application/

Davis, E. 1998. Ground Water Issue: Steam Injection for Soil and Aquifer Remediation. EPA 540/S-97/505, 16 pp. http://www.epa.gov/ada/download/issue/steaminj.pdf

Davis, E. 1997. Ground Water Issue: How Heat Can Enhance In-Situ Soil and Aquifer Remediation: Important Chemical Properties and Guidance on Choosing the Appropriate Technique. EPA 540/S-97/502, 18 pp. http://www.epa.gov/ada/download/issue/heatenh.pdf

Gavaskar, Arun, Mohit Bhargava, and Wendy Condit. 2007. Final Report: Cost and Performance Review of Electrical Resistance Heating (ERH) for Source Treatment.

Naval Facilities Engineering Service Center, TR-2279-ENV, 133 pp. http://costperformance.org/remediation/pdf/Navy-ERH_Review.pdf

Zero-Valent Iron Injection

EPA, 2008. Nanotechnology for Site Remediation. EPA 542-F-08-009. http://www.clu-in.org/542f08009

EPA. 2004. Demonstration Injection of In Situ Dehalogenation of DNAPL through Injection of Emulsified Zero-Valent Iron at Launch Complex 34 in Cape Canaveral Air Force Station Florida: Innovative Technology Evaluation Report. EPA/540/R-07/006. http://www.epa.gov/nrmrl/pubs/540r07006/540r07006.pdf

U.S. Department of the Navy. 2003. Final Cost and Performance Report - Ferox$^{\text{sm}}$ Injection Technology Demonstration Parcel C, Remedial Unit C4, Hunters Point Shipyard, San Francisco, California, July 11, 2003. DS.A013.10177 http://costperformance.org/pdf/20040701_352.pdf

Combined Remedies

NAVFAC. 2004. Guidance for Optimizing Remedy Evaluation, Selection, and Design, User's Guide. UG-2060-ENV. http://www.clu-in.org/download/remed/Navy-OPT-doc-UG-2060-OPT.pdf

NOTICE AND DISCLAIMER

Preparation of this report has been funded wholly or in part by EPA under Contract Number 68-W-03-038. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. A PDF version of this report is available for viewing or downloading from the Hazardous Waste Cleanup Information (Clu-In) web site at http://clu-in.org. For more information regarding this report, contact Linda Fiedler of EPA's Office of Superfund Remediation and Technology Innovation, at (703)603-7194 or fiedler.linda@epa.gov.

Appendix A

DNAPL Remediation Project Profiles

The DNAPL remediation projects profiled here were conducted as full-scale remediation projects rather than research demonstrations, and the sampling efforts typically were not sufficient to establish the exact quantity of DNAPL originally present. Most of these sites have reached regulatory cleanup goals and require no further action with no further monitoring.

Confidential Chemical Manufacturing Facility, Portland, Indiana

Technology Used: In situ conductive heating and vacuum (in situ thermal desorption)

Regulatory Program: State Voluntary Cleanup Program

Project Duration: July to December 1997

Information Last Updated: 2008

Site Information: The 16-acre chemical manufacturing facility is located in the southern portion of Portland, Indiana, southeast of the Salamonie River. Since 1886, the area has been used as a lumberyard for the manufacture of wheels, hard rubber products used in automobiles, and plastic exterior automobile parts. The site has four buildings including a north plant building that is currently being used part-time for the reworking of automotive parts. A sampling event conducted in June 1994 revealed the presence of volatile organic compounds (VOCs) in soil and groundwater. Additional investigations performed from July 1995 to February 1996 confirmed the presence of VOCs in subsurface soil of two areas near the north plant building. Contamination in one area covered 150 ft by 50 ft to a depth of 18 ft, and the contamination in the other extended to an area of 30 ft by 20 ft to a depth of 11 ft.

Contaminants: Chlorinated solvents (PCE, TCE, and 1,1-DCE) were detected in the unsaturated zone at levels up to 3,500 mg/kg, 79 mg/kg, and 0.65 mg/kg, respectively. The elevated concentration of PCE suggested the presence of DNAPL. VOCs were not found above the cleanup goals in groundwater after treatment.

Hydrogeology: The facility overlies a heterogeneous combination of fill, clayey sand, and construction debris, to a depth of about 7 ft. Tills, consisting of moist, silty clay extend to a depth of 18 to 19 ft bgs. Fine to coarse gray sand with some gravel are found beneath the till at depths greater than 19 ft and extending to a maximum of 30 ft. The estimated hydraulic conductivity of the till was 10^{-8} cm/s. Groundwater occurs at approximately 22 ft bgs.

Project Goals: Soil cleanup goals were established based on the Indiana Department of Environmental Management (IDEM) Tier II Cleanup Goals for Industrial Land Use http://www.in.gov/idem/5516.htm

Cleanup Criteria for Confidential Chemical Manufacturing Facility, Portland, Indiana (Tier II)

Contaminant	Tier II Cleanup Level for Soil (mg/kg)
1,1-DCE	0.080
TCE	25
PCE	8

Cleanup Approach: Site investigations began in 1994. The in situ conductive heating system began operation in July 1997 to treat contaminated soil in two source areas. A total of 130 heater/vacuum wells were installed on a 7.5-ft triangular spacing in the first source area to a depth of 19 ft. Fifteen heater/vacuum wells were installed on a 7.5-ft triangular spacing to depths of 12 ft in the second source area. The heaters in these wells operated at a temperature of 1,400 - 1,600°F, to raise the subsurface temperatures within the treatment zone to an average of 275°F.

The heater/vacuum wells also extracted soil gas. Off-gases were treated with a flameless thermal oxidizer, cooled by a heat exchanger, and then passed through a carbon adsorption bed. Off-gases were monitored for hydrogen chloride, which was used as an indicator of the decomposition of chlorinated solvents. Off-gases were treated with an 1800 standard cubic feet per minute (scfm) flameless thermal oxidizer with an operating temperature range of 1,800-1,900°F, cooled by a heat exchanger, then passed through a carbon adsorption bed.

To determine the effectiveness of the treatment system, about 50 soil samples were collected from the coldest locations within the treatment zone farthest from each heater well and analyzed for VOCs. Based on the results, heating was discontinued in December 1997. Confirmation sampling was conducted after monitoring the soil temperatures for six months.

Project Time Line:

1994 – 1996 Site investigations performed

7/97 – 12/97 In situ conductive heating performed

Project Results: Following treatment, results of confirmation sampling showed that PCE and TCE concentrations were below the cleanup goals. No confirmation samples were available for the smaller, 1,1-DCE contaminated zone area. The table below shows contaminant concentrations at locations that had relatively higher concentrations before treatment. Based on the results, the IDEM issued a NFA letter for this property. Information about the date or conditions of the NFA letter was not available.

Comparison of Selected Pre-Heating and Post-Heating Contaminant Concentrations in Soil

Sampling Location	Depth (ft)	Contaminant Concentration (mg/kg)			
		Before Treatment		After Treatment	
		PCE	TCE	PCE	TCE
SA 13	9-10	3,500	79	0.011	0.020
GP 31	15-16	570	Not sampled	0.18	0.008
SA 4	4-5	23	0.25	0.530	ND
SB 20	4-5	2.9	0.67	0.046	ND
SB 19	12-14	76	1.6	0.048	ND

ND - non-detect (detection limits not provided)

Source: Federal Remediation Technologies Roundtable. 2003. “Cost and Performance Report: In situ Conductive Heating at the Confidential Chemical Manufacturing Facility, Portland, Indiana.”
http://costperformance.org

Avery Dennison Site, Waukegan, Illinois

Technology: ERH

Regulatory Program: Illinois EPA Site Remediation Program

Project Duration: December 1999 to November 2000

Information Last Updated: 2008

Site Information: The Avery Dennison site is located in the Waukegan-Gurnee Industrial Park in Waukegan, Illinois. Film coating operations were performed at this site from 1975 to 1992. MC was used in these operations and transferred to above-ground storage tanks via underground piping. Site investigations showed the occurrence of MC in the soil and groundwater in several areas of the site.

Contaminants: Approximately 16,000 ft^3 of soil was contaminated with MC to depths as great as 24 ft bgs. Concentrations of MC ranged to a high of 50,000 mg/kg and averaged 1,900 mg/kg. Information about the concentration of MC in groundwater was not available.

Hydrogeology: The geology underlying the two-acre site is predominantly heterogeneous silty-clay glacial till to a depth of about 180 ft bgs. An 8-ft-thick running sand unit occurs around 22 ft bgs. Groundwater is typically found around 25 ft bgs with perched water units encountered at as shallow as 6 ft bgs. Bedrock is found at depths ranging from 180 to 270 ft bgs.

Project Goals: The remediation objective at the Avery Dennison site was to reduce the concentration of MC in the soil to below 24 mg/kg, based on IEPA's Tiered Approach to Corrective Action Objectives.

Cleanup Approach: The treatment area was divided into 20 treatment cells. For each treatment cell, electrodes were installed around the perimeter to a depth of 24 ft. A total of 95 electrodes were installed including six below an active street, and 16 inside the existing building. Two thermocouples were installed in the center of each treatment cell, at the shallowest (4 ft bgs) and deepest levels of contamination (24 ft bgs). In addition, 34 vacuum extraction wells and five horizontal wells were installed to extract soil vapor and steam. The designed power input was 1,250 kilowatts (kW). After six months of operation, target soils reached an average temperature of 80^{o}C, with central areas reaching boiling temperatures.

Project Time Line:

1985 – Removal Action

1988 – Installation of grout curtain around the former bulk storage area

1991-1994 – Soil vapor extraction performed at former bulk storage area. This was ineffective and discontinued at the end of 1994.

1992-1994 – Pump and treat of groundwater

1994-1998 – Air sparging of groundwater

12/99 – ERH initiated in western portion

6/00 – ERH initiated in eastern portion

11/00 – ERH completed

4/01 – IEPA issued NFR letter

Project Results: Very little MC was recovered by the vacuum systems. Analysis of soil samples collected in areas of known high MC concentrations had high concentrations of chloride ions indicating that the MC was destroyed in place by hydrolysis. A total of 125 soil samples were collected and analyzed for MC. The average MC concentration in soil was reduced to 2.51 mg/kg, which is below the cleanup goal. Based on the confirmatory sampling results, in April 2001, the IEPA issued a NFR letter, which specified several engineering and institutional controls, including a prohibition on installing and using potable water supply wells in a specified area around the site. Redevelopment was restricted to industrial/ commercial reuse, and the site was subsequently redeveloped into an office and warehouse park.

Sources: Current Environmental Solutions website: http://www.cesiweb.com. Federal Remediation Technologies Roundtable. 2003. "Cost and Performance Report: Electrical Resistive Heating at the Avery Dennison Site, Waukegan, Illinois." http://costperformance.org.

Camelot Cleaners, West Fargo, North Dakota

Technology: ERH

Regulatory Program: U.S. EPA, Region 8 Superfund

Project Duration: June 2004 to July 2006

Information Last Updated: 2008

Site Information: Camelot Cleaners is an operating drycleaner that uses PCE as its cleaning solvent. The cleanup footprint is about 10,300 ft^2 with depths of the contamination ranging to 56 ft bgs. The area includes part of the yard of an occupied residence.

Contaminants: PCE and its degradation products (TCE and DCE) were detected in soil and groundwater. PCE concentrations were up to 2,200 mg/kg in soil and 89 mg/L in groundwater. The contaminated volume of soil was estimated to be about 370,000 ft^3 with the deepest zone targeted at 56 bgs.

Hydrogeology: Camelot Cleaners is underlain by low-permeability clay with goethite infilling of joints and fractures. Groundwater occurs between 3 and 7 ft bgs and tends to be perched. The regional aquifer is at approximately 60 to 70 ft bgs.

Project Goals: The project goals were to reduce PCE levels to less than 3 mg/kg in soil and total VOCs to less than 1 mg/L in groundwater.

Cleanup Approach: The deployment of the six-phase electrical heating system included 56 multi-zone electrode/vent assemblies and several horizontal soil vapor extraction wells. In especially clayey horizons, the extraction wells were augmented with dual vacuum extraction wells. Soil temperature was recorded at ten temperature monitoring piezometers. Nine multi-level monitoring wells were installed around the perimeter of the site to monitor existing conditions and cleanup success, and to ensure that any subsurface migration of contaminants would be detected. The system removed about 5,188 pounds of contaminants.

Project Time Line:

6/04 – Site construction began

2/05 – Heating began

11/05 – Heating was stopped and the horizontal extraction well system was turned off

1/06 – Dual vacuum extraction well system was turned off following cool-down period

7/06 – EPA removed the electrode and vent assemblies, and after discussion with the North Dakota Department of Health, the groundwater monitoring wells were abandoned.

Project Results: A total of 5,188 pounds of VOC mass was removed within one year of ERH operation. EPA confirmation sampling indicated that soil contamination had been reduced by 99.96 to 100% and groundwater concentrations had been reduced by 99.98%. Only one area had concentrations of PCE over 3 mg/kg, and all the groundwater samples were under 1 mg/L. The site is now in a no further action, no further groundwater monitoring required status.

Sources: DNAPL Remediation In Low Permeability Clays Camelot Cleaners Superfund Site Fargo, ND
http://www.cesiweb.com.

Personal communication with Joyce Ackerman, U.S. EPA Region 8, April 27, 2007 and April 28, 2008.

Former MGP Gasholder, North Adams, Massachusetts

Technology: Thermally enhanced free product recovery, in situ thermal solidification (ISTS), and in situ thermal desorption (ISTD)

Regulatory Program: Massachusetts Department of Environmental Protection

Project Duration: August 2003 to June 2005

Information Last Updated: 2008

Site Information: The former MGP in North Adams, Massachusetts, operated from the 1860s to the 1950s. When the 18-ft deep, 62-ft-diameter gasholder was decommissioned, it was backfilled with soil and debris enclosing a volume of approximately 2,013 yd^3. Based on limited soil investigations within the gasholder, residual coal tar was present throughout the soil. The bottom four feet of soil were saturated with coal tar DNAPL.

Contaminants: The contaminants of concern at the site are semivolatile organic compounds associated with coal tar. The maximum concentrations of some of the contaminants detected were: benzo(a)pyrene (650 mg/kg), naphthalene (14,000 mg/kg), benzene (6,200 mg/kg), and TPH (230,000 mg/kg).

Hydrogeology: The contents of the gasholder comprise a mixture of sand, gravel, cobbles, and other fill material. The regional aquifer is located beneath. Perched groundwater was found within the gasholder at 3 ft bgs.

Project Goals: The project goals, derived from a human health risk assessment, depended on the depth. Within 6 to 15 ft bgs, the goals were to eliminate DNAPL and reduce contaminants below the Massachusetts Contingency Plan's upper concentration limits for a potential construction worker exposure scenario, e.g., benzo(a)pyrene (300 mg/kg), naphthalene (10,000 mg/kg), benzene (2,000 mg/kg), and TPH (10,000 mg/kg). Within the bottom of the gasholder (15 to 18 ft bgs), the goal was to eliminate DNAPL so that there would not be a risk of future release of DNAPL to groundwater. The regional aquifer occurs below the base of the gasholder.

Cleanup Approach: Three levels of heating were conducted: 1) Low-temperature heating for thermally enhanced free product recovery of coal tar from the gasholder; 2) Moderate-temperature heating for ISTS of coal tar at the bottom of the gasholder; and 3) High-temperature heating and ISTD in the midsection of the gasholder (6-15 ft bgs).

Twenty-five thermal wells─19 heater-only wells and 6 heater-vacuum wells─were installed to the base of the gasholder. Prior to heating, 100,000 gallons of water were pumped from the gasholder and treated by passing it through an oil/water separator followed by clay-carbon media and activated carbon.

Next, low-temperature heating was conducted to remove free-flowing coal tar DNAPL. Air was injected into each thermal well to maintain oxidizing conditions within the lower part of the gasholder throughout the remediation process. Thermocouple arrays were used to ensure that subsurface temperatures within the treatment zone reached target goals.

The temperature was then raised to or slightly above the boiling point of water to eliminate 16,000 gallons of additional DNAPL via ISTS. The temperature was raised again to 325°C to volatilize, boil, pyrolize, and oxidize the remaining contaminants through ISTD. Vapors were treated using a regenerative thermal oxidizer with a vapor phase activated carbon unit for backup.

Project Time Line:

11/03 – Site construction

2/04 – Dewatering tar recovery

7/04 to 3/05 – Full power heating

6/05 – Demobilization

Project Results: The intermediate heating recovered 16,000 gallons of coal tar. Within the upper portion of the gasholder (6 to 15 ft bgs), full heating brought average concentrations of all constituents of concern below the Massachusetts upper concentration limits. The final averages were: 0.33 mg/kg benzo(a)pyrene, 5.7 mg/kg naphthalene, 0.35 mg/kg benzene, and 43.15 mg/kg TPH. Within the bottom of the gasholder (15 to 18 ft bgs), full heating reduced concentrations of benzene to 0.95 mg/kg and naphthalene to 70 mg/kg. In the process, the previously liquid coal tar was thermochemically solidified to material that had the appearance of asphalt and no longer a DNAPL consistent with the findings of Hayes (2002).

All goals for the project were met. The owner filed for an Activity and Use Limitation to the Massachusetts Department of Environmental Protection, rather than a No Further Action Determination, because unrestricted use was not obtainable for the site as a whole. Elsewhere on the MGP property, contaminants were allowed to remain in place beneath a cap.

Sources: Fact sheet. Commercial Project—MGP Gasholder. TerraTherm® Inc.
http://www.terratherm.com

Baker, Ralph S., et al. In Situ Thermal Destruction (ISTD) of MGP Waste in a Former Gasholder: Design and Installation.
http://www.terratherm.com/resources/TechPapers/Terratherm%20Paper%20556%20-%20Monterey.pdf

Baker, Ralph, et al. Demonstration of Three Levels of In-Situ Heating for Remediation of a Former MGP Site.
http://www.terratherm.com/resources/TechPapers/Baker%20et%20al.%202006%20Monterey%20MGP.pdf

Hayes, Thomas D. 2002. Development of In Situ Thermochemical Solidification for the Risk Based Treatment of Coal-Derived Dense Nonaqueous Phase Liquids. GRI-04/0215. Prepared by Gas Technology Institute, Des Plaines, IL for Gas Research Institute.

Former Wood Treatment Area, Alhambra, California

Technology Used: In situ thermal desorption (ISTD)

Regulatory Program: Voluntary action under California Department of Toxic Substances Control (DTSC) Expedited Remedial Action Program

Project Duration: May 2002 – February 2007

Information Last Updated: 2008

Site Information: Southern California Edison's 33-acre facility in Alhambra currently is used for storage, maintenance, and employee training. A portion of the facility, the 2-acre former wood treatment area, was used from approximately 1922-1957 to treat utility poles by immersing them in creosote. Pentachlorophenol (PCP) was also used briefly before operations were shut down. Spills and/or leaks led to the contamination of underlying soil.

Contaminants: PAHs and PCP were present in site soil at maximum concentrations of 35,000 mg/kg and 58 mg/kg, respectively, and mean concentrations of 2,306 mg/kg and <1 mg/kg. Dioxins, expressed as 2,3,7,8-tetrachlorodibenzodioxin (TCDD) Toxic Equivalency Quotient (TEQ), were present at a maximum concentration of 0.194 mg/kg and mean concentration of 0.018 mg/kg. The PCP used at the site is believed to be the source of the dioxins. Approximately 16,500 yd^3 of contaminated soil required treatment.

Hydrogeology: The facility is underlain by fill and silty sand interbedded with sand, silt, and clay. The water table is greater than 240 feet bgs.

Project Goals: The following table shows the soil remediation standards for the treatment area.

Cleanup Criteria for the Former Wood Treatment Area

Contaminant	Soil Remediation Standard (mg/kg)
Total PAHs	0.065*
Pentachlorophenol	2.5
Dioxins	0.001**

*Expressed as (B(a)P-eq)

** Expressed as 2,3,7,8-TCDD TEQ.

Cleanup Approach: The ISTD process involved simultaneous application of thermal conduction heating and vacuum to treat the contaminated soil in situ. A total of 785 thermal wells (131 heater-vacuum and 654 heater-only wells) were installed on a hexagonal grid within the 31,430 ft^2 target treatment zone. The heater-vacuum wells were installed at the center of each hexagon, and the heater-only wells were installed at 7-ft intervals on center. The wells ranged from 7 to 102 ft in depth.

To avoid exceeding the local power supply, treatment proceeded in two phases. Prior to Phase 1 of heating, a light aggregate cement surface was poured over the wellfield for insulation and to provide a vapor seal that prevented steam and vapor loss to the atmosphere. To improve the insulation during Phase 2, a similar cement was poured above and below a layer of insulation board.

The target soil temperature of 620ºF was attained in approximately 6 months of Phase 1 heating and was maintained for three days. Gases emerging from the heated soil were collected under vacuum and conveyed to an air quality control system, which consisted of a thermal oxidizer, heat exchanger to cool the gases, and vessels of granular activated carbon in series. Following wellfield cooldown, Phase 2 heating was initiated. Continuous emissions monitoring, vapor sampling, and source tests were used to monitor system performance.

Project Time Line:

00 – Treatability study and selection of conductive heating

6/02 – 4/04 Phase 1 In Situ Thermal Desorption treatment

7/04 – 9/05 Phase 2 In Situ Thermal Desorption treatment

3/06 – Demobilization from site

2/8/07 – DTSC issues Remedial Action Completion Report Approval and Certification

Project Results: The site-wide mean benzo(a)pyrene equivalent and 2,3,7,8 TCDD TEQ concentrations in soil were reduced from 30,600 µg/kg and 18 µg/kg, respectively, to 59 µg/kg and 0.11 µg/kg. These concentrations are below their respective 65 µg/kg and 1 µg/kg cleanup goals. The mean PCP soil concentration was 1.25 mg/kg. PCP was not detected in any of the soil samples at or above the remediation goal of 2.5 mg/kg.

Dioxin emissions were 0.0084 ng TEQ/dsm^3 compared to the 0.2 ng TEQ/ dsm^3 standard. In February 2007, the California Department of Toxic Substances Control issued a Remedial Action Completion Report Approval and Certification stating that the treatment area had been remediated to allow for unrestricted land use and that no further action was required. The cost of treatment was estimated to be 40% lower than the cost for excavation.

Sources: Fact sheet: Former Wood Treatment Area. TerraTherm® Commercial Project-California.
http://www.terratherm.com/CaseStudies/WS%20Final%20Alhambra%20Sheet.pdf

Baker, Ralph S. Devon Tarmasiewicz, and John M. Bierschenk (TerraTherm, Inc.), Jennie King and Tony Landler (Southern California Edison), and Doug Sheppard (Lopez and Associates Engineers). 2007. Completion of In-Situ Thermal Remediation of PAHs, PCP, and Dioxins at a Former Wood Treatment Facility. Presented at IT3 ’07 Conference, May 14-18, 2007 in Phoenix, AZ.
http://www.terratherm.com/resources/TechPapers/07-A-88-AWMA-IT3-Baker%20rev%20a.pdf

Visalia Pole Yard, Visalia, California

Technology Used: Grout wall, pump and Treat (P&T), in situ thermal desorption (steam), and excavation

Regulatory Program: US EPA Superfund NPL site with state lead

Project Duration: 1976 to 2008

Information Last Updated: February 2009

Site Information: Southern California Edison operated a 20 acre fabrication yard (Visalia Pole Yard) to produce wooden poles for use in the distribution of electricity throughout the utility's service territory from 1925 to 1980. Western red cedar trees were logged and transported to the yard, debarked, shaped, and chemically preserved, Until 1968, chemical preservation consisted of immersion of the poles in heated bulk creosote. From 1968 to cessation of operations, a solution of pentachlorophenol and diesel was substituted as the wood preservative (DTSC 2005).

Contaminants: Substantial releases of creosote which contains numerous polycyclic aromatic hydrocarbons including benzo(a)-pyrene, pentachlorophenol (PCP), which contains polychlorinated dibenzo-p-dioxin and furan impurities, and diesel fuel used as a carrier fluid for the PCP have occurred. Other contaminants of concern include chrysene, 2-methylnaphthalene, naphthalene, and phenanthrene (EPA 1994).

Hydrogeology: The sediments underlying the VPY are composed of alluvial-fan deposit from the Kaweah River and its distributaries. The important hydrostratigraphic units beneath the site are as follows: the shallow aquifer (30 to 50 feet bgs; dewatered since the 1980s), the shallow aquitard (50 to 75 feet bgs), the intermediate aquifer (75 to 100 feet bgs), the intermediate aquitard (100 to 125 feet bgs), and the deep aquifer (125 to about 180 feet bgs). Aquitards generally consist of silty materials whereas aquifers are composed of sand. Testing of the intermediate aquifer indicated a transmissivity of approximately 50,000 gallons per day per foot (gpd/ft) and the shallow aquitard restricts vertical movement of the groundwater when saturated. Short-term pumping from the deeper aquifer affects water in the intermediate aquifer (DTSC undated).

Project Goals: The following table shows the remediation goals for several of the contaminants of concern.

Cleanup Goals

Parameter	Soil	Groundwater
Pentachlorophenol	17 mg/kg	1µg/L
Benzo(a)pyrene	0.39 mg/kg	0.2 µg/L
TCDDequivalent[1]	0.001 mg/kg	30 pg/L

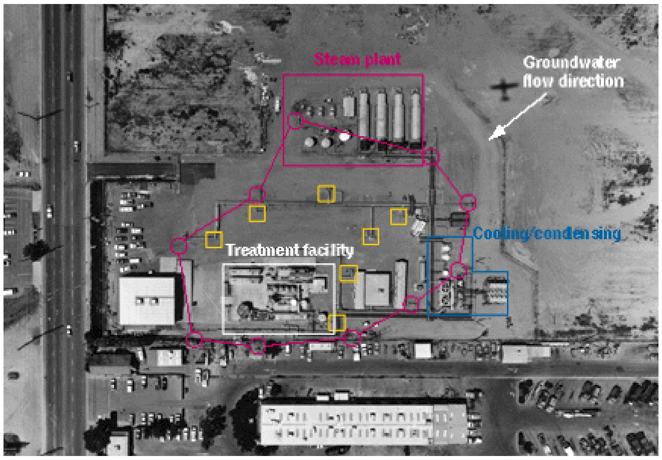
[1] Dioxin concentration expressed as 2,3,7,8-tetrachlorodibenzodioxin

Source:DTSC 2005

Cleanup Approach: Excavation and disposal of affected soils has occurred on numerous occasions beginning in 1972. Cleanup of the groundwater began in 1975 with the installation of a pump and treat system. In 1977 a slurry wall was built and keyed into the shallow aquitard to about 60 feet bgs (DTSC undated).

In 1997 it was decided to use in situ steam desorption as a means for remediating the source zones. The system applied steam and air to the subsurface and the steam front was monitored using electrical resistance tomography. The steam remedy operated in two phases, between May 1997 and June 2000. Phase 1 operations focused on the intermediate aquifer, with injection and extraction wells screened between 80 and 100 feet bgs. Phase 2 operations began in November 1998 and included steam injection and extraction below the intermediate aquitard, with injection wells screened between 125 and 145 feet bgs. Phase 2 operations continued until June 2000, when a precipitous drop in the rate of removal of WTCs was measured (DTSC undated).

Following cessation of the steam treatment, the enhanced biological degradation system was installed and operated (SCE, 2001) to augment existing physical processes that were initiated by the steam treatment and to encourage natural biological processes to flourish. This system was in operation from June 2000 until March 2004. It included vadose zone bioventing and saturated zone biosparging, coupled with continued groundwater pump-and-treat operations. Construction completion of the enhanced biological degradation system was documented in the 2001 Preliminary Close Out Report (DTSC undated).



An Aerial View of the Visalia Site. Injection Wells are Shown in Magenta circles. Extraction Wells are Yellow squares.

Courtesy: DOE

A post-remediation soil investigation of the surface soils was conducted at this site in November 2004. Tetrachlorodibenzo-p-dioxin (TCDD) was detected slightly above the cleanup standards at four locations. As a result of the 2005 Five-Year Review, contaminated surface soil (soil between zero and ten feet below grade) was removed in July 2006 and verified with confirmatory sampling to be below the cleanup standards prescribed in the ROD (DTSC undated).

Project Time Line:

1972—onward Excavation and removal activities
1975—2004 Pump and treat
1976-1977—Placement of slurry wall
May 1997—June 2000 Two phase steam injection
June 2000—March 2004 Enhanced biological degradation system
July 2006 Removal of PCP hotspot (approximately two-thirds cubic yard)
May 2007 Covenant to Restrict Use of Property Environmental Restriction

Project Results: While the cleanup did not leave the land open to unrestricted use, soil cleanup goals were met in the first ten feet of the subsurface. This is the interval considered necessary for construction purposes of commercial or industrial properties (SCE 2008).

The steam remediation effort removed approximately 1,330,000 pounds of organic chemicals from the subsurface (SCE 2008).

The pump and treat system combined with the bio enhancement system polished the groundwater to an extent that risk based concentration goals were met as well as the three MCL values (DTSC undated).

The City of Visalia has indicated an interest in purchasing the property, following delisting, for an expansion of their current General Services operations (DTSC undated).

Sources: DOE. 2000. Hydrous Pyrolysis Oxidation/Dynamic Underground Stripping, EM-0504, 26 pp. http://www.osti.gov/bridge/product.biblio.jsp?osti_id=766922

DTSC. undated. Final Close Out Report Southern California Edison Visalia Pole Yard Superfund Site Visalia, Tulare County, California, 11 pp. http://www.envirostor.dtsc.ca.gov/public/profile_report.asp?global_id=54490002

DTSC. 2005. Southern California Edison Company, Visalia Pole Yard Superfund Site, 5-Year Review, 14 pp. http://www.envirostor.dtsc.ca.gov/public/profile_report.asp?global_id=54490002

EPA. 1994. Record of Decision: Southern California Edison Co. (Visalia Poleyard), EPA ID: CAD980816466, OU 01, Visalia, CA, 06/10/1994, 13 pp. http://cfpub.epa.gov/superrods/index.cfm?fuseaction=data.siterods&siteid=0902061

EPA Region IX. 2001. Preliminary Close Out Report, Southern California Edison Visalia Pole Yard.

Southern California Edison Company (SCE). 2001. Visalia Steam Remedial Action Plan, Construction Complete Report. http://www.envirostor.dtsc.ca.gov/public/profile_report.asp?global_id=54490002

Southern California Edison Company. 2008. Remedial Action Completion Report 2008, 9 pp. http://www.envirostor.dtsc.ca.gov/public/profile_report.asp?global_id=54490002

Southern Maryland Wood Treating Site, Hollywood, Maryland

Technology Used: Excavation and ex situ thermal desorption with some offsite disposal, P&T

Regulatory Program: Superfund

Project Duration: Construction of the thermal desorption units began in October 1997 and treatment was completed by October 2001.

Information Last Updated: 2008

Site Information: The Southern Maryland Wood Treating facility was owned and operated by the Southern Maryland Wood Treating Company from 1965 to 1978. Wood treating operations were conducted on approximately 25 acres of the 94-acre property. Wood was pressure-treated using creosote and PCP, and the liquid process wastes were disposed in six unlined lagoons. Seepage from the lagoons contaminated the underlying soil and groundwater. Contaminated groundwater discharged to an onsite pond contaminating surface water and sediments. In addition, groundwater and pond water discharges to Old Tom's Run contaminated the stream sediments. Contaminated ground-water was not detected in perimeter monitoring wells or nearby private drinking water wells. Storage of treated wood onsite contaminated surface soil.

Contaminants: PAHs and benzene with DNAPL well below the surface of the shallow groundwater table.

Hydrogeology: Silty and clayey sand extends to a maximum depth of 40 ft bgs at the site. The sand is underlain by a low-permeability, dense blue clay that is approximately 20 ft thick. DNAPL was observed atop this clay layer in the area below the lagoons. The drinking water aquifers of the underlying Chesapeake Group are located approximately 285 to 600 ft bgs. Drinking water wells in the area were not found to be contaminated.

Project Goals: The remedy required that soil and groundwater be cleaned up to residential standards. PAHs in surface and subsurface soil were to be cleaned up to 0.1 mg/kg (B(a)P-eq), and 1.0 mg/kg (B(a)P-eq), respectively. The cleanup goals for sediment were 0.4 mg/kg PCP, 3.2 mg/kg low molecular weight PAHs and 9.6 mg/kg high molecular weight PAHs.


Before: Floating Contamination on Pond, Summer 1999


After: Restored Wetland Swale, Spring 2001

Cleanup Approach: Contaminated soil and sediment were excavated from the site and placed into one of two onsite thermal desorbers equipped with vapor recovery systems. The lagoon area was dewatered prior to excavation, and the water was treated onsite. Approximately 270,600 tons of contaminated soil and sediment were treated and backfilled onsite. Highly contaminated soil and sediments not readily treated by thermal desorption were shipped offsite for proper disposal.

Surface water from the onsite pond was pumped and treated until the source soil and sediment were cleaned up.

The site was regraded and revegetated with a diverse mixture of wildflowers and grains suitable for wildlife habitat.

Project Time Line:

3/14/85 First removal action (excavation of contaminated pond sediment)

6/10/96 Site placed on the National Priorities List

6/29/93 Second removal action (included construction of an underflow dam to reduce flow of contaminants from the pond to the stream)

10/7/97 Construction activities began

2/00 Excavation of stream began

1/17/01 Soil and sediment treatment complete

8/01 Remedial Action Completion Report issued

2003 Two years of groundwater monitoring complete

11/18/04 Ready for Reuse determination issued by EPA for unrestricted use of site

4/5/05 Site deleted from NPL

Project Results: All cleanup goals were met. Two years of groundwater monitoring that followed soil and sediment cleanup verified that the cleanup was a success. In 2004, a Ready for Reuse determination was issued by EPA for unrestricted use of the site.

Sources: U.S. EPA, 2004. Ready for Reuse Determination Southern Maryland Wood Treating Superfund Site, November 18.

U.S. EPA, 1999. Five-Year Review Report: Southern Maryland Wood Treating Superfund Site, Hollywood, Maryland. September 30.
http://cfpub.epa.gov/fiveyear/index.cfm?fuseaction=fyrsearch.showSitePage&id=0300305

U.S. EPA, 1995. EPA Superfund Record of Decision: Southern Maryland Wood Treating, EPA ID: MDD980704852, OU 2, Hollywood, Maryland. (EPA/ROD/R03-95/197) September 8.
http://cfpub.epa.gov/superrods/index.cfm?fuseaction=data.siterods&siteid=0300305

Former Southern California Edison Manufactured Gas Plant (MGP) Site, Long Beach, California

Technologies: ISCO (ozonation), excavation

Regulatory Program: Voluntary action under DTSC's Expedited Remedial Action Program

Project Duration: 1998 to 2003

Information Last Updated: 2003

Site Information: The Former Southern Edison MGP site produced gas from oil and coal from 1902 to 1913, and contaminated soil and groundwater with PAH and TPH. The 340-ft by 230-ft strip of land is wedged between a freeway and the Los Angeles River flood control channel. A dense infrastructure of power transmission cables, underground utilities, and elevated bridges made conventional treatment difficult.

Contaminants: The initial concentrations of soil contaminants measured at the site were 2,484 mg/kg total PAH and 27,800 mg/kg TPH. The chemicals of potential concern identified for soil included seven carcinogenic PAHs, nine noncarcinogenic PAHs, and TPH. A benzo(a)pyrene equivalent (B(a)P-eq) value was calculated for each carcinogenic PAH and summed together to estimate the total B(a)P-eq concentration. Prior to treatment, B(a)P-eq in soil was slightly higher than 100 mg/kg.

Dissolved concentrations in groundwater were as high as 912 µg/L TPH, 4.82 µg/L benzene, 20 µg/L naphthalene, and 0.34 µg/L benzo(a)-pyrene.

Hydrogeology: The site is underlain by a thin layer of fill overlying poorly sorted medium- to fine-grained sand. The water table is approximately 10 ft bgs.

Project Goals: The remedial strategy for the site was to meet an industrial cleanup objective of 1.75 mg/kg B(a)P-eq in soil.

Cleanup Approach: ISCO through ozonation was conducted to treat soil and groundwater. In October 1998, 33 vertical sparging wells were installed in the contamination plume. The sparging wells were made of Teflon tubing for most of their length, and stainless steel rods wrapped with stainless steel wire mesh over the lower 25 ft for the distribution of ozone. In addition, a single horizontal sparging well with a 135-ft screened section was installed through the center of the plume approximately 6 ft below the water table.

Ozone was pulsed into the wells in both the saturated and vadose zones to promote chemical oxidation and enhanced biodegradation. Ozone generation was initiated in January 1999 and continued until system shutdown in January 2001. Approximately 19,100 pounds of ozone and 280,000 pounds of oxygen were generated and injected. An SVE system was used to prevent unreacted ozone from reaching the surface. Approximately 215 yd^3 of highly contaminated soil were excavated and disposed offsite.

Project Time Line:

10/98-11/98 – In situ ozonation system constructed

12/98 – Pilot test conducted

1999-2003 – Ozone generation conducted

11/22/05 – Site removed from Expedited Remedial Action Program

Project Results: Groundwater concentrations were reduced below detectable levels after the first quarter of ozone treatment. The concentration of benzo(a)pyrene was reduced to less than the 0.2 µg/L MCL. Site-wide soil concentrations were reduced from more than 100 mg/kg to 1.4 mg/kg of B(a)P-eq. PAH and TPH concentrations in groundwater were reduced to non-detect levels after the first injection. A thin lens of contaminated soil that contains up to 105 mg/kg of B(a)P-eq remains at depth. Because of the position of highway foundations, the lens could not be treated. DTSC will issue a Certificate of Completion once deed restrictions are recorded for the property.

Sources: In-Situ Oxidative Technologies, Inc. Case Study: Former MGP Site. Southern California Edison. Undated. http://www.insituoxidation.com/images/CASE-21%20MGP%20Site,%20California.pdf

Department of Toxic Substances Control, Edison/Long Beach II MGP (Ocean Blvd), Envirostor. http://www.envirostor.dtsc.ca.gov/public/profile_report.asp?global_id=19490213

Dablow, Jay, Mark Seaman, and Bruce Marvin, IT Corporation, 2001. In Situ Ozonation to Remediate Recalcitrant Organic Contamination. Paper presented at the 2001 International Containment & Remediation Technology Conference and Exhibition, Orlando, FL. http://www.containment.fsu.edu/cd/content/pdf/352.pdf

Former Cowboy Cleaners Site, Broomfield, Colorado

Technology: ISCO (potassium permanganate)

Regulatory Program: Colorado Voluntary Cleanup Program

Project Duration: 2001 to 2002

Information Last Updated: 2003

Site Information: The Former Cowboy Cleaners site is located in Broomfield, Colorado, near Denver. A site investigation revealed soil and groundwater contamination. The approximate 1.5-acre plume occupied portions of five separately owned properties and crossed beneath a street. Small portions of the plume also flowed beneath a retail building and a residence. The remediation was handled under the Colorado Voluntary Cleanup Program.

Contaminants: Groundwater at the site is contaminated with PCE. Maximum initial concentration of PCE was 1,900 µg/L (suspected DNAPL).

Hydrogeology: The site is underlain by a stiff clay to silty (sometimes sandy) clay at 3 ft bgs and a sandy clay layer at 8 ft bgs. Groundwater is at 25 bgs.

Project Goals: The State of Colorado determined that the low risks to potential receptors justified a remediation of the source areas, allowing the groundwater plume to clean up naturally over time.

Cleanup Approach: A system of 12 nested injectors was installed in the source area. Semi-permanent injectors constructed of one-inch diameter PVC screen and riser were installed to allow the controlled injection of permanganate reagent directly into the contaminated area. Each injector was installed with a sand pack to just above the screen, and grouted to the surface. Once the grout set, a charge of permanganate was pressure-injected into each injector. A 10% by weight solution of permanganate was introduced into each injector, with as much volume as each injector would take, to a maximum of 100 gallons. The injectors were then connected to each other in ranks, and to a head tank by PVC piping. Continuous gravity feeding to all of the injectors was then started. Each injector was equipped with valves to control flow, and the system was kept in balance for about four to five months. Up to 300 gallons per day of 1-2% solution were fed into the system during remediation.

Most of the injectors were completed above the water table to avoid drainage of reagent directly into groundwater without extensive soil contact. To control PCE that was mobilized into groundwater from the soil source area, a line of injectors (curtain wall) was installed down stream. These injectors were operated at very low volumes, and controlled based on the results of a monitoring well immediately downgradient.

Project Time Line:

09/01 – Application of permanganate

01/02 – Post-treatment monitoring

08/02 – Post-treatment monitoring complete

02/03 – NFA Determination letter issued by Colorado Department of Public Health and Environment

Project Results: One month into the remediation process, the PCE concentration had dropped to 926 µg/L and decreased further to 48 µg/L in about a year. Downgradient PCE concentrations decreased from 40 µg/L to 15 µg/L within a year. Quarterly monitoring showed PCE concentrations in source-area groundwater were reduced by 99% and downgradient concentrations were less than the Colorado drinking water MCL. In February 2003, the State of Colorado issued a NFA Determination Approval, stating that the property could be used for commercial purposes, and did not pose an unacceptable risk to human health and the environment.

Sources: Colorado Department of Public Health and Environment. 2003. NFA Approval. James Viellenave. December 16, 2003.

E-mail to Raji Ganguli, Tetra Tech EM, Inc. providing information on the Former Cowboy Cleaners Site in Broomfield, Colorado.

Viellenave, J.H., J.P. Lauer, and J.V. Fontana. 2002. Using Risk Based Cleanup Goals for ISCO of PCE in Vadose Zone Soils Under a Voluntary Cleanup Program. Paper presented at IPEC 2002. http://ipec.utulsa.edu/Conf2002/viellenave_lauer_fontana_66.pdf

Dry Clean USA No. 11502, Orlando, Florida

Technologies: ISCO (hydrogen peroxide), P&T, SVE

Regulatory Program: Florida Department of Environmental Protection’s Drycleaning Program

Project Duration: April 1999 to October 2005

Information Last Updated: 2008

Site Information: The Former Dry Clean USA operated in a shopping plaza in Orlando, Florida, from 1988 to 1998. Investigations indicated that PCE was released to the soil beneath the floor slab of the facility in the area where the drycleaning machine was located. Releases also occurred from the sanitary sewer line.

SVE and P&T systems were run between April 1999 to November 2002 with only 9.8 lbs of VOCs recovered through SVE and a negligible amount of VOCs recovered through P&T.

Contaminants: PCE was detected at concentrations of up to 27,300 µg/L in groundwater and 3.9 mg/kg in soil. The contaminant plume extends to about 68-ft bgs and is 800-ft long and 300-ft wide.

Hydrogeology: The site is underlain by a slightly silty, fine- to medium-grained sand to a depth of 47 ft bgs. This unit is in turn underlain by a 6-ft-thick, slightly sandy clay followed by a 20-ft-thick, fine- to medium-grained sand that is interbedded with clayey sand. A 4-ft-thick fine to coarse sand with shell fragments overlays a hard, phosphatic, limestone bedrock that occurs 93 to 94 ft bgs. The depth to groundwater is 8 to 10 ft bgs.

Project Goals: The goal was to treat PCE to the Florida MCL of 3 µg/L for groundwater and 30 µg/kg (leachability) for soil.

Cleanup Approach: SVE for soil contamination and P&T for groundwater were successful in reducing groundwater contamination levels to <10 µg/L. Rebound did occur near the source area, so a 1% hydrogen peroxide solution was used as a polishing step.

Project Time Line:

4/99 – SVE and P&T systems start

12/01/00 – SVE turned off

1/17/01 – P&T system shut down

2/26/01 – P&T system restarted because of rebound

11/02 – P&T system turned off

10/04/05 – 10/05/05 – Peroxide injections

2/07 – Site Rehabilitation Completion Order signed

Project Results: One year of post oxidation groundwater monitoring showed concentrations of PCE ranging from non-detect to 3 µg/L. The Site Rehabilitation Completion Order was signed February 16, 2007, and all wells were abandoned.

Sources: State Coalition for Remediation of Drycleaners profile. Dry Clean USA #11502. June 2008. http://www.drycleancoalition.org/profiles/display.cfm?id=24

Personal communication with William Linn, May 8, 2007.

Naval Submarine Base Kings Bay Site 11, Camden County, Georgia

Technologies: P&T, ISCO (Fenton's reagent), biostimulation, MNA

Regulatory Program: RCRA Corrective Action

Project Duration: 1993 to present

Project Last Updated: 2004

Site Information: Site 11, the former Camden County Landfill, is located on Kings Bay Naval Submarine Base. The 25-acre site was used for municipal waste disposal from 1973 until 1980. Trenches 2-3 m deep were excavated, filled with trash, and covered.

Contaminants: Chlorinated solvents that were disposed in the landfill are the source of a groundwater contaminant plume estimated to be 700-ft long, 200-ft wide, and 30- to 40-ft deep. Measured concentrations of the contaminants of concern ranged as high as 8,500 µg/L PCE, 550 µg/L TCE, 1,300 µg/L *cis*-DCE, and 4,500 µg/L vinyl chloride. Profiling with direct push equipment identified two localized DNAPL source areas.

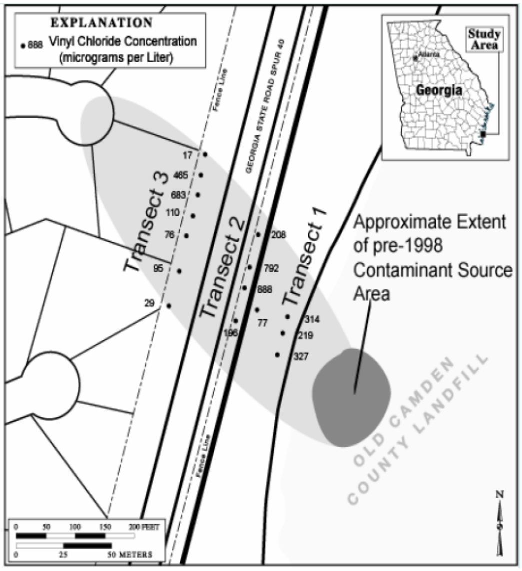
Hydrogeology: Site 11 is underlain by marginal marine sediments of barrier island and back-barrier lagoon origin. The most permeable sand underlying the site is between 32 and 42 ft bgs. This permeable zone is underlain and overlain by a finer-grained sand and clay unit, which is characterized by lower hydraulic conductivity. A layer of organic-rich sand overlies the aquifer. As precipitation infiltrates this organic layer, it becomes anaerobic, thereby forming a naturally occurring anaerobic biodegradation system. Groundwater is encountered at about 6 ft bgs. An important feature of the groundwater chemistry is that the sulfate-reducing conditions predominate near the landfill while iron-reducing conditions exist further downgradient. The sulfate reducing conditions favor degradation of PCE, TCE, and DCE, while the iron-reducing conditions favor degradation of vinyl chloride.

Organic rich layer at outcrop

Courtesy USGS

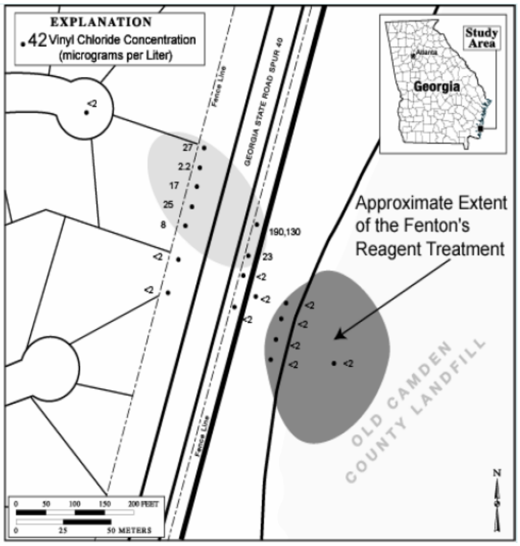
Project Goals: The goal of remedial action at the landfill was to reduce contaminant concentrations in the groundwater plume to levels below the MCLs established by the Georgia Department of Natural Resources (GDNR).

Cleanup Approach: P&T was chosen to contain and treat the groundwater plume with UV oxidation. The P&T system, which was installed in 1993, was expected to operate for at least fifty years to meet GDNR's cleanup goals. This projection was based on



Vinyl Chloride Plume before Cleanup

Courtesy: USGS



Vinyl Chloride Plume after Cleanup (January 2004)

Courtesy: USGS

the high concentrations of chlorinated compounds at the site and their low solubility, and on P&T performance data.

The July 1998 corrective action plan called for containment of the plume at the Navy property line. Containment would be facilitated with extraction wells at the perimeter of the installation. The extraction wells would operate until contaminant concentrations were low enough for MNA to be effective on any offsite contamination.

ISCO was selected to treat total VOCs in the source area to below 100 µg/L. Since it was not considered possible to achieve zero levels of contamination in the source area, the corrective action plan relied on the reasonable expectation that after removal of the source material, the downgradient plume would attenuate. The USGS used natural attenuation software to calculate the levels of residual contamination in the source area that would allow downgradient attenuation to meet the remediation goals. These calculations provided rational performance standards for the source removal contractors.

The treatment area consisted of an estimated 3,000 tons of contaminated soil and 80,000 gallons of contaminated groundwater.

In November 1998, two extraction wells and six process monitoring wells were installed along with 23 specially designed injection wells that were placed in and around the source area. The monitoring wells were sampled twice daily and analyzed for pH, specific conductance, alkalinity, iron, sulfate, sulfide, dissolved hydrogen, and dissolved oxygen as well as any change in contaminant concentrations.

Injection Well

Courtesy U.S. Navy

Fenton's reagent containing 50% hydrogen peroxide was injected twice. The first injection focused on the central part of the contaminant plume, while the second focused on the downgradient areas that were not treated during the first injection. Following the second injection, during which 21 new injectors were added, elevated contaminant concentrations (1,700 µg/L) were detected near one injector indicating the presence of a previously unidentified source area. Thus, two more injections were conducted with the final injection in November 2001.

Since adding Fenton's reagent to an aquifer can change both the geochemistry and the microbial population, monitoring was performed. Measurements in one monitoring well showed an increase in dissolved oxygen from non-detect before injection to over 7 mg/L after injection. Also, microbial activity decreased after each injection. Dissolved hydrogen concentrations indicated that the injection of the ferrous iron activator had

Courtesy: U.S. Navy

shifted the microbial activity from sulfate- and iron-reducing to a more purely iron-reducing environment. To reverse this trend, biostimulation was conducted by injecting a solution of emulsified vegetable oil (35% soybean oil with lecithin and 65% water) into the aquifer after the third and fourth injections to return the subsurface to an anaerobic environment and restore some of the sulfate-reducing activity that increases PCE and TCE degradation. Microbial activity generally rebounded within a few months of each Fenton's reagent injection.

In all, about 48,000 gallons of 50% hydrogen peroxide solution and a similar volume of ferrous sulfate catalyst were injected into the aquifer—principally in the more permeable zone between 32 and 42 ft bgs. In addition, about 25,000 gallons of the emulsified soybean oil solution were injected following the third and fourth injections of Fenton's reagent application.

Project Time Line:

1993─Began P&T containment system

November 1998 to February 1999─Performed first ISCO treatment

June 1999 to July 1999─Performed second ISCO treatment

Fall 1999─Shut down P&T system

July 1999 to January 2001─Performed third ISCO treatment

November 2001─Performed fourth and final ISCO treatment

Project Results: Levels of total chlorinated hydrocarbons in the most contaminated area decreased from nearly 200,000 µg/L in 1999 to 120 µg/L in 2002. As of 2004, they ranged from <1 to 13.9 µg/L. The plume size shrank by about 70%.

The USGS modeling, supported by field data, indicated that when the concentrations of total chlorinated hydrocarbons in groundwater were lowered to about 100 µg/L, MNA would complete cleanup of the plume in about three years. As of May 2003, no exceedances of MCLs occurred in any of the offsite monitoring wells, and many of the onsite monitoring wells had no measurable levels of contaminants. As a result, the P&T system was shut off two months after the second ISCO treatment, and MNA has been implemented as the final corrective action for the landfill. There was no need for further treatment with UV oxidation. Shutting down the P&T system slowed the transport rate of contaminants downgradient, which increased the effectiveness of the biodegradation process.

The estimated cost of the remedial action from 1991 to 1997 was $9.8 million. The estimated cost for the ISCO and biostimulation is approximately $5 million. This represents a $9 million savings over the estimated $15 million that the P&T system would have cost.

Sources: Chapelle, F.H. and P.M. Bradley. 1999. Selecting remediation goals by assessing the natural attenuation capacity of ground-water systems. Proceedings of the Technical Meeting Charleston, South Carolina. March 8-12, 1999, Volume 3 of 3 Subsurface Contamination From Point Sources, Water-Resources Investigations Report 99-4018C. U.S. Geological Survey http://toxics.usgs.gov/pubs/wri99-4018/Volume3/keynote/3102_Chapelle/index.html

Chapelle, F.H., P.M. Bradley, and C.C. Casey. 2005. Behavior of a chlorinated ethene plume following source-area treatment with Fenton's reagent. Ground Water Monitoring & Remediation, Vol. 25 No 2, p 131-141, Spring

Chapelle, F.H. and M. Singletary. 2006. Combining Source Area Treatment with Monitored Natural Attenuation, NSB Kings Bay. PowerPoint presentation from Federal Remediation Roundtable meeting http://www.frtr.gov/pdf/meetings/may07/chapelle_presentation.pdf

FRTR. 2000. In situ Chemical Oxidation Using Fenton's Reagent at Naval Submarine Base Kings Bay, Site 11, Camden County, Georgia. Federal Remediation Roundtable http://costperformance.org/pdf/KingsBay.PDF

Spinner, J. 2004. Groundwater Almost Clean. The Periscope April 29, 2004 http://www.kingsbayperiscope.com/stories/042904/kin_groundwater001.shtml

NAVFAC SOUTHDIV. Undated. Site 11, Old Camden County Landfill, Remedial Action Operation, Summary Report: Remedial Action Operation Optimization. U.S. Navy, 8 pp http://costperformance.org/pdf/KingsBay_ChemOx.pdf

Former Sta-Lube Site, Rancho Dominguez, California

Technologies: SVE, P&T, large-diameter auger excavation with offsite disposal, ISCO (catalyzed hydrogen peroxide to activate sodium persulfate)

Regulatory Program: California Regional Water Quality Control Board (RWQCB), Los Angeles Region

Project Duration: June 2005 to June 2008

Information Last Updated: 2008

Site Information: The former Sta-Lube site occupies 2.8 acres. From 1968-1986, Sta-Lube, Inc. manufactured paint, varnish remover, and fuel additives and blended and packaged hand cleaners, greases, and petroleum-based lubricants.

Contaminants: Past industrial activities at the site used a variety of chemicals, including petroleum hydrocarbon derivatives and solvents such as methylene chloride. Site investigations indicated that soil and groundwater were contaminated with volatile organic compounds; methylene chloride was the main contaminant of concern. A past release of methylene chloride from a leaking UST caused extensive contamination. In 1995, the dissolved plume measured 200-feet long by 80-feet wide. By 2005, the size of the plume had been reduced to 80-feet long by 30-ft wide, most of which was under the building. The highest concentration of methylene chloride detected in the groundwater was 2,600,000 µg/L, well exceeding the 1% solubility limit of 200,000 µg/L.

A membrane interface probe (MIP) survey later indicated that methylene chloride DNAPL was trapped in sandy stringers within the clayey soil underlying the building.

Hydrogeology: The site is located within the Central Groundwater Basin, which is part of the Los Angeles Coastal Plain. The near-surface sediments at the site are part of the Bellflower Aquiclude, a portion of the Recent Alluvium primarily comprising silts and clays. These fine-grained sediments are found beneath the Sta-Lube site to a depth of approximately 45 feet bgs. The depth to the water table is approximately 40 feet bgs. Using the MIP, an 8-foot thick clay zone with thin sand stringers (4-8 inches) was delineated between 40 to 48 feet bgs, while coarse sand is found from 48 feet to over 130 feet bgs.

The groundwater beneath the Sta-Lube site correlates regionally with the Gaspur Aquifer. The bottom of the Gaspur Aquifer is approximately 140 feet beneath the Sta-Lube site. Beneath this aquifer, several clay-lens aquitards limit vertical migration of the contaminant to the Silverado and Sunnyside Aquifers, which are at depths of approximately 450 to 700 feet bgs. These deeper aquifers are considered high-quality drinking water aquifers.

The California Water Company has indicated that the closest active drinking water well is located 1,750 feet to the southwest of the Sta-Lube site. The well screen is set at 301 to 650 feet bgs and penetrates the Silverado and Sunnyside Aquifers. The groundwater flow direction in the upper saturated zone is towards the southwest placing the well downgradient of the site. However, the Sta-Lube plume is located at 40 to 60 feet bgs, which is the upper 20 feet of the saturated zone beneath the site.

Project Goals: After 6 years of SVE, P&T, and a large-diameter auger excavation, the overall goal of implementing ISCO was to quickly attain closure of the site from the RWQCB. The cleanup goal was to attain concentrations less than 50 µg/L of methylene chloride in groundwater.

Cleanup Approach: A P&T system was operated at the Sta-Lube site starting in 1997 to treat the dissolved-phase plume. The P&T system operated until 2003. An SVE system supplemented with hot air injection was operated at the site starting in May 2000 and continuing until October 2001. Concentrations of methylene chloride in groundwater from the pumping wells were below 100 µg/L, and the soil and groundwater were close to attaining closure from the RWQCB. However, when the systems were turned off, the concentrations of methylene chloride rebounded significantly suggesting presence of DNAPL.

A supplemental site investigation conducted using MIP revealed DNAPL source zones in sandy stringers trapped within clayey zones at depths of 40 to 48 feet. To remove the DNAPL, these source zones were excavated to a depth of 48 feet using large-diameter augers. The excavated soil, which was contaminated (266 cubic yards), was staged and disposed of offsite. Despite these efforts, groundwater contamination levels still remained high (Table 1). Further investigation revealed methylene chloride had migrated into the clayey soil beneath the building and was slowly seeping out and contaminating the groundwater.

Table 1. Groundwater Contaminant Concentrations Measured June 14, 2004

Contaminant	**Concentration Range (µg/L)**
Acetone	ND – 220
Benzene	ND - 6.7
Toluene	ND - 34
Bromochloromethane	ND - 110
1,1-DCA	ND - 27
1,1-DCE	ND - 89
Trans-1,2-DCE	ND - 73
Bromoform	ND - 16
Dibromochloromethane	ND - 11
Chloroform	ND - 88
Methylene Chloride	ND – 18,000
1,1,2,2-TCA	ND - 25

ND = non-detect

On December 15, 2004, the RWQCB approved ISCO using catalyzed hydrogen peroxide activation of sodium persulfate (Klozür®) for groundwater remediation.

Activated sodium persulfate is a strong oxidant that creates sulfate radicals, which are effective in treating dissolved recalcitrant contaminants. The catalyzed hydrogen peroxide (a Fenton's type reaction) attacks contaminants directly with the hydroxyl radicals that are produced. The Fenton's reaction is a highly exothermic reaction that helps to strip the sorbed contaminants from the soil and convert them to the dissolved phase.

A total of 23 application wells were installed at the site–16 inside and 7 outside the building (Figure 1)–with an estimated radius of influence of 8 to 12 feet. The target groundwater remediation zone was 40 to 48 feet below grade surface.


Figure 1. ISCO Application Wells

Courtesy: Gary Cronk

Approximately 7,700 gallons of 22% sodium persulfate solution was injected over the course of six days. This was followed by an injection of 12,044 gallons of 17.5% hydrogen peroxide for 14 days to activate the persulfate. Downhole thermocouples monitored the temperature underground to ensure a temperature of 120 to 160°F for optimum generation of hydroxyl radicals with minimal decomposition of the hydrogen peroxide. Logistical challenges included the use of angled wells to minimize disruption of business operations in the building and safely performing injections inside an active facility. The reaction of catalyzed peroxide produces hydroxyl radicals, heat, and oxygen which tend to force treated groundwater and vapor up to the ground surface via conduits (e.g., soil crevices, abandoned borings, utility lines, etc.). Therefore, the flow of the injectants had to be optimized to control the reaction.

Project Time Line:

1997-2003—Operation of pump and treat system to treat dissolved-phase plume.

2000-2001—Operation of SVE and hot air injection to treat the vadose zone soils.

2003—Large-diameter auger excavation of DNAPL source area and disposal of contaminated soil offsite. Subsequent discovery of additional DNAPL beneath the building.

December 15, 2004— RWQCB approves use of ISCO to treat contaminated soil beneath building and the groundwater contaminant plume emanating from it.

June 2005—Persulfate and peroxide injected into treatment area.

November 2005—Cleanup goal of 50 µg/L methylene chloride is reached.

2005-2008—Quarterly monitoring

June 2008—California RWQCB grants final closure of site.

Project Results: Monitoring results indicated that ISCO reduced methylene chloride levels by 94% to 97% within 4 months following treatment and below the 50 µg/L cleanup goal within 5 months (Figure 2). The most significant reduction observed was a decrease from 15,000 to 18 µg/L in one well. Quarterly monitoring followed and in June 2008, the site obtained final closure from the California RWQCB.

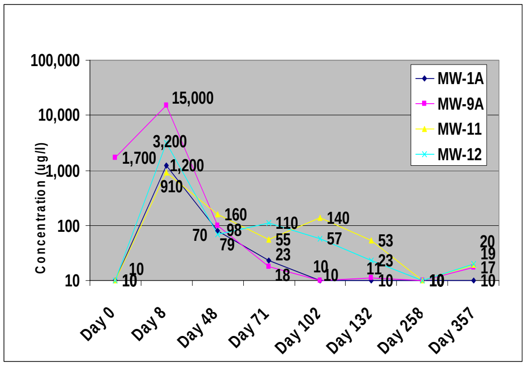


Figure 2. Methylene Chloride Concentrations in Groundwater During ISCO

Courtesy: Gary Cronk

Sources: Personal communication with Gary Cronk, September 18, 2007.

Cronk, Gary. 2006. Optimization of a chemical oxidation treatment train process for groundwater remediation" Presentation at the Battelle 5th International Conference on Remediation of Chlorinated and Recalcitrant Compounds. May 25, 2006. Monterey, CA. http://jagconsultinggroup.com/uploads/Full_Paper_-_Cronk_Battelle_2006.pdf

California Regional Water Quality Control Board, Los Angeles Region. Letter from Executive Officer, Jonathan S. Bishop, to Judi Proetel of Sta-Lube, Inc.

FMC Environmental Solutions. Klozur™ Resource Center. Project Description In-Situ Chemical Oxidation, Activated Persulfate Treatment of Methylene Chloride Chemical Plant in Los Angeles, CA. http://www.envsolutions.fmc.com/Portals/fao/Content/Docs/Remediation%20of%20Methylene%20Chloride%20Plume%20Using%20H2O2%20Catalyzed%20Persulfate_MECX.pdf

Pasley Solvents and Chemicals, Inc., Hempstead, New York

Technologies: SVE, air sparging

Regulatory Program: U.S. EPA Superfund

Project Duration: November 1997 to August 2003

Information Last Updated: 2007

Site Information: Pasley Solvents and Chemicals, Inc., is a former tank farm that stored oils, solvents, and other chemicals in above-ground tanks prior to transferring them to 55-gallon drums for delivery to customers. The property is about 75 ft wide and 275 ft long. Poor housekeeping and spills have contaminated soil and groundwater with VOCs and semivolatile organic compounds (SVOCs).

Contaminants: The contaminants of concern at the site were 1,1-DCA, 1,1-DCE, *trans*-DCE, chloroform, TCE, toluene, chlorobenzene, ethylbenzene, and xylenes. The highest concentration of total VOCs (mostly PCE and *trans*-1,2-DCE) and SVOCs detected in surface soil was 603 mg/kg and 204 mg/kg, respectively. The maximum concentration of total VOCs measured in groundwater was 37 mg/L (mostly *trans*-1,2-DCE). The highest TCE concentration was 320 µg/L, well higher than the 5 µg/L MCL. The 60-ft by 400-ft groundwater contaminant plume extended beyond the site boundary.

Hydrogeology: The site is underlain by 60 ft of glacial outwash deposits consisting of unconsolidated sand and gravel. These deposits are underlain by the Magothy Aquifer, a 400- to 500-ft thick formation consisting of fine sand with discontinuous layers of silt and clay. Public water supply wells for the nearby Town of Hempstead draw water from the Magothy Aquifer.

Project Goals: The project goals were to clean up the site to residential risk levels and MCLs.

Cleanup Approach: Chemical source areas in the vadose zone were treated with SVE, and the groundwater plume was treated using air sparging wells to encourage aerobic bioremediation and volatilization.

For the onsite contamination, 19 2-inch PVC air sparging wells screened 50 to 52 ft bgs; eight shallow 2-inch PVC SVE wells, screened 5 to 10 ft bgs; eight 4-inch PVC SVE wells, screened 15 to 20 ft bgs; and five monitoring well clusters were installed. To treat the offsite plume, 15 2-inch PVC air sparging wells, screened 50 to 52 ft bgs; five 2-inch PVC SVE wells, screened 15 to 20 ft bgs; and six monitoring-well clusters were installed. Collected vapors were treated with activated carbon. In accordance with the Consent Decree and O&M Manual, the O&M period was to be performed for a minimum of five years followed by post-remediation monitoring.

Project Time Line:

6/97 – Construction of the remedy begins

10/97 – Remedy construction completed

11/97 – Remedy becomes operational

10/02 – SVE/AS system shut down to test for rebound

July 2000 and April 2003 – Confirmation soil sampling

2004 – Remediation equipment removed from site

2004-2006 – Semi-annual groundwater monitoring

2006 – NFA discontinue groundwater monitoring

Project Results: Soil confirmation sampling indicated that residential cleanup values (all under 1 mg/kg for the contaminants of concern) were met. Concentrations of total VOCs in monitoring wells also met groundwater treatment goals. Within two years of air sparging operation, concentrations of total VOCs in onsite monitoring wells ranged from non-detect to 4 µg/L, which was down from original concentrations ranging as high as 7,496 µg/L. After five years, concentrations in offsite monitoring wells were all below MCLs for 12 straight quarters.

Sources: Personal communication with Sherrel Henry, U.S. EPA Region 2, April 2, 2007.

U.S. EPA. 1992. Record of Decision: Pasley Solvents & Chemicals, Inc. EPA ID: NYD991292004, OU 01 Hempstead, NY. http://www.epa.gov/superfund/sites/rods/fulltext/r0292171.pdf

U.S. EPA. 2004. Five-Year Review Report Pasley Solvents and Chemical Site Town of Hempstead Nassau County, New York. http://www.epa.gov/superfund/sites/fiveyear/f04-02026.pdf

Appendix B

Suspected DNAPL Thresholds Based On Solubility Relative to One Percent of Aqueous Solubility

Suspected DNAPL Thresholds Based on Solubility Relative to 1% of Aqueous Solubility

Chlorinated Solvent (CAS Number)	**Aqueous Solubility (µg/L @ 20^{o}C)**	**1% of Aqueous Solubility (µg/L @ 20^{o}C)**
PCE (127-18-4)	150,000	1,500
TCE (79-01-6)	1,100,000	11,000
cis-DCE (156-59-2)	3,500,000	35,000
trans-1,2-DCE (156-60-5)	600,000	6,000
1,1-DCE (75-35-4)	400,000	4,000
1,1,1-TCA (71-55-6)	1,360,000	13,600
1,1,2-TCA (79-00-5)	4,500,000	45,000
1,2-DCA (107-06-2)	8,690,000	86,900
1,1-DCA (75-34-3)	5,500,000	55,000
Carbon Disulfide(75-15-0)	2,100,000	21,000
Carbon Tetrachloride (56-23-5)	800,000	8,000
Chlorobenzene (108-90-7)	500,000	5,000
Chloroform (67-66-3)	8,000,000	80,000
Hexachlorobutadiene (87-68-3)	2,550	25
Methylene Chloride (75-09-2)	20,000,000	200,000
1,1,2-Trichlorofluoromethane (75-69-4)	1,100,000	11,000
1,1,2-Trichlorotrifluorethane (76-13-1)	200,000	2,000

Notes:

1. The source for all Aqueous Solubility and 1 Percent Rule except 1,2 *cis* DCE: Cohen, R. and J. Mercer. 1993. DNAPL Site Evaluation, EPA 600/R-93/022. http://www.cluin.org/download/contaminantfocus/dnapl/600r93022.pdf

2. Source for 1,2-*cis* DCE solubility datum: Howard, P. (ed.).1989. Handbook of Environmental Fate and Exposure Data for Organic Chemicals. Lewis Publishers.

3. DCA (dichloroethane), DCE (dichloroethene) PCE (tetrachloroethene), TCA (trichloroethane), TCE (trichloroethene)

If the chemicals are part of a mixture, then their solubility will be less than the solubility of the pure substances. The effective solubility of each component can be estimated using Raoult's Law and is equal to the mole fraction of the component in the NAPL times its pure form solubility (Cohen and Mercer 1993).

Appendix C

Acronyms and Abbreviations

µg/L	micrograms per liter
bgs	below ground surface
B(a)P	benzo(a)pyrene
B(a)P-eq	benzo(a)pyrene equivalent
CEAM	Conceptual Environmental Assessment Model
COC	certificate of completion
DCE	dichloroethene
DNAPL	dense non-aqueous phase liquid
DTSC	Department of Toxic Substances Control
EPA	U.S. Environmental Protection Agency
ERH	electrical resistive heating
ft	foot or feet
ft^2	square foot or feet
ft^3	cubic foot or feet
gpm	gallons per minute
GW	groundwater
HRC®	Hydrogen Release Compound
IC	institutional controls
IDEM	Indiana Department of Environmental Management
IEPA	Illinois Environmental Protection Agency
ISTD	in situ thermal desorption
L	liter
MADEP	Massachusetts Department of Environmental Protection
MC	methylene chloride
MCL	maximum contaminant level (EPA)
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MGP	manufactured gas plant
MNA	monitored natural attenuation
ND	non-detectable
NFA	no further action
NFR	no further remediation
NPL	National Priorities List
P&T	pump and treat
PAH	polycyclic aromatic hydrocarbon
PCE	tetrachloroethene
RBEL	risk-based exposure level
RCRA	Resource Conservation and Recovery Act
SCE	Southern California Edison
scfm	standard cubic feet per minute
SVE	soil vapor extraction
SVOC	semivolatile organic compound
TACO	tiered approach to correction action objectives
1,1,1-TCA	trichloroethane
TCE	trichloroethene
TCEQ	Texas Commission on Environmental Quality
TPH	total petroleum hydrocarbons
TRRP	Texas Risk Reduction Program
VC	vinyl chloride
VOC	volatile organic compound
yd^3	cubic yard