

1                   **PERFORMANCE OF DNAPL SOURCE DEPLETION TECHNOLOGIES**  
2                   **AT 59 CHLORINATED SOLVENT-IMPACTED SITES**

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7                   **ABSTRACT**

8                   Performance and rebound of intensive source depletion technologies were  
9                   evaluated at 59 chlorinated solvent sites where remediation targeted dense non-aqueous  
10                  phase liquid (DNAPL) source zones. The four technologies included in the study are  
11                  chemical oxidation, enhanced bioremediation, thermal treatment, and  
12                  surfactant/cosolvent flushing. Performance was evaluated by examining temporal  
13                  groundwater concentration data before and after source remediation was performed.  
14                  Results indicated that all four technologies have median concentration reductions of 88%  
15                  or greater for the parent chlorinated volatile organic compound (CVOC). Approximately  
16                  75% of the source depletion projects were able to achieve a 70% reduction in parent  
17                  compound concentrations. A median reduction in total CVOC concentrations (parent  
18                  plus daughter compounds) of 72% was observed at 12 chemical oxidation sites and 62%  
19                  at 21 enhanced bioremediation sites. Rebound was assessed at sites having at least one  
20                  year of post-treatment data. Rebound occurrence was most prevalent at sites  
21                  implementing chemical oxidation. At chemical oxidation sites where rebound was  
22                  evaluated (n=7), the median parent CVOC concentration reduction was 90% immediately  
23                  following treatment compared to 78% at the end of post-treatment monitoring (i.e., one to

1 five years after treatment). For enhanced bioremediation sites where rebound was  
2 evaluated (n=10), median parent CVOC concentration reduction changed from 77% to  
3 96% over the post-treatment monitoring period. Minimal concentration change was  
4 observed over the post-treatment monitoring period at surfactant/cosolvent sites (n=2)  
5 and thermal treatment sites (n=1) evaluated for rebound. Based on current data, none of  
6 the 59 source depletion projects was able to meet Maximum Contaminant Levels (MCLs)  
7 throughout the treatment zone for all CVOCs.

## 8 **INTRODUCTION**

9 Remediation of sites affected with dense non-aqueous phase liquid (DNAPL)  
10 comprised of chlorinated volatile organic compounds (CVOCs) presents significant  
11 technical and economic challenges (Kavanaugh et al. 2003). While conventional  
12 treatment technologies such as pump-and-treat or containment are often able to control  
13 contaminant plumes emanating from DNAPL source zones, they involve extended  
14 operating periods (perhaps decades) and potentially high life-cycle costs. Therefore,  
15 application of more aggressive source depletion technologies, such as chemical oxidation,  
16 enhanced bioremediation, thermal treatment, and surfactant/cosolvent flushing, in  
17 DNAPL source zones has become more common.

18 Chemical oxidation and enhanced bioremediation rely on in-situ destruction of  
19 DNAPL constituents, such as tetrachloroethene (PCE), trichloroethene (TCE), or 1,1,1-  
20 trichloroethane (1,1,1-TCA), to achieve remediation objectives. For chemical oxidation,  
21 contaminant destruction occurs via addition of an oxidant, such as hydrogen peroxide,  
22 permanganate, or ozone, which initiates a chemical reaction whereby the contaminant is  
23 oxidized to innocuous reaction products. Enhanced bioremediation, as the name implies,

1 takes advantage of natural microbial processes, such as reductive dechlorination, by  
2 supplying a rate-limiting substrate (i.e., electron donor addition), sometimes with the  
3 addition of microorganisms (i.e., bioaugmentation) to increase the rate and extent of  
4 biodegradation. Enhanced bioremediation, which has primarily been used to treat  
5 dissolved phase contamination, is increasingly being applied within DNAPL source  
6 zones to enhance dissolution rates (Parsons 2004, U.S. DOE 2002).

7 Thermal treatment and surfactant/cosolvent flushing technologies remediate  
8 DNAPL contaminants through nondestructive phase transfer processes and/or by  
9 increasing DNAPL mobility for recovery. The most common thermal technologies  
10 include steam heating and electrical resistive heating (ERH), both of which heat the  
11 saturated zone thereby increasing contaminant volatilization rates. At higher  
12 temperatures (i.e., greater than 100 °C) thermal destruction of contaminants may also  
13 occur (U.S. EPA 2004a). Addition of surfactants or cosolvents serves to enhance  
14 DNAPL recovery through increased solubility of DNAPL constituents and/or increased  
15 mobility of the DNAPL. Both thermal and surfactant/cosolvent technologies typically  
16 involve groundwater recovery and ex-situ treatment of recovered contaminants.

17 There are several potential advantages to implementing aggressive DNAPL  
18 treatment technologies (Kavanaugh et al. 2003). From a risk management perspective,  
19 source depletion benefits include reduced exposure risk to human and ecological  
20 receptors that results from decreasing the mass, volume, toxicity, or mobility of the  
21 DNAPL and reducing the concentration and flux of dissolved DNAPL constituents.  
22 From an economic standpoint, source depletion may result in reduced life-cycle costs by  
23 minimizing the remediation timeframe and reducing the duration and cost of other control

1 measures (e.g., engineering controls such as hydraulic containment, as well as  
2 institutional controls such as restricted land use) that are often implemented at DNAPL  
3 sites. While the potential benefits of DNAPL source depletion are apparent, the  
4 uncertainties associated with implementing and evaluating such treatments complicate  
5 the tasks of quantifying the benefits and translating the results to attainment of remedial  
6 goals.

7         Assessing performance of DNAPL source depletion technologies is necessary in  
8 order to determine whether such intensive, costly measures are capable of achieving  
9 remedial goals. However, assessing performance is complicated by the variability in  
10 remedial goals and metrics used to determine whether those goals are met (ITRC 2004,  
11 Kavanaugh et al. 2003). At some sites, measurements of the change in DNAPL mass  
12 and/or contaminant flux is used as a performance metric. However, the remedial goals at  
13 most sites with impacted groundwater are based on reducing groundwater concentrations  
14 to regulatory standards (e.g., MCLs or risk-based values). Since remedial goals are often  
15 based on dissolved contaminant concentrations, most sites where source depletion has  
16 been applied rely on groundwater concentrations to track remediation performance.

17         As discussed by an expert panel in a recent U.S. EPA document on DNAPL  
18 source depletion (Kavanaugh et al. 2003), there have been numerous applications of  
19 innovative technologies within DNAPL source zones, but documentation of remediation  
20 performance and cost is often inadequate to determine overall treatment effectiveness.  
21 Furthermore, comprehensive data sets are rarely made available in the literature to allow  
22 for an independent evaluation of remediation performance. The lack of well-documented  
23 performance evaluations and accurate cost data led the EPA panel to conclude that “the

1 degree of uncertainty in the costs and benefits of applying source depletion technologies  
2 is currently at levels that discourage widespread use of the available source depletion  
3 technologies at DNAPL sites,” and “such documentation would provide important  
4 insights on the benefits that could be achieved even with partial DNAPL source  
5 depletion” (Kavanaugh et al. 2003). The EPA panel identified “a thorough and  
6 independent review of a selected number of DNAPL sites where sufficient  
7 documentation is available to assess the performance of source depletion using multiple  
8 metrics” as a “primary research need.”

9         A recent study addressed the relative success of chlorinated solvent DNAPL  
10 source zone remediation technologies based on a literature review and survey of DNAPL  
11 remediation sites (GeoSyntec 2004). While this study compiled data from many sites for  
12 several technologies, it did not include a rigorous evaluation of remedial success. Rather,  
13 remediation success was semi-quantitatively evaluated using estimates of mass removal  
14 and decrease in mass flux reported by those implementing the remediation. The methods  
15 used by respondents to determine mass removal and mass flux decrease were not  
16 reported. Another recent study by U.S. EPA (2004b) reviewed DNAPL remediation at  
17 sites where regulatory closure had been attained or was near attainment. The review  
18 covered only eight sites, of which seven had achieved closure using risk-based  
19 concentration goals and most sites required implementation of institutional controls  
20 and/or land use restrictions.

21         This study presents results of a rigorous, independent performance evaluation of  
22 four DNAPL source depletion technologies (chemical oxidation, enhanced  
23 bioremediation, thermal treatment, and surfactant/cosolvent flushing) by comparing

1 actual groundwater concentrations of chlorinated compounds before and after treatment.  
2 Temporal groundwater concentration data were collected from site reports submitted to  
3 regulatory agencies, results of a DNAPL remediation survey, and literature reports.  
4 Long-term effectiveness of DNAPL source depletion technologies was evaluated by  
5 examining the temporal data for occurrence of rebound following treatment. All results  
6 reported in this study were calculated from actual concentration versus time data and  
7 concentration reduction values reported in the literature were not used. A companion  
8 study reports costs associated with these treatments (McDade et al. 2005). An electronic  
9 decision-support system featuring a customizable database containing data from this  
10 project will be available for free download at [www.gsi-net.com](http://www.gsi-net.com) in summer 2005.

## 11 **METHODS**

### 12 **Data Collection Methods**

13 Data from three sources were compiled to evaluate source zone remediation  
14 performance and rebound: i) published literature, ii) site reports submitted to state  
15 regulatory agencies, and iii) a survey of DNAPL source zone remediation projects. Sites  
16 using the following technologies for source depletion were included in the project:  
17 enhanced bioremediation, chemical oxidation, thermal treatment, and  
18 surfactant/cosolvent treatment. For each site, groundwater concentration data for up to  
19 four wells within the treatment zone were collected. Data were collected only at sites  
20 having a concentration record with data from before treatment (or at startup of the  
21 remediation system) and after treatment. If available, other site data was collected  
22 including distance of monitoring well to treatment point, groundwater seepage velocity,  
23 predominant lithology of the treatment zone, and treatment cost, volume, and duration.

1 **Performance and Rebound Evaluation Methods**

2 Geometric mean groundwater concentrations were calculated for the period  
3 before treatment and then the period after treatment for each well. The percent reduction  
4 in concentration observed after treatment relative to before treatment was determined for  
5 each well, and the median concentration reduction of all site wells was calculated as the  
6 final performance metric for each site. At sites where source treatment is on-going,  
7 concentration data from the most recent year was used to determine the after treatment  
8 concentration. The performance analysis was conducted for the parent CVOCs (e.g.,  
9 PCE; TCE (at sites with little PCE); chlorobenzene; and pentachlorophenol) and total  
10 CVOCs (TCVOCs; e.g., parent CVOC plus degradation daughter products). Only  
11 enhanced bioremediation sites and chemical oxidation sites had sufficient data records to  
12 evaluate performance in terms of TCVOCs.

13 Rebound was evaluated at sites having at least one year of post-treatment  
14 monitoring data. Rebound was calculated as the percent difference between geometric  
15 mean concentrations of the first half of the post-treatment data record and geometric  
16 mean concentrations of the last half of the post-treatment data record. For sites with two  
17 or more years of post-treatment data, geometric mean concentrations from the first year  
18 of post-treatment data were compared to geometric mean concentrations from the last  
19 year of post-treatment data. Rebound was considered to have occurred when  
20 concentrations increased at least 25% over the post-treatment monitoring period. The  
21 rebound analysis was conducted for the parent chlorinated compound only.

22 **RESULTS AND DISCUSSION**

1 Concentration versus time data for 144 wells at 59 source depletion sites were  
2 collected. The data included 26 enhanced bioremediation sites, 23 chemical oxidation  
3 sites, 6 thermal sites, and 4 surfactant/cosolvent sites. The locations and brief summaries  
4 of the sites are given in Table 1. Nearly 40% of the data was collected from reports  
5 submitted to either the Texas Commission on Environmental Quality (TCEQ) Voluntary  
6 Cleanup Program (VCP) or the Florida Department of Environmental Protection (FDEP)  
7 Drycleaning Solvent Cleanup Program. Data for 20% of the sites was submitted in  
8 response to a DNAPL source zone remediation survey conducted as part of an on-going  
9 Strategic Environmental Research and Development Program (SERDP) project. The  
10 remaining data (40%) was collected from literature reports, conference presentations, or  
11 conference proceedings. As shown on Table 1, the concentration records for data  
12 collected from state agency reports and the SERDP survey were typically longer (median  
13 = 5 years) than those reported in the literature (median = 1 year).

14 Temporal concentration records, normalized to the initial measured concentration,  
15 for all monitoring wells are provided on Figure 1. Since only the magnitude in  
16 concentration changes is presented in Figure 1, the geometric mean of pre-treatment  
17 groundwater concentrations was calculated for each site to provide insight to actual  
18 concentrations. The median geometric mean pre-treatment concentration for all sites,  
19 grouped by technology, was as follows: 48 mg/L at surfactant/cosolvent sites, 7.9 mg/L  
20 at thermal sites, 5.1 mg/L at enhanced bioremediation sites, and 2.0 mg/L at chemical  
21 oxidation sites. Maximum pre-treatment concentrations at any well ranged from 4 to 900  
22 mg/L at surfactant/cosolvent sites; 1.3 to 1,070 mg/L at thermal sites; 0.4 to 1,700 mg/L  
23 at enhanced bioremediation sites; and 0.5 to 1,110 mg/L at chemical oxidation sites.



Site No.	Site Name (if available)	Site Location	Hydrogeology	Amendment <sup>1</sup>	Scale	Data Source <sup>2</sup>	Data Record (yr)
<b>Enhanced Bioremediation Sites</b>							
B-01	Dry Cleaning Facility	Dallas, TX	Fine-grained	HRC	Full	TCEQ VCP Reports	7.3
B-02	Dry Cleaning Facility	Houston, TX	Fine-grained	Bioaug, ORC	Full	TCEQ VCP Reports	5.9
B-03	Dry Cleaning Facility	Dallas, TX	Fine-grained	HRC	Full	TCEQ VCP Reports	2.9
B-04	Dry Cleaning Facility	Massachusetts	Fractured rock	HRC	Full	SERDP Survey	1.8
B-05	Industrial Facility	Florida	Fine-grained	Soybean oil	Full	SERDP Survey	3.9
B-06	Industrial Facility	New Hampshire	Fine-grained	Lactate, yeast	Full	SERDP Survey	15.9
B-07	Dry Cleaning Facility	Jacksonville, FL	Fine-grained	HRC	Full	FDEP Reports	3.6
B-08	Dry Cleaning Facility	Orlando, FL	Fine-grained	HRC	Full	FDEP Reports	5.4
B-09	Industrial Facility	Fort Worth, TX	Fine-grained	HRC	Pilot	TCEQ VCP Reports	0.5
B-10	Dry Cleaning Facility	Dallas, TX	Fine-grained	HRC	Pilot	TCEQ VCP Reports	7.3
B-11	Dry Cleaning Facility	Portland, OR	Fine-grained	HRC, HRC-X	Pilot	SERDP Survey	5.5
B-12	Industrial Facility	New Hampshire	Coarse-grained	Lactate, yeast	Pilot	SERDP Survey	15.8
B-13	Industrial Facility	New Hampshire	Fine-grained	Lactate, yeast	Pilot	SERDP Survey	1.7
B-14	Dry Cleaning Facility	Austin, TX	Fine-grained	Bioaug, nutrients	Full	TCEQ VCP Reports	6.7
B-15	Dry Cleaning Facility	Houston, TX	Fine-grained	HRC, HRC-X	Pilot	TCEQ VCP Reports	7.0
B-16	Dry Cleaning Facility	Dallas, TX	Fine-grained	Lactate, ethanol	Pilot	TCEQ VCP Reports	5.9
B-17	Industrial Facility	Tennessee	Fine-grained	HRC	Full	SERDP Survey	3.6
B-18	Industrial Facility	San Jose, CA	Fine-grained	HRC	Full	Literature Reports	4.2
B-19	Industrial Facility	South Carolina	Coarse-grained	Molasses	Full	SERDP Survey	1.6
B-20	Industrial Facility	Southeast US	Fine-grained	Molasses	Full	SERDP Survey	2.3
B-21	Duluth International Airport	Duluth, MN	Fine-grained	HRC	Pilot	Literature Reports	0.8
B-22	Test Area North	Idaho Falls, ID	Fractured rock	Lactate	Pilot	Literature Reports	1.0
B-23	Pinellas STAR Center	Largo, FL	Fine-grained	Lactate, methanol	Pilot	Literature Reports	0.4
B-24	Manufacturing Facility	Houston, TX	Fine-grained	Methanol, nutrients	Full	Literature Reports	3.5
B-25	Industrial Facility	Rochester, NY	Fine-grained	HRC	Full	Literature Reports	0.3
B-26	Washington Square Mall	Germantown, WI	Coarse-grained	Molasses	Full	Literature Reports	1.2
<b>Chemical Oxidation Sites</b>							
C-01	Dry Cleaning Facility	Houston, TX	Fine-grained	KMnO4	Full	TCEQ VCP Reports	6.1
C-02	Industrial Facility	Pensacola, FL	Coarse-grained	H2O2	Full	SERDP Survey	6.5
C-03	Dry Cleaning Facility	Jacksonville, FL	Fine-grained	H2O2	Full	FDEP Reports	1.8
C-04	Dry Cleaning Facility	Florida	Coarse-grained	H2O2	Full	FDEP Reports	3.5
C-05	Dry Cleaning Facility	Jacksonville, FL	Fine-grained	KMnO4, TBA	Pilot	FDEP Reports	4.7
C-06	Industrial Facility	Dallas, TX	Fine-grained	NaMnO4	Pilot	TCEQ VCP Reports	0.6
C-07	Dry Cleaning Facility	Dallas, TX	Coarse-grained	KMnO4	Full	TCEQ VCP Reports	5.3
C-08	Dry Cleaning Facility	Houston, TX	Fine-grained	CleanOx®, KMnO4	Full	TCEQ VCP Reports	5.4
C-09	Dry Cleaning Facility	Dallas, TX	Fine-grained	H2O2	Full	TCEQ VCP Reports	3.1
C-10	Dry Cleaning Facility	Dallas, TX	Fine-grained	KMnO4	Full	TCEQ VCP Reports	5.8
C-11	Dry Cleaning Facility	Houston, TX	Fine-grained	KMnO4	Full	TCEQ VCP Reports	5.0
C-12	Broward Co	Florida	Coarse-grained	KMnO4	Full	Literature Reports	1.1
C-13	Dry Cleaning Facility	Houston, TX	Fine-grained	KMnO4	Full	TCEQ VCP Reports	8.6
C-14	Dry Cleaning Facility	Houston, TX	Fine-grained	CleanOx®, KMnO4	Full	TCEQ VCP Reports	4.5
C-15	Charleston SWMU 196	Charleston, SC	Fine-grained	H2O2	Full	Literature Reports	2.4
C-16	News Publisher Facility	Framingham, MA	Fine-grained	H2O2	Full	Literature Reports	0.1
C-17	Savannah River	Aiken, SC	Fine-grained	H2O2	Full	Literature Reports	0.5
C-18	Dry Cleaning Facility	Hutchinson, KS	Fine-grained	Ozone	Pilot	Literature Reports	0.4
C-19	Kings Bay Naval Base	Camden Co, GA	Coarse-grained	H2O2	Full	Literature Reports	0.9
C-20	Dry Cleaning Facility	Rockville, MD	Fractured rock	H2O2, NaMnO4	Full	Literature Reports	1.1
C-21	Portsmouth Gas Plant	Piketon, OH	Coarse-grained	KMnO4	Full	Literature Reports	0.3
C-22	Kansas City Plant	Kansas City, MO	Fine-grained	KMnO4	Full	Literature Reports	0.1
C-23	Launch Complex 34	Cape Canaveral, FL	Fine-grained	KMnO4	Pilot	Literature Reports	0.5
<b>Thermal Sites</b>							
T-01	Industrial Facility	Illinois	Fine-grained	6-Phase ERH	Full	SERDP Survey	2.1
T-02	Industrial Facility	Florida	Fine-grained	Steam, 3-Phase	Full	SERDP Survey	4.4
T-03	Visalia	Visalia, CA	Coarse-grained	Steam	Full	Literature Reports	5.8
T-04	Charleston Naval Complex	Charleston, SC	Fine-grained	3-Phase ERH	Full	Literature Reports	2.7
T-05	Manufacturing Plant	Not Available	Fine-grained	Steam	Full	Literature Reports	0.5
T-06	Cape Canaveral	Cape Canaveral, FL	Fine-grained	6-Phase ERH	Full	Literature Reports	1.9
<b>Surfactant/Cosolvent Sites</b>							
S-01	Dry Cleaning Facility	Jacksonville, FL	Fine-grained	Ethanol	Pilot	FDEP Reports	5.3
S-02	Hill Air Force Base	Hill AFB, UT	Coarse-grained	Aerosol MA-80I	Full	Literature Reports	0.2
S-03	Camp Lejeune Site 88	Jacksonville, NC	Fine-grained	Alfoterra 145-4PO	Pilot	Literature Reports	1.8
S-04	Bachman Road Site	Oscoda, MI	Coarse-grained	Tween 80	Pilot	Literature Reports	1.4

1 **TABLE 1. Summary of Source Depletion Sites.** <sup>1</sup> HRC = hydrogen release compound; HRC-X = HRC extended  
2 release formula; Bioaug = bioaugmentation; ORC = oxygen release compound; KMnO4 = potassium permanganate; H2O2 = hydrogen  
3 peroxide; TBA = tertiary butyl alcohol; NaMnO4 = sodium permanganate; ERH = electrical resistance heating. <sup>2</sup> TCEQ VCP = Texas  
4 Commission on Environmental Quality Voluntary Cleanup Program; SERDP = Strategic Environmental Research and Development  
5 Program; FDEP = Florida Department of Environmental Protection

1 Based on maximum pre-treatment concentration data, all four technologies have been  
2 applied at sites with very high groundwater concentrations. But on average,  
3 surfactant/cosolvent technology was applied at sites with highest concentrations and  
4 chemical oxidation was applied at sites with lowest concentrations.

5 In addition to pre-treatment concentrations, other site characteristics including  
6 hydrogeology (e.g., fine-grained, coarse-grained, or fractured rock) were evaluated to  
7 determine if there was a relationship to the technology selected. As shown on Table 1,  
8 nearly 75% of the sites reported the treatment zone consisted of fine-grained material  
9 (e.g., silts, clays, and silty/clayey sands). Treatment zone stratigraphy was characterized  
10 as fine-grained at 88% of enhanced bioremediation sites, at 83% of thermal sites, at 73%  
11 of chemical oxidation sites, and at 50% of surfactant/cosolvent sites. Chemical oxidation  
12 had the most applications (6) in coarse-grained material (e.g., sands, gravels). The  
13 treatment zone at only three sites, two implementing enhanced bioremediation and one  
14 implementing chemical oxidation, consisted of fractured rock. Seepage velocity and site  
15 type (i.e., dry cleaner, industrial, military) also did not correlate to the selected  
16 technology (data not shown).

17 Performance results of source depletion technologies, based on groundwater  
18 concentration reductions of the parent chlorinated compound within the treatment zone,  
19 are illustrated on Figure 2a. All four technologies exhibited median parent reductions of  
20 88% or greater, and enhanced bioremediation, thermal, and surfactant/cosolvent had  
21 median parent reductions of 95% or greater. All sites showed some reduction in parent  
22 concentrations except for two chemical oxidation sites that had median concentration  
23 increases in the parent compound of 27% and 55% (i.e., -27% and -55% percent

1 reduction). Surfactant sites had the least variance in parent concentration reductions with  
2 minimum and maximum reductions ranging from 91% to 99.9%. However,  
3 surfactant/cosolvent treatment had the least representation in the study with only 4 sites.

4 Performance, in terms of parent CVOC reduction, did not appear to be related to  
5 groundwater seepage velocity, treatment volume, or distance from the well to the nearest  
6 treatment point. Performance was independent of these parameters as indicated by R-  
7 squared values of less than 0.1 for each regression (data not shown). The lack of any  
8 relationship between concentration reduction and distance to the nearest treatment point  
9 may be a result of the close proximity of most monitoring points to the treatment point.  
10 For 97 monitoring points where the distance to the nearest treatment point was available,  
11 the median distance from the monitoring point to the nearest treatment point was 7 ft and  
12 75% were within 13 ft of a treatment point.

13 Data records for sites implementing enhanced bioremediation and chemical  
14 oxidation were sufficient to evaluate performance in terms of reduction in TCVOC  
15 concentrations (parent plus daughter products). For TCVOCs, chemical oxidation  
16 slightly outperformed enhanced bioremediation with median concentration reductions of  
17 72% compared to 62% for enhanced bioremediation (Figure 2b). All chemical oxidation  
18 sites where TCVOC performance was evaluated had an overall decrease in TCVOC  
19 concentrations (the two sites where parent concentrations increased did not have  
20 sufficient data to evaluate TCVOCs). On the other hand, over 25% of the enhanced  
21 bioremediation sites had an increase in TCVOC concentrations (i.e., 25<sup>th</sup> percentile = -  
22 15%, where a negative number indicates a concentration increase).

1           Some degree of accumulation of biodegradation daughter products is not  
2 unexpected when implementing enhanced bioremediation, as this technology results in  
3 the breakdown of more highly chlorinated compounds to lesser chlorinated compounds  
4 (Wiedemeier et al. 1999). At some sites, reductive dechlorination of PCE and TCE may  
5 lead to an accumulation and persistence of chlorinated intermediates such as *cis*-1,2-  
6 dichloroethene (*cis*-DCE) and vinyl chloride (Parsons 2004). However, these less  
7 chlorinated compounds may be amenable to additional degradation processes such as  
8 biological oxidation (Bradley and Chapelle 1996, Bradley and Chapelle 1998). While  
9 there are downfalls to production of the lesser chlorinated intermediates, such as greater  
10 toxicity and lower regulatory standards for vinyl chloride, there are also potential  
11 advantages to their production in DNAPL source zones. In many cases, increasing  
12 concentrations of daughter products is a goal of bioremediation as recent studies (Carr et  
13 al. 2000, Cope and Hughes 2001, Adamson et al. 2003) have reported enhanced  
14 dissolution rates of DNAPL constituents as a result of daughter products within the  
15 source zone, which may lead to decreased remediation timeframes.

16           Researchers have suggested that technologies including chemical oxidation,  
17 thermal treatment, and surfactant/cosolvent flushing may also enhance natural  
18 bioremediation processes (USEPA 2004, Kavanaugh et al. 2003, Marley et al. 2003).  
19 Comparison of concentration reductions for parent CVOC to TCVOCs for chemical  
20 oxidation sites suggests that bioremediation was not enhanced as a result of chemical  
21 oxidation treatment at many of the sites studied. Since no thermal sites had daughter  
22 product concentration data, TCVOC reduction could not be used to evaluate whether  
23 thermally enhanced bioremediation occurred at these sites. One cosolvent flushing site

1 (Table 1, Site S-01) did have TCVOC concentration data and daughter product  
2 concentrations exceeded parent CVOC concentrations, indicating bioremediation  
3 processes may have been enhanced. Other researchers studying this site (Mravik et al.  
4 2003) concluded that bioremediation was enhanced in the presence of residual cosolvent.  
5 Although no surfactant sites had TCVOC data, a recent study on the effects of surfactants  
6 on reductive dechlorination of chlorinated ethenes concluded that surfactants are likely to  
7 inhibit reductive dechlorination to some degree, particularly reduction beyond *cis*-DCE to  
8 vinyl chloride and ethene (McGuire and Hughes 2003).

9 A notable characteristic of DNAPL source zone depletion projects is the duration  
10 over which the technology is actively applied. For this study, treatment duration was  
11 measured as the time period beginning when application of the treatment was initialized  
12 until treatment ceased. For enhanced bioremediation and chemical oxidation treatments,  
13 which often involve multiple injection events, the treatment duration was the time  
14 between the first and last injection events.

15 As summarized on Table 2, sites implementing enhanced bioremediation had both  
16 the longest median duration (427 days) and the greatest variation in treatment duration (1  
17 to 2,123 days). Notably, 43% of enhanced bioremediation sites reporting treatment  
18 duration (n=21) implemented one-time injections, while 26% of chemical oxidation sites  
19 (n=19) used one-time injections. Chemical oxidation and thermal treatment technologies  
20 had similar median treatment durations (212 and 228 days, respectively), while  
21 surfactant/cosolvent had the lowest median duration (46 days). Duration of  
22 surfactant/cosolvent treatments also varied least with a range of 6 to 58 days. These  
23 results are comparable to those reported in a recent DNAPL remediation survey

1 (GeoSyntec 2004), which had median treatment durations for enhanced bioremediation,  
 2 chemical oxidation, and thermal treatment sites of 380 days, 183 days, and 167 days,  
 3 respectively. The GeoSyntec study did not report treatment duration for  
 4 surfactant/cosolvent sites.

Treatment Duration (days) Summary Statistics	Enhanced Bioremediation	Chemical Oxidation	Thermal Treatment	Surfactant/ Cosolvent
Minimum	1	1	142	6
25 <sup>th</sup> Percentile	1	29	174	26
Median	427	212	228	46
75 <sup>th</sup> Percentile	639	457	320	52
Maximum	2,123	731	1,127	58
n	21	19	5	4

5 **TABLE 2. Treatment Duration Summary Statistics.**

6 For some technologies, treatment duration may extend beyond the period of active  
 7 treatment. Examples include enhanced bioremediation using a slow-release electron  
 8 donor and thermal treatments where elevated temperatures persist beyond the period of  
 9 active heating. Extended treatment beyond the active treatment period is evident at  
 10 many enhanced bioremediation sites included in this study as temporal records (see  
 11 Figure 1) show that concentrations continue to decline several years after treatment. The  
 12 period of active treatment may also affect costs related to implementing the remedy. In a  
 13 companion cost analysis of the sites presented in this study, McDade et al. (2005) report  
 14 that treatment duration is inversely related to treatment cost (in terms of dollars per cubic  
 15 yard), though at a low correlation ( $R^2 = 0.25$ ).

16 The occurrence of rebound (i.e., an increase in groundwater concentrations  
 17 following treatment completion) is another important factor in evaluating the success of  
 18 source depletion technologies. Many case studies and literature reports document  
 19 decreases in concentrations following source depletion activities. However, the data

1 presented is typically of short duration and does not allow a complete assessment of  
 2 whether or not the reduction achieved was permanent (Parsons 2004, USEPA 2004,  
 3 USEPA 2001, ESTCP 1999, USEPA 1998). Of the few studies that have monitored  
 4 concentrations for extended periods beyond completion of source depletion activities,  
 5 several have observed some level of concentration rebound (ITRC 2004, ESTCP 1999).  
 6 In order to more accurately assess the occurrence of rebound, sites with concentration  
 7 records including at least one year of post-treatment data were evaluated.

8 Results of the rebound analysis are presented on Table 3 and Figures 3 and 4.  
 9 Rebound was analyzed for 43 wells at 20 sites (10 enhanced bioremediation sites, 7  
 10 chemical oxidation sites, 2 surfactant/cosolvent sites, and 1 thermal site). On an  
 11 individual well basis (Table 3 and Figure 3), rebound was observed in 20% of wells at  
 12 enhanced bioremediation sites, in 81% of wells at chemical oxidation sites, and was not  
 13 observed at surfactant/cosolvent and thermal sites. As shown on Figure 3, concentrations  
 14 in several wells at chemical oxidation sites rebounded by as much as 1 to 2 orders of  
 15 magnitude throughout the post-treatment monitoring period. In fact, at 30% of the  
 16 chemical oxidation rebound wells, rebound resulted in concentrations higher than pre-  
 17 treatment conditions. For rebound wells at enhanced bioremediation sites, the increased  
 18 concentrations observed during the post-treatment period were still below pre-treatment  
 19 concentrations.

Source Depletion Technology	Percent of sites with rebound <sup>1</sup> at 1 or more well	Percent of sites with rebound at >50% of wells	Number of wells analyzed for rebound	Number of wells with rebound
Enhanced bioremediation	40	10	20	4
Chemical oxidation	88	57	16	13
Thermal treatment	50	0	1	0
Surfactant/cosolvent	0	0	6	0

1 **TABLE 3. Evaluation of Rebound at Source Depletion Sites.** <sup>1</sup>For this study,  
2 rebound occurrence is defined as an increase  $\geq 25\%$  in post-treatment groundwater concentrations (see  
3 Methods section). Rebound was only evaluated at sites having at least one year of post-treatment  
4 monitoring data.

5 Figure 4 presents a comparison of median concentration changes from before  
6 treatment began to concentrations immediately following treatment and at the end of the  
7 post-monitoring data record (minimum post-monitoring record of 1 year, maximum post-  
8 monitoring period of 5.5 years). For most enhanced bioremediation and surfactant/  
9 cosolvent flushing sites, concentrations continued to decrease after treatment. At  
10 enhanced bioremediation sites, more decrease was observed, with a median reduction in  
11 concentration of 77% in parent CVOC immediately following treatment changing to a  
12 96% reduction at the end of the post-monitoring record. Possible explanations of these  
13 results are 1) residual electron donor continued to promote bioremediation even after  
14 injections ceased, and 2) the treatment created conditions more conducive to support  
15 natural bioremediation without the need for enhancement. The continued concentration  
16 reduction in the parent CVOC over the post-treatment period at the surfactant/cosolvent  
17 sites is interesting since this observation is likely due to biodegradation rather than  
18 flushing. Recent studies by Ramsburg et al. (2004) and Mravick et al. (2003) support this  
19 conclusion.

20 Rebound at the seven chemical oxidation sites caused the remediation  
21 performance to deteriorate in the period after the treatment, as the median concentration  
22 reduction was 90% immediately after treatment compared to only a 78% reduction at the  
23 end of post-treatment monitoring (at least a year later). It is unclear why rebound was  
24 most prevalent at chemical oxidation sites. One factor considered was pre-treatment



1 groundwater concentrations. Results from an analysis of pre-treatment groundwater  
2 concentrations at the wells evaluated for rebound (data not shown) were similar to results  
3 obtained from the same analysis for all wells (discussed above). Pre-treatment  
4 groundwater concentrations were typically lower at chemical oxidation sites than at sites  
5 implementing other technologies.

6 Other possible explanations for the occurrence of rebound at chemical oxidation  
7 sites are i) DNAPL diffusion from low permeability zones following treatment, ii)  
8 alteration of naturally-occurring organic carbon and other geochemical conditions, and  
9 iii) decreased microbial activity following treatment due to toxicity effects of the oxidant.  
10 Since diffusion from low permeability regions would also be expected at bioremediation  
11 sites and surfactant sites (where rebound was less prevalent), it is unlikely that diffusion  
12 from a low permeability matrix accounts for the observed rebound at chemical oxidation  
13 sites. At the four chemical oxidation sites where rebound was observed in >50% of  
14 wells, the treatment zone stratigraphy was characterized as fine-grained (e.g., silts, clays,  
15 and silty/clayey sands) at two sites and coarse-grained (e.g., sands and gravels) at two  
16 sites. This limited data supports the conclusion that diffusion from low permeability  
17 zones is unlikely to fully account for rebound at chemical oxidation sites.

18 In aquifers affected with chlorinated solvents, naturally-occurring organic carbon  
19 may serve as sorption material as well as electron donor for intrinsic biodegradation. As  
20 naturally-occurring organic carbon is depleted by chemical oxidation, contaminant  
21 sorption sites and electron donor available to bacteria are decreased, which may cause  
22 contaminant concentrations to increase following treatment. Since organic carbon data  
23 was not available for the sites studied, this hypothesis could not be evaluated.

1           The addition of chemical oxidants may also lead to decreased microbial activity  
2 within the treatment zone, thereby limiting the naturally-occurring biodegradation of  
3 contaminants remaining in the treatment zone, as well as contaminants flushed from  
4 untreated areas. Decreased microbial activity following chemical oxidation of TCE  
5 DNAPL using potassium permanganate was recently observed in laboratory column  
6 studies by Hrapovic et al. (2005). In these studies, the authors observed no microbial  
7 activity following permanganate flushing until the influent was changed from distilled  
8 water (containing ethanol and acetate as electron donors) to site groundwater, which  
9 introduced new microorganisms. Researchers have suggested that the presence of  
10 residual oxidant, oxygen produced during chemical oxidation, and low pH values are  
11 likely to limit intrinsic biodegradation following chemical oxidation of CVOCs (Kastner  
12 et al. 2000; Christ et al. 2005).

13           Data from a DNAPL remediation survey (GeoSyntec 2004) also found the  
14 occurrence of rebound was more prevalent at chemical oxidation sites compared to sites  
15 implementing other technologies. In that study, a total of 21 sites indicated that rebound  
16 had been evaluated, and one-third (7 sites) reported rebound did occur. Of the seven  
17 confirmed rebound sites, five (71%) represented chemical oxidation sites. Five  
18 additional chemical oxidation sites (50%) reported that rebound did not occur. The other  
19 two sites with rebound implemented thermal treatment and excavation as DNAPL  
20 removal technologies. Rebound was not observed at any of the three enhanced  
21 bioremediation sites evaluated as part of the GeoSyntec (2004) study. The criteria used  
22 by survey respondents to evaluate rebound were not reported.

1           Results of this study indicate that all four technologies are capable of achieving  
2 significant reductions in the dissolved phase concentration of the parent chlorinated  
3 compound within the treatment zone. Approximately 75% of the sites exhibited at least  
4 70% reduction in source zone parent CVOC concentrations. Enhanced bioremediation  
5 was less successful at removing total CVOCs because daughter products were generated,  
6 but had the advantage of continued source depletion after treatment. Chemical oxidation  
7 had better removal of total CVOCs (parent plus daughter compounds) but had  
8 significantly more rebound. Thermal treatment and surfactant treatment showed good  
9 performance, but these technologies had more limited datasets. Surfactant/cosolvent  
10 treatment has significantly higher costs than thermal treatment, enhanced bioremediation,  
11 or chemical oxidation (McDade et al. 2005).

12           The relationship between source concentration reduction and source mass  
13 reduction is of interest to assessing the performance of source depletion projects. Falta et  
14 al. (2005a and 2005b) recently presented site data and analytical modeling results  
15 illustrating source concentration reduction versus mass reduction relationships. For this  
16 study, reductions in source zone DNAPL mass were reported for eleven sites. Figure 5  
17 contains a plot of source groundwater concentration reduction (calculated by the authors)  
18 versus mass reduction (calculated by site personnel) for the eleven sites. As shown on  
19 Figure 5, the concentration reduction achieved for a given mass reduction was within  
20 30% of a 1:1 relationship at most sites. As discussed by the U.S. EPA expert panel  
21 (Kavanaugh et al. 2003) and others (e.g., Stroo et al. 2003, Sale and McWhorter 2001),  
22 reductions in groundwater concentrations resulting from mass removal are highly  
23 influenced by the source architecture (i.e., DNAPL distribution and geometry within the

1 subsurface). Results from modeling studies and limited site data have suggested that at  
2 homogeneous sites with pooled DNAPL, large reductions in source mass (e.g., >90%)  
3 may be necessary to achieve significant improvements in groundwater quality (Sale and  
4 McWhorter 2001; Falta et al. 2005a); while at heterogeneous sites with most DNAPL  
5 located in high permeability zones, significant improvements in groundwater quality can  
6 occur even for modest reductions (e.g. 50 to 70%) in source mass (Rao and Jawitz 2003;  
7 Falta et al. 2005a). The mass reduction data reported for the sites in the current study  
8 suggests that at sites where detailed knowledge of source architecture is absent, it is  
9 reasonable to approximate the concentration reduction resulting from source depletion as  
10 directly proportional to mass reduction (i.e., there are points on either side of the 1:1 line  
11 on Figure 5).

12         It remains unclear how the improvements in groundwater quality achieved within  
13 the source zone will affect remediation timeframes at these sites. Newell and Adamson  
14 (2005) have developed a planning-level tool to help evaluate the benefits of partial source  
15 depletion in terms of remediation timeframe. For a source depletion project that removes  
16 90% of DNAPL mass and has a goal to reduce concentration by a factor of 1000 (e.g.,  
17 from 5 to 0.005 mg/L), the planning-level tool predicts the reduction in remediation  
18 timeframe over natural attenuation alone to be approximately 33%.

19         Since the source depletion technologies evaluated in this paper were applied in  
20 DNAPL source zones that had relatively high initial dissolved concentrations, common  
21 regulatory standards, such as MCLs, were not achieved in most cases. Though several  
22 sites achieved MCLs at some wells, none of the sites attained and sustained MCLs for all  
23 chlorinated compounds at all wells. Given the inability of most source depletion

1 technologies to achieve the primary remediation goal of returning groundwater to usable  
2 conditions, it is likely that some type of site management (e.g., institutional controls,  
3 long-term monitoring, monitored natural attenuation, or containment controls) will be  
4 necessary at many of these sites.

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## 10 **REFERENCES**

- 11 Adamson, D.T., J.M. McDade, and J.B. Hughes. 2003. Inoculation of a DNAPL Source  
12 Zone to Initiate Reductive Dechlorination of PCE. *Environmental Science and*  
13 *Technology*, 37(13), 2525-2533.
- 14 Bradley, P.M. and F.H. Chapelle. 1996. Anaerobic mineralization of vinyl chloride in  
15 Fe(III)-reducing aquifer sediments. *Environmental Science and Technology*,  
16 30(6), 2084-2086.
- 17 Bradley, P.M. and F.H. Chapelle. 1998. Effect of contaminant concentration on aerobic  
18 microbial mineralization of DCE and VC in stream-bed sediments.  
19 *Environmental Science and Technology*, 32(5), 553-557.
- 20 Carr, C.S., S.Garg, and J.B. Hughes. 2000. Effect of Dechlorinating Bacteria on the  
21 Longevity and Composition of PCE-containing Nonaqueous Phase Liquids Under  
22 Equilibrium Dissolution Conditions. *Environmental Science and Technology*,  
23 34(6), 1088-1094.

- 1 Christ J.A., C.A. Ramsburg, L.M. Abriola, K.D. Pennell, and F.E. Löffler. 2005.  
2 Coupling Aggressive Mass Removal with Microbial Reductive Dechlorination for  
3 Remediation of DNAPL Source Zones: A Review and Assessment.  
4 *Environmental Health Perspectives*, 113(4), 465-477.
- 5 Cope, N. and J.B. Hughes. 2001. Biologically-enhanced Removal of PCE from NAPL  
6 Source Zones. *Environmental Science and Technology*, 35(10), 2014-2021.
- 7 Environmental Security Technology Certification Program (ESTCP). 1999. Technology  
8 Status Review: In Situ Oxidation. [http://www.estcp.org/documents/techdocs/  
9 ISO\\_Report.pdf](http://www.estcp.org/documents/techdocs/ISO_Report.pdf)
- 10 Falta, R.W., P.S. Rao, and N. Basu. 2005a. Assessing the impacts of Partial Mass  
11 Depletion in DNAPL Source Zones: I. Analytical Modeling of Source Strength  
12 Functions and Plume Response. *Journal of Contaminant Hydrology*, in press.
- 13 Falta, R.W., N. Basu, and P.S. Rao. 2005b. Assessing the impacts of Partial Mass  
14 Depletion in DNAPL Source Zones: II. Coupling Source Strength Functions to  
15 Plume Evolution. *Journal of Contaminant Hydrology*, in press.
- 16 GeoSyntec Consultants. 2004. Assessing the Feasibility of DNAPL Source Zone  
17 Remediation: Review of Case Studies. Port Hueneme, California: Naval  
18 Facilities Engineering Services Center.
- 19 Hrapovic, L., B.E. Sleep, D.J. Major, E.D. Hood. 2005. Laboratory Study of Treatment  
20 of Trichloroethene by Chemical Oxidation Followed by Bioremediation.  
21 *Environmental Science and Technology*, 39(8), 2888-2897.

1 Interstate Technology and Regulatory Council (ITRC). 2004. Strategies for Monitoring  
2 the Performance of DNAPL Source Zone Remedies. Dense Nonaqueous-Phase  
3 Liquids Team. <http://www.itrcweb.org/DNAPLs-5.pdf>

4 Kastner J.R., J. Santo Domingo, M. Denham, M. Molina, and R. Brigmon. 2000. Effect  
5 of chemical oxidation on subsurface microbiology and trichloroethene (TCE)  
6 biodegradation. *Bioremediation Journal*, 4:219-236.

7 Kavanaugh, M.C., S.C. Rao, L. Abriola, J. Cherry, G. Destouni, R. Falta, D. Major, J.  
8 Mercer, C. Newell, T. Sale, S. Shoemaker, R. Siegrist, G. Teutsch, and K. Udell.  
9 2003. The DNAPL Remediation Challenge: Is There a Case for Source  
10 Depletion? Ada, Oklahoma: U.S. Environmental Protection Agency, National  
11 Risk Management Research Laboratory, EPA/600/R-03/143.

12 Marley, M., J.M. Parikh, E.X. Droste, A.M. Lee, P.M. Dinardo, B.A. Woody, P. Chheda  
13 and G. Hoag. 2003. Enhanced Reductive Dechlorination Resulting From A  
14 Chemical Oxidation Pilot Test, In: *In Situ and On-Site Bioremediation 2003*, ed.  
15 V.S. Magar and M.E. Kelley, Columbus, OH: Battelle Press.

16 McDade, J.M., T.M. McGuire, and C.J. Newell. 2005. Analysis of DNAPL source-  
17 depletion costs at 36 field sites. *Remediation Journal*, 15(2), 9-18.

18 McGuire, T.M. and J.B. Hughes. 2003. Effects of Surfactants on the Dechlorination of  
19 Chlorinated Ethenes. *Environmental Toxicology and Chemistry*, 22(11), 2630-  
20 2638.

21 Mravik, S.C., R.K. Sillan, A.L. Wood, and G.W. Sewell. 2003. Field evaluation of the  
22 solvent extraction residual biotreatment technology. *Environmental Science and  
23 Technology*, 37(21), 5040-5049.

1 Newell, C.J. and D.T. Adamson, 2005. Planning-level source decay models to evaluate  
2 impact of source depletion on remediation timeframe. *Remediation*, accepted for  
3 publication.

4 Parsons Corporation. 2004. Principles and Practices of Enhanced Anaerobic  
5 Bioremediation of Chlorinated Solvents. Brooks City-Base, Texas: Air Force  
6 Center for Environmental Excellence. [http://www.afcee.brooks.af.mil/products/  
7 techtrans/Bioremediation/downloads/PrinciplesandPractices.pdf](http://www.afcee.brooks.af.mil/products/techtrans/Bioremediation/downloads/PrinciplesandPractices.pdf)

8 Ramsburg, C.A., L.M. Abriola, K.D. Pennell, F.E. Loffler, M. Gamache, B.K. Amos, and  
9 E.A. Petrovskis. 2004. Stimulated microbial reductive dechlorination following  
10 surfactant treatment at the Bachman Road site. *Environmental Science and  
11 Technology*, 38(22), 5902-5914.

12 Rao, P.S.C. and J.W. Jawitz. 2003. Comment on “Steady-state mass transfer from  
13 single-component dense non-aqueous phase liquids in uniform flow fields” by  
14 T.C. Sale and D.B. McWhorter, *Water Resources Research*, 39:1068.

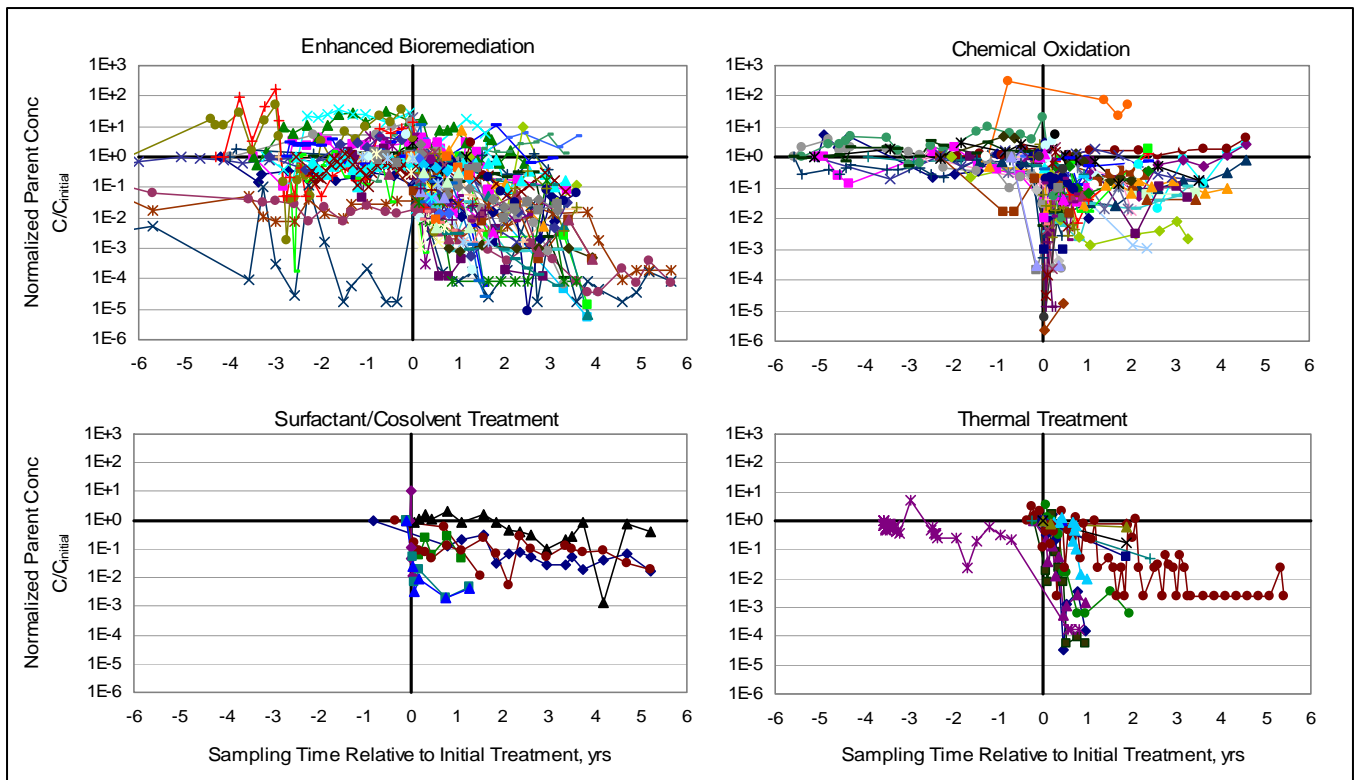
15 Sale, T.C. and D.B. McWhorter. 2001. Steady state mass transfer from single-  
16 component dense nonaqueous phase liquids in uniform flow fields. *Water  
17 Resources Research*, 37(2), 393-404.

18 Stroo, H.F., M. Unger, C.H. Ward, M.C. Kavanaugh, C. Vogel, A. Leeson, J.A.  
19 Marqusee, and B.P. Smith. 2003. Remediating Chlorinated Solvent Source Zones.  
20 *Environmental Science and Technology*, 37(11), 224A-230A.

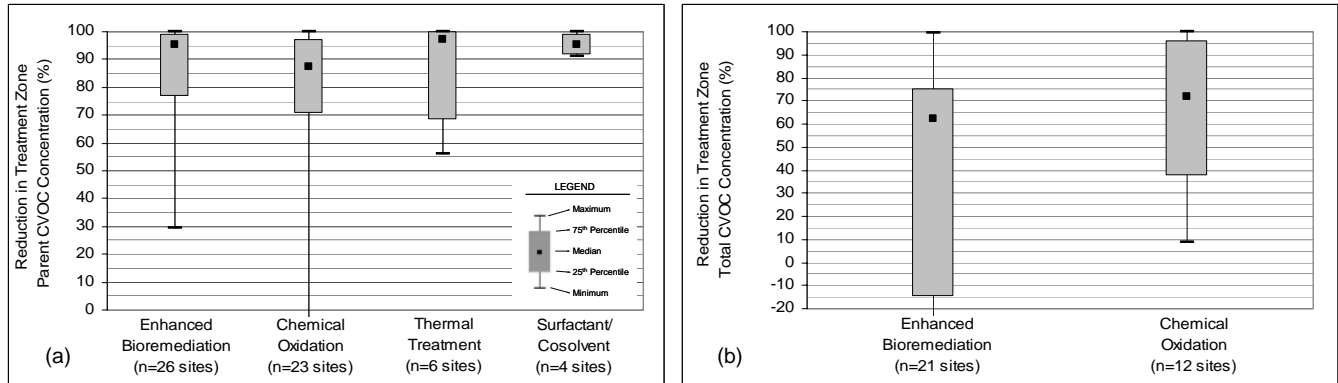
21 U.S. Department of Energy (U.S. DOE). 2002. DNAPL Bioremediation-RTDF. Office  
22 of Environmental Management. Innovative Technology Summary Report,  
23 DOE/EM-0625.



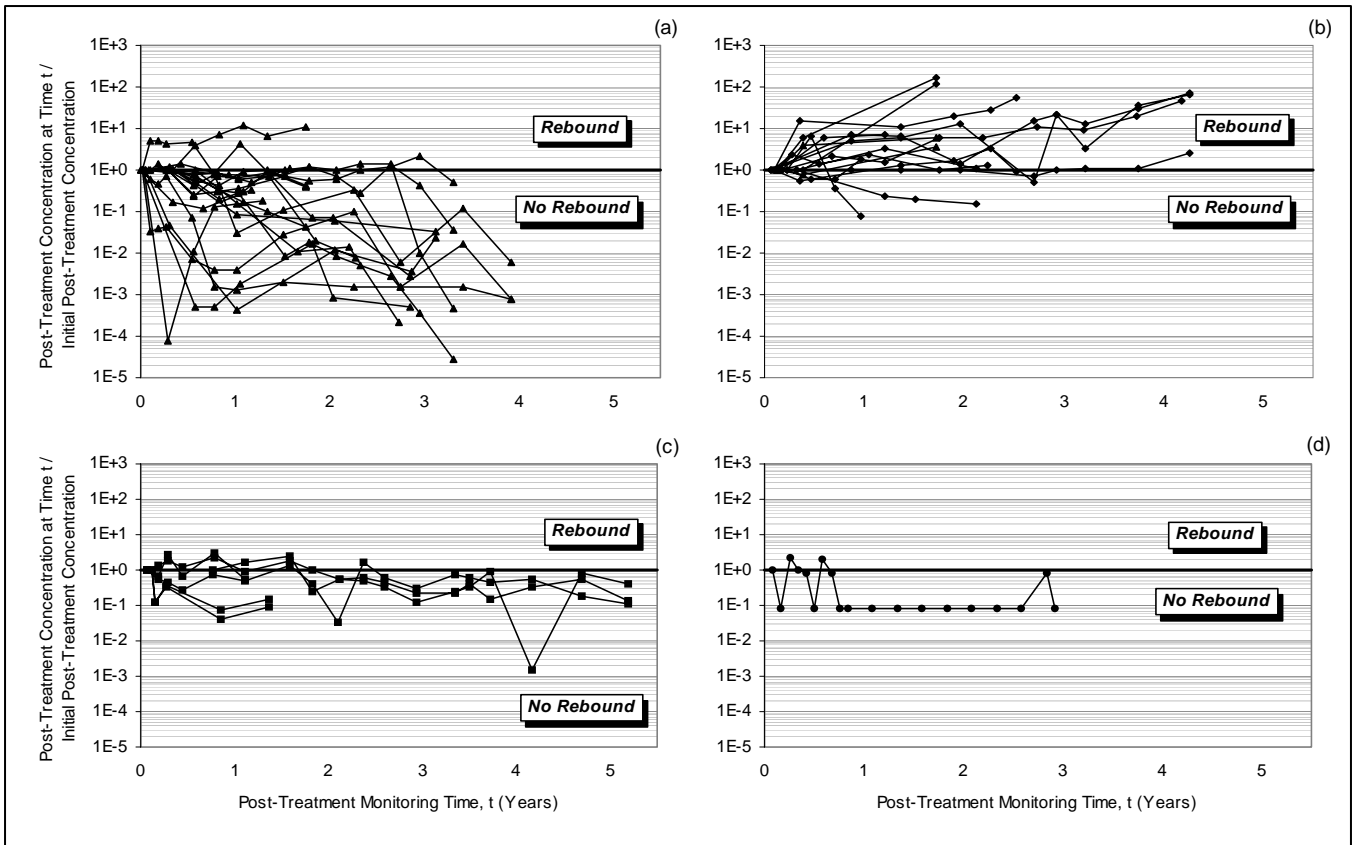
- 1 U.S. Environmental Protection Agency (U.S. EPA). 1998. Field Applications of In Situ  
2 Remediation Technologies: Chemical Oxidation. Office of Solid Waste and  
3 Emergency Response, EPA 542-R-98-008.
- 4 U.S. Environmental Protection Agency (U.S. EPA). 2001. Use of Bioremediation at  
5 Superfund Sites. Office of Solid Waste and Emergency Response, EPA 542-R-  
6 01-019.
- 7 U.S. Environmental Protection Agency (U.S. EPA). 2004a. In Situ Thermal Treatment  
8 of Chlorinated Solvents: Fundamentals and Field Applications. Office of Solid  
9 Waste and Emergency Response, EPA 542-R-04-010.
- 10 U.S. Environmental Protection Agency (U.S. EPA). 2004b. DNAPL Remediation:  
11 Selected Projects Approaching Regulatory Closure. Office of Solid Waste and  
12 Emergency Response, EPA 542-R-04-016.
- 13 Wiedemeier, T.H., H.S. Rifai, C.J. Newell, and J.T. Wilson. 1999. *Natural Attenuation*  
14 *of Fuels and Chlorinated Solvents in the Subsurface*. New York: John Wiley &  
15 Sons.



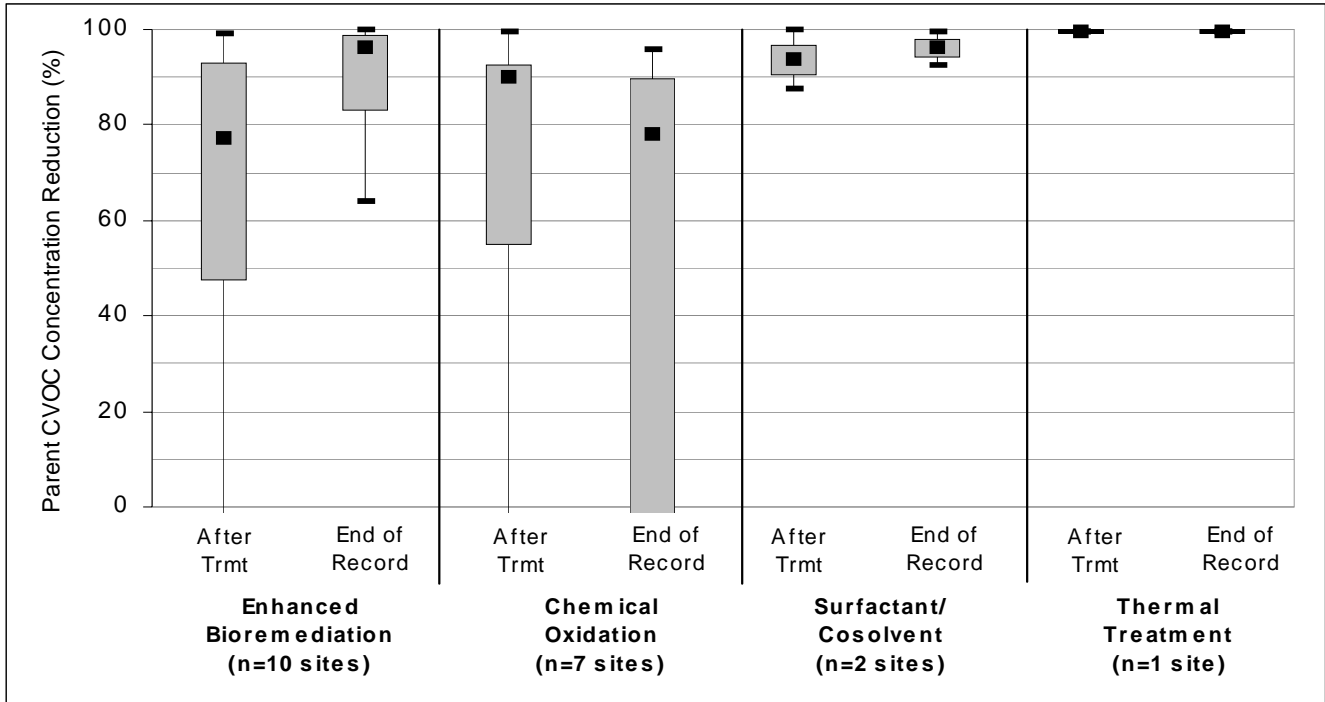
**FIGURE 1. Temporal Concentration Records for Wells at Source Depletion Sites.** Concentration is normalized by the initial measured concentration. Sampling time is normalized by the time of the initial source depletion treatment.



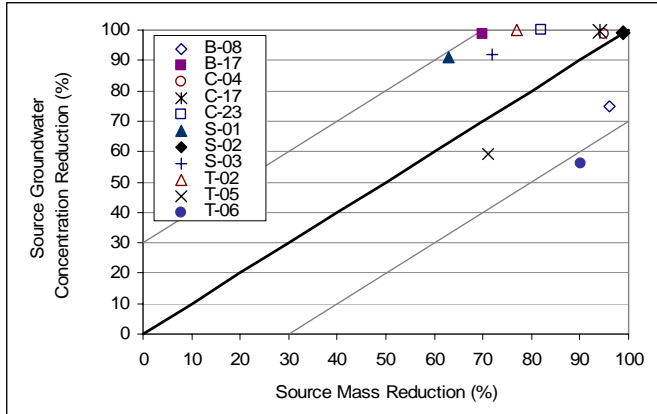
**FIGURE 2. Performance of Source Depletion Technologies: Reduction in Parent CVOC (a) and Total CVOC (b) Concentration within the Treatment Zone.** (a) Minimum reduction for chemical oxidation = -55% (value not shown). (b) Minimum reduction for enhanced bioremediation = -150% (value not shown). Only sites implementing enhanced bioremediation and chemical oxidation had sufficient data records to evaluate total CVOCs. Negative value indicates a concentration increase.



**FIGURE 3. Change in Post-Treatment Groundwater Concentrations. (a) Enhanced Bioremediation Sites (n=20 wells); (b) Chemical Oxidation Sites (n=16 wells); (c) Surfactant/Cosolvent Sites (n=6 wells); (d) Thermal Treatment Sites (n=1 well).**



**FIGURE 4. Rebound Assessment at Source Depletion Sites: Concentration Reduction from before Treatment to Immediately after Treatment and at End of Data Record.** Minimum reduction after treatment for enhanced bioremediation = -174%; minimum reduction after treatment for chemical oxidation = -9%; 25<sup>th</sup> percentile and minimum reduction at end of record for chemical oxidation = -45% and -216%, respectively (values not shown). Negative values indicate a concentration increase. See Figure 2 for box-and-whisker diagram legend.



**FIGURE 5. Calculated Source Zone Groundwater Concentration Reductions for Reported Source Zone Mass Reductions at 11 Source Depletion Sites.** Black line represents directly proportional relationship between source mass reduction and groundwater concentration reduction and the gray lines represent  $\pm 30\%$  of the directly proportional relationship. See Table 1 for site and technology descriptions of the eleven sites shown using the site numbers indicated in the legend.