

1           **ANALYSIS OF DNAPL SOURCE DEPLETION COSTS AT 36 FIELD SITES**

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6   **ABSTRACT**

7   A recent U.S. Environmental Protection Agency expert panel on dense non-aqueous  
8   phase liquid (DNAPL) remediation concluded that uncertainty in the costs and benefits of  
9   applying source depletion technologies (i.e., active remediation in source zones) is one  
10   key factor that discourages widespread use of these technologies at DNAPL sites  
11   (Kavanaugh et al., 2003). To reduce this uncertainty, a detailed evaluation of  
12   remediation costs for four active source depletion technologies was conducted. The  
13   source depletion technologies evaluated were enhanced bioremediation, chemical  
14   oxidation, surfactant/cosolvent flushing, and thermal treatments. An extensive review of  
15   peer-reviewed literature, conference proceedings, state and federal government agency  
16   reports, Internet databases, and technical surveys yielded cost and performance data at 36  
17   full-scale and pilot-scale source depletion sites. The data indicated that enhanced  
18   bioremediation has the lowest median cost per treatment volume of \$29/yd<sup>3</sup> (n=11),  
19   followed by thermal, chemical oxidation, and surfactant/cosolvent at \$88/yd<sup>3</sup> (n=13),  
20   \$125/yd<sup>3</sup> (n=6), and \$385/yd<sup>3</sup> (n=6), respectively. Only a slight correlation was observed  
21   between treatment size and total treatment cost; however, longer treatment durations  
22   correlated to lower treatment costs per volume. Treatment performance appeared to be  
23   independent of unit treatment costs. The resulting cost statistics and unit costs can be  
24   used to compare the cost of source depletion projects against the life-cycle cost of long-

1 term plume management techniques such as monitored natural attenuation or plume  
2 containment.

3

#### 4 **INTRODUCTION**

5 Dense non-aqueous phase liquid (DNAPL) sites pose a unique and difficult  
6 challenge to environmental professionals in the remediation of groundwater. Initially,  
7 sites with chlorinated solvent-contaminated groundwater were remediated using plume  
8 management techniques, with pump-and-treat systems being the most common selection.  
9 Most reports indicate that pump-and-treat systems have been ineffective at treating  
10 contaminated groundwater even after years of groundwater pumping (NRC, 1999,  
11 Pankow and Cherry, 1996). An increased understanding of the ineffectiveness of pump-  
12 and-treat systems came during the 1990s (USEPA, 1989). More comprehensive site  
13 characterization and evaluation led to an understanding that many of these sites contained  
14 DNAPL source mass, even in cases where DNAPL is not directly encountered (USEPA,  
15 1993). Capillary forces act to restrict the mobility of non-aqueous phase contaminants in  
16 the subsurface, meaning that advective flushing of an aqueous phase contaminant through  
17 a pump-and-treat strategy is limited by mass transfer. The presence of DNAPL, whether  
18 in the residual or pooled form, can provide a continuous and long-term source of  
19 contaminant for a groundwater plume with a life span of several decades to centuries,  
20 depending upon the type of contaminant (Lowe et al., 1999).

21 As the understanding of DNAPL sites increased, new technologies were  
22 developed and used to address the cleanup of DNAPL sites. Technologies such as air  
23 sparging, enhanced bioremediation, chemical oxidation, surfactant flushing, cosolvent

1 flushing, reactive barriers, and thermal treatments have been developed and tested in  
2 laboratory, pilot, and full-scale demonstrations (NRC, 1999). These technologies can  
3 reduce the remediation timeframes to achieve groundwater constituent assessment levels  
4 over pump-and-treat systems because they directly treat the DNAPL source material.  
5 Unfortunately, there is still a great deal of uncertainty in the costs and benefits of these  
6 technologies compared with non-active remediation approaches, and this uncertainty has  
7 discouraged their widespread use in the treatment of sites with a DNAPL source zone  
8 (Kavanaugh et al., 2003). To address this knowledge gap, a U.S. Environmental  
9 Protection Agency (EPA) expert panel on DNAPL remediation identified the need for a  
10 survey of DNAPL source depletion projects to provide actual information on costs and  
11 benefits (Kavanaugh et al., 2003).

12 This paper presents the findings from a project funded by the Strategic  
13 Environmental Research and Development Program (SERDP) to develop a source  
14 remediation cost and performance database for DNAPL source depletion remediation  
15 technologies. Four active remediation technologies were chosen for the cost and  
16 performance database: i) enhanced bioremediation, ii) chemical oxidation, iii)  
17 surfactant/cosolvent flushing, and iv) thermal treatment. Peer-reviewed literature, federal  
18 and state agency reports, internet websites, and a detailed survey were used to gather  
19 information on sites that used one of these four active remediation technologies to  
20 address DNAPL source zone contamination. Over 60 sites were evaluated for both cost  
21 and performance data, with 36 sites providing enough information on project costs. This  
22 paper provides a detailed summary of cost information.

23

1 **DATA COLLECTION METHODS**

2 Sites where either i) enhanced bioremediation, ii) chemical oxidation, iii)  
3 surfactant/cosolvent flushing, or iv) thermal treatment (includes steam, 3-phase, and 6-  
4 phase electrical resistance heating) was performed were located, reviewed, and evaluated  
5 using a collection of internet databases, state and federal agency reports, peer-reviewed  
6 literature, and a detailed survey sent to environmental professionals. Exhibit 1 provides a  
7 list of resources used.

8 Over 60 sites were reviewed. Collected performance data included concentration  
9 reduction and/or percent of DNAPL mass removed, size (volume and area treated), and  
10 cost data. The cost data incorporated whether actual project costs or estimated total costs  
11 were reported for full-scale implementation of a source depletion technology. A total of  
12 36 sites across the United States had sufficient performance, size, and cost data for the  
13 evaluation. The following is a breakdown of these 36 field sites based on the  
14 implemented source depletion technology: i) 11 enhanced bioremediation sites, ii) 13  
15 chemical oxidation sites, iii) 6 surfactant/cosolvent flushing sites, and iv) 6 thermal sites.  
16 Of the 36 field sites, 26 source depletion projects were classified as “full-scale”  
17 applications of the technology compared to 10 “pilot-scale” projects. Exhibits 2 and 3  
18 provide a summary of the sites and include treatment volume, total cost, and cost per  
19 volume in both cost per cubic yard and cost per acre.

20 **EVALUATION OF COST INFORMATION**

21 A breakdown of the total treatment cost versus the treatment volume for each of  
22 the remediation technologies is provided in Exhibit 4. For the four technologies, a linear  
23 regression was applied to each data set, and  $R^2$  values for the trend lines were used to

1 evaluate the best fit of the data. Thermal treatment demonstrated the strongest correlation  
2 ( $R^2 = 0.9684$ ) between increased total cost and increased treatment volume, followed by  
3 enhanced bioremediation ( $R^2 = 0.38$ ). Both chemical oxidation and surfactant/cosolvent  
4 technologies demonstrated lesser but similar correlations ( $R^2 = 0.1316$  and  $0.2401$ ,  
5 respectively). Exhibit 3 provides a summary of total project costs. For chemical  
6 oxidation and surfactant/cosolvent technologies, costs were generally between \$100,000  
7 and \$2.6 million. Enhanced bioremediation demonstrated the widest range of total costs  
8 (\$20,000 to \$35.4 million), followed by thermal technology total project costs (\$138,000  
9 to \$20.0 million).

10 Exhibit 5 provides a comparison of the minimum, median, maximum, 25<sup>th</sup>, and  
11 75<sup>th</sup> percentiles of the four active remediation technologies' cost per volume treated  
12 (\$/yd<sup>3</sup>). Enhanced bioremediation had the lowest median cost per cubic yard at \$29/yd<sup>3</sup>,  
13 while surfactant/cosolvent flushing had the highest median cost per cubic yard at  
14 \$385/yd<sup>3</sup>. Chemical oxidation and thermal technologies had median costs per volume of  
15 \$125/yd<sup>3</sup> and \$88/yd<sup>3</sup>, respectively. Further evaluation of the 25<sup>th</sup> to 75<sup>th</sup> percentiles  
16 shows that thermal treatment technologies exhibit the narrowest range in cost per volume,  
17 while surfactant/cosolvent sites exhibit the widest range.

18 Lower costs for enhanced bioremediation are probably related to the cheaper unit  
19 cost of enhanced bioremediation amendments (electron donor). Costs reported for  
20 molasses (~\$0.50/lb), are cheaper than surfactants (~\$1.30/lb) and chemical oxidants  
21 (potassium permanganate ~\$1.50 /lb to \$2.00/lb, USEPA, 1999, Ramsburg and Pennell,  
22 2001). However, some enhanced bioremediation treatment sites use slow release electron  
23 donors, which have a unit cost of \$5/lb to \$7/lb (AFCEE, 2004). The use of less substrate

1 (in pounds), direct push technologies for delivery, or larger well spacing are possible  
2 factors that result in lower costs for sites using slow release electron donors. In the case  
3 of both chemical oxidation and surfactant source depletion sites, often pore volumes (on  
4 the order of thousands to tens of thousands of gallons of amendment) are injected (Lowe  
5 et al., 1999).

## 6 **EVALUATION OF PERFORMANCE VERSUS COST**

7 Additional analysis of cost data compared the cost per volume and performance  
8 data. For the sites in Exhibit 2, the literature was reviewed to determine the percent  
9 reduction (or increase in the case of site C-01), using the pre-treatment and post-treatment  
10 concentrations (a more detailed performance database and analysis is provided in  
11 McGuire et al., submitted October 2004). Several sites reported concentration data for  
12 more than one well, so a median percent reduction was used when more than one well  
13 was used to determine percent reduction. Two sites did not report concentration data;  
14 however, both sites, S-05 and S-06 on Exhibit 2, did report estimated cost information  
15 and were used in the evaluation of cost in the above section.

16 Cost and performance were compared to determine if sites that had a higher cost  
17 per volume, also had a higher percent reduction in source zone concentration. This is  
18 essentially asking the question that if more money is spent per volume treated, is better  
19 performance achieved? Exhibit 6 demonstrates the percent reduction of the remediation  
20 technologies versus the cost per volume for each site, with a total of 34 sites represented  
21 in the four graphs. The data from Exhibit 6 illustrate that the technology performance  
22 appears to be independent of the cost spent per volume. In particular, there were 14 sites  
23 that demonstrated performance of 99 percent or greater percent concentration reduction,

1 and the median cost per volume of those sites was \$146/yd<sup>3</sup>. In comparison, there were 7  
2 sites that demonstrated performance of 70 percent or less percent concentration reduction,  
3 and the median cost per volume of those sites was \$116/yd<sup>3</sup>. The minimum cost of sites  
4 demonstrating 99 percent or greater percent concentration reduction was site B-02 at  
5 \$2/yd<sup>3</sup>, while the maximum cost was site S-04 at \$1563/yd<sup>3</sup>. The minimum cost of sites  
6 demonstrating 70 percent or less percent concentration reduction was site B-04 at  
7 \$20/yd<sup>3</sup>, and the maximum cost was for site C-01 at \$194/yd<sup>3</sup>. Site C-01 also exhibited  
8 the poorest performance demonstrating an *increase* of 26.6% in constituent concentration  
9 with a cost of \$194/yd<sup>3</sup>. Site S-01 had the highest cost per volume at \$5,500/yd<sup>3</sup> and  
10 demonstrated a 91.2 percent reduction in constituent concentration. Conversely, site B-  
11 02 had the lowest cost per volume at \$2/yd<sup>3</sup> and demonstrated a 99.6 percent reduction in  
12 constituent concentration.

13 Site treatment costs per volume are correlated more to the volume treated (i.e.,  
14 economies of scale effect) than performance. Performance differences are more than  
15 likely due to heterogeneities in the lithology and conditions of individual sites, thus costs  
16 for implementing these technologies can vary significantly from site to site (Lowe et al.,  
17 1999).

## 18 **EVALUATION OF TREATMENT DURATION AND COST**

19 In addition to performance data, treatment duration was evaluated to determine if  
20 a correlation between longer treatment timeframes and increased cost per volume for  
21 source depletion technologies existed. A total of 32 sites had treatment duration data  
22 available, and the median value for the 32 sites was 210 days. Treatment duration versus  
23 treatment cost per volume data is provided in Exhibit 7. From Exhibit 7, there is a slight

1 correlation ( $R^2 = 0.2528$ ) between cost per volume and treatment duration. The site with  
2 the longest treatment duration (over 2,100 days), site B-02, also had the lowest cost per  
3 volume treated ( $\$2/\text{yd}^3$ ). Six sites had treatment durations of less than one week, and  
4 these sites exhibited a range of treatment costs per volume between  $\$20/\text{yd}^3$  and  
5  $\$5,500/\text{yd}^3$ , with a median of  $\$135/\text{yd}^3$ . There were 12 sites with treatment durations of  
6 greater than one year, and these sites exhibited a range of treatment costs per volume  
7 between  $\$2/\text{yd}^3$  and  $\$518/\text{yd}^3$ , with a median cost per volume of  $\$54/\text{yd}^3$ .

8        Finally, several sites have reported information comparing the cost of pump-and-  
9 treat technologies versus active remediation technologies. In particular, the Visalia,  
10 California thermal treatment site (site T-03) reported that using a pump-and-treat system  
11 to remediate a wood-treatment site source zone would cost approximately  $\$110/\text{yd}^3$   
12 compared to  $\$60/\text{yd}^3$  using thermal treatment (USDOE, 2000). However, the report also  
13 stated that pump-and-treat would have a cheaper life cycle cost for sites with treatment  
14 volumes greater than 0.5-1.0 million cubic yards. The Visalia pump-and-treat system is  
15 based on the system operating for a period of 30 years, and a net-present value  
16 calculation with a 3.8% discount rate. A pilot-scale treatment test using surfactant  
17 technology was performed at the Bachman Road site in Oscoda, Michigan (site S-04),  
18 and the site reported that full-scale implementation of surfactant treatment would cost  
19 between  $\$382,000$  and  $\$443,000$  as compared to using pump-and-treat, which would cost  
20  $\$1.2$  million (Ramsburg and Pennell, 2001). Note that both of the cost estimates for the  
21 Visalia and Bachman Road sites did not include any costs for management of the plume  
22 after source depletion, even though target concentration levels were not achieved at either  
23 site. Based on cost data from this project, median source depletion technology costs vary

1 between \$29/yd<sup>3</sup> and \$385/yd<sup>3</sup>, which compares favorably with the reported costs of  
2 pump-and-treat of \$78/yd<sup>3</sup> to \$200/yd<sup>3</sup> (Lowe et al., 1999).

### 3 **CONCLUSIONS**

4 Remediation costs from 36 sites where one of four active source depletion  
5 technologies had been applied were compiled. An analysis of these data showed:

- 6 • A slight correlation exists between increased total treatment cost and increased  
7 treatment volume.
- 8 • Enhanced bioremediation had the lowest median treatment cost per volume at  
9 \$29/yd<sup>3</sup>.
- 10 • Surfactant/cosolvent treatment had the highest median treatment cost per volume  
11 at \$385/yd<sup>3</sup>.
- 12 • Lower unit cost for enhanced bioremediation sites may be related to cheaper cost  
13 of amendments and smaller volumes of amendments applied to treatment of site.
- 14 • Technology performance is independent of cost spent per volume.
- 15 • There is a slight correlation between shorter treatment durations versus increased  
16 cost per volume.
- 17 • Several sites have reported cheaper cost per volume and/or total treatment costs  
18 using active remediation technologies versus pump-and-treat systems.

19 Data from this cost evaluation will be available as part of a web-based Decision Support  
20 System (available from [www.gsi-net.com](http://www.gsi-net.com) in late 2005), which will allow users to select  
21 certain site criteria and view site performance and cost data based on selected site criteria.  
22 Site managers can use the unit cost data to develop planning level cost estimates for  
23 different source depletion technologies. In addition, the statistical distributions of

1 remediation costs presented in the database can also used in cost studies that rely on  
2 Monte Carlo simulations or other statistical tools.

### 3 **ACKNOWLEDGEMENTS**

4           The Strategic Environmental Research and Development Program provided  
5 funding for this project. The authors would like to thank all organizations and  
6 individuals that responded to the technical survey developed as part of this project.

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<b>Peer-Reviewed Literature</b>	<i>Environmental Science and Technology</i>
	<i>Groundwater</i>
	<i>Groundwater Monitoring and Remediation</i>
	<i>Journal of Contaminant Hydrology</i>
	<i>Surfactants and Cosolvents for NAPL Remediation: A Technology Practices Manual</i>
	Battelle Conference Proceedings
<b>Agencies</b>	Federal Remediation Technologies Roundtable
	Florida Department of Environmental Protection
	Interagency DNAPL Consortium
	Interstate Technology and Regulatory Council
	Lawrence Livermore National Laboratory
	Texas Commission on Environmental Quality
United States Environmental Protection Agency	
United States Department of Defense	
<b>Survey/Websites</b>	SERDP survey
	CLU-IN website, <a href="http://www.clu-in.org">www.clu-in.org</a>

**Exhibit 1. Summary of Resources Used During Remediation Technology Research.**  
SERDP = Strategic Environmental Research and Development Program

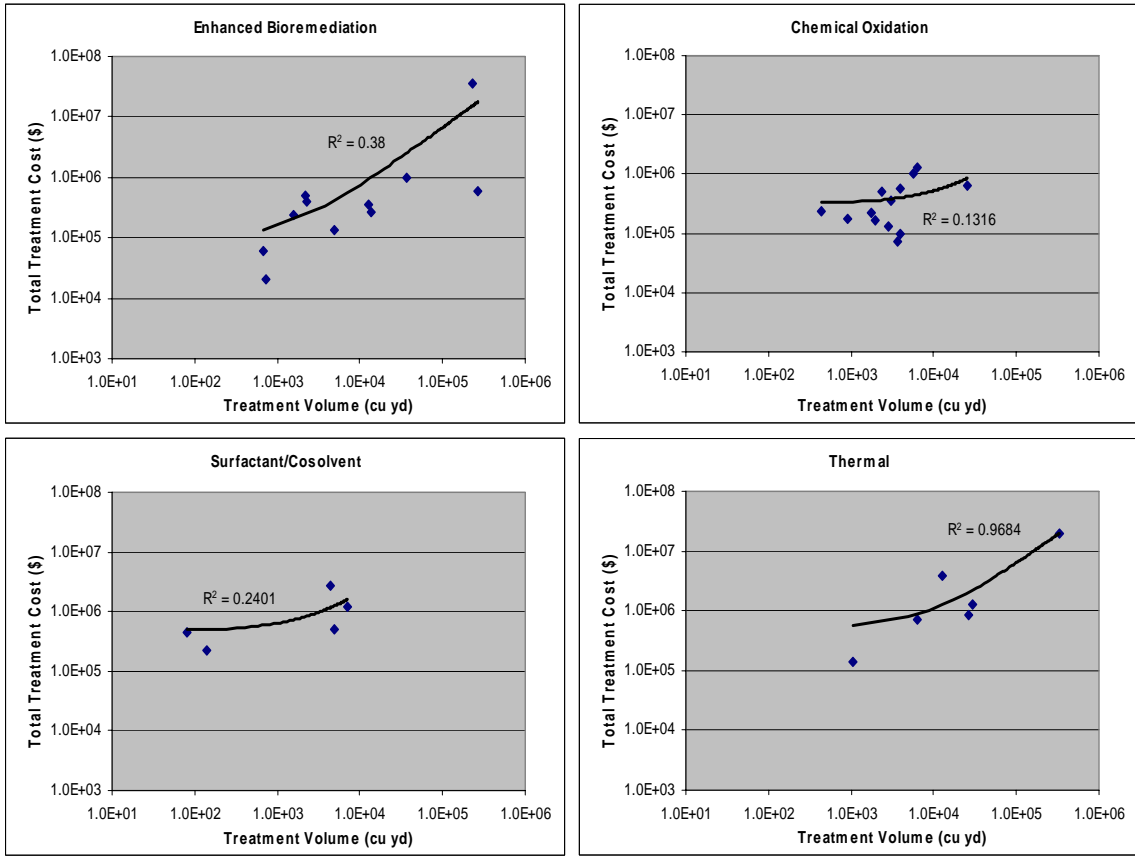
Site No.	Site Name	Site Location	Scale	Treatment Size (yd <sup>3</sup> )	Total Cost (\$)	Cost per Volume (\$/yd <sup>3</sup> )
<b><i>Enhanced Bioremediation Sites</i></b>						
B-01	Industrial Facility	Florida	Full	1,556	235,000	151
B-02	Industrial Facility	New Hampshire	Full	266,667	600,000	2
B-03	Dry Cleaning Facility	Jacksonville, FL	Full	12,643	354,000	28
B-04	Dry Cleaning Facility	Orlando, FL	Full	13,519	265,000	20
B-05	Industrial Facility	Concord, NH	Pilot	667	60,000	90
B-06	Industrial Facility	Tennessee	Full	2,222	500,000	225
B-07	Industrial Facility	San Jose, CA	Full	4,823	137,900	29
B-08	Duluth International Airport	Duluth, MN	Pilot	740	20,000	27
B-09	Test Area North	Idaho Falls, ID	Pilot	233,000	35,410,000	152
B-10	Pinellas STAR Center	Largo, FL	Pilot	2,250	400,000	178
B-11	Former Manufacturing Facility	Houston, TX	Full	36,700	1,000,000	27
<b><i>Chemical Oxidation Sites</i></b>						
C-01	Industrial Facility	Pensacola, FL	Full	917	178,338	194
C-02	Dry Cleaning Facility	Jacksonville, FL	Full	3,060	355,000	116
C-03	Dry Cleaning Facility	Florida	Full	1,947	167,415	86
C-04	Dry Cleaning Facility	Jacksonville, FL	Pilot	444	230,000	518
C-05	Dry Cleaning Facility	Dallas, TX	Full	3,600	73,000	20
C-06	Dry Cleaning Facility	Houston, TX	Full	25,555	642,400	25
C-07	Dry Cleaning Facility	Houston, TX	Full	2,844	134,700	47
C-08	Westinghouse Savannah River	Aiken, SC	Full	2,370	511,000	216
C-09	Ideal Cleaners	Hutchinson, KS	Pilot	4,000	95,000	24
C-10	Kings Bay Naval Base	Camden Co., GA	Full	1,778	223,000	125
C-11	Portsmouth Gas Diffusion Plant	Piketon, OH	Full	4,000	562,000	141
C-12	Kansas City Plant	Kansas City, MO	Full	5,600	1,000,000	179
C-13	Launch Complex 34	Cape Canaveral, FL	Pilot	6,250	1,270,000	203
<b><i>Surfactant/Cosolvent Sites</i></b>						
S-01	Dry Cleaning Facility	Jacksonville, FL	Pilot	80	440,000	5500
S-02	Hill Air Force Base	Hill AFB, UT	Full	7,034	1,200,000	171
S-03	Camp Lejeune Site 88	Jacksonville, NC	Pilot	4,444	2,662,000	599
S-04	Bachman Road Site	Oscoda, MI	Pilot	142	222,000	1563
S-05	Union Pacific Site <sup>1</sup>	Laramie, WY	Pilot	5,000	500,000	100
S-06	Alameda NAS	Alameda, CA	Pilot	NA	NA	66
<b><i>Thermal Sites</i></b>						
T-01	Industrial Facility	Illinois	Full	26,667	853,344	32
T-02	Industrial Facility	Florida	Full	12,963	3,883,000	300
T-03	Visalia	Visalia, CA	Full	332,222	20,000,000	60
T-04	Manufacturing Plant	NA	Full	1,040	138,000	133
T-05	Cape Canaveral	Cape Canaveral, FL	Full	6,250	726,000	116
T-06	Area M DOE Site	Savannah River, GA	Pilot	29,088	1,277,300	44

**Exhibit 2. Summary of Remediation Technology Sites.** NA = Data not available;

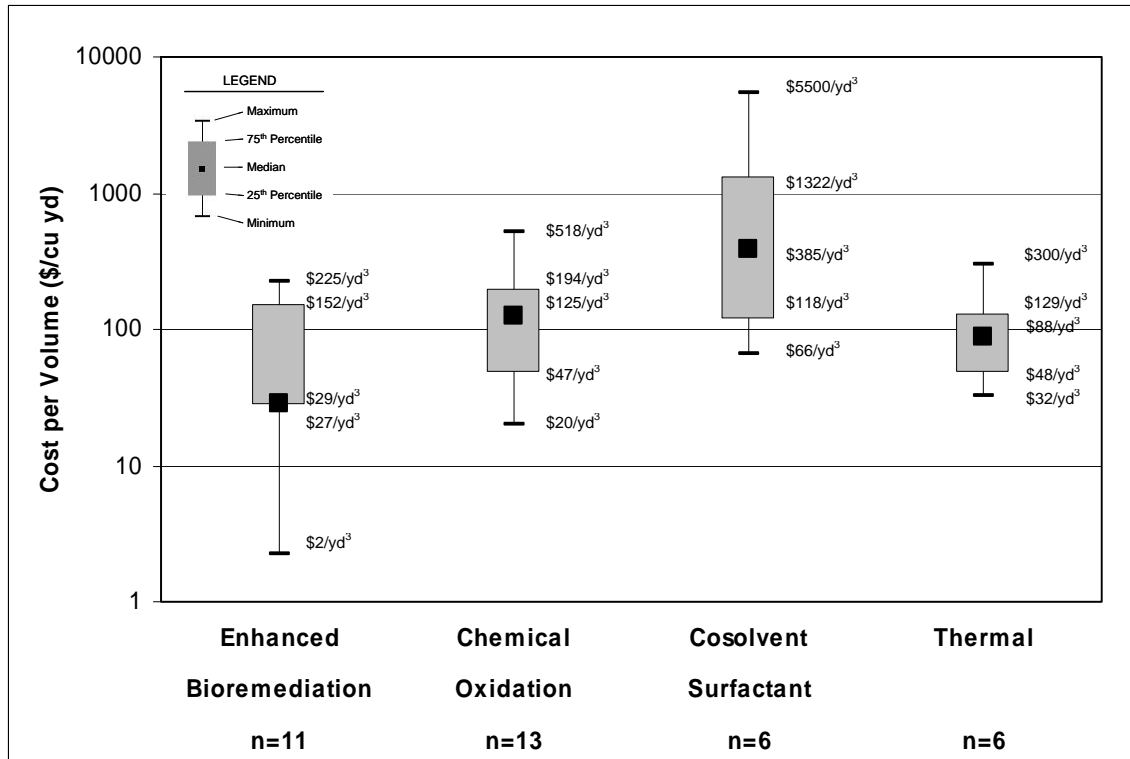
<sup>1</sup> = Total project cost and volume reported as an estimate in site literature.

<b>Technology</b>	<b>Total Project Costs</b>		
	<b>Minimum</b>	<b>Median</b>	<b>Maximum</b>
Enhanced Bioremediation	\$20,000	\$354,000	\$35,410,000
Chemical Oxidation	\$73,000	\$230,000	\$1,270,000
Surfactant/Cosolvent	\$222,000	\$500,000	\$2,662,000
Thermal	\$138,000	\$1,065,322	\$20,000,000
<b>Total</b>	<b>\$20,000</b>	<b>\$440,000</b>	<b>\$35,410,000</b>

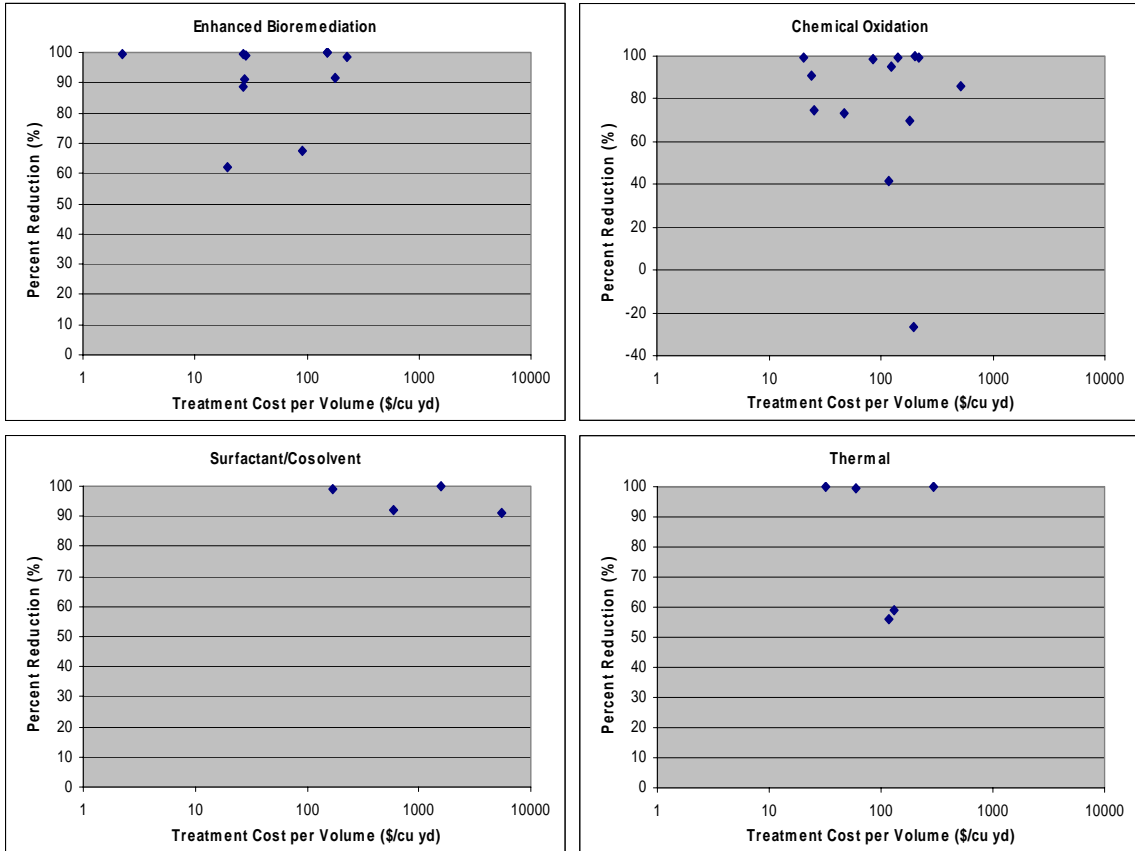
**Exhibit 3. Summary of Total Project Costs for Enhanced Bioremediation, Chemical Oxidation, Surfactant/Cosolvent, and Thermal Technologies.** Note that site S-06 did not report total project costs and is not included in this summary.



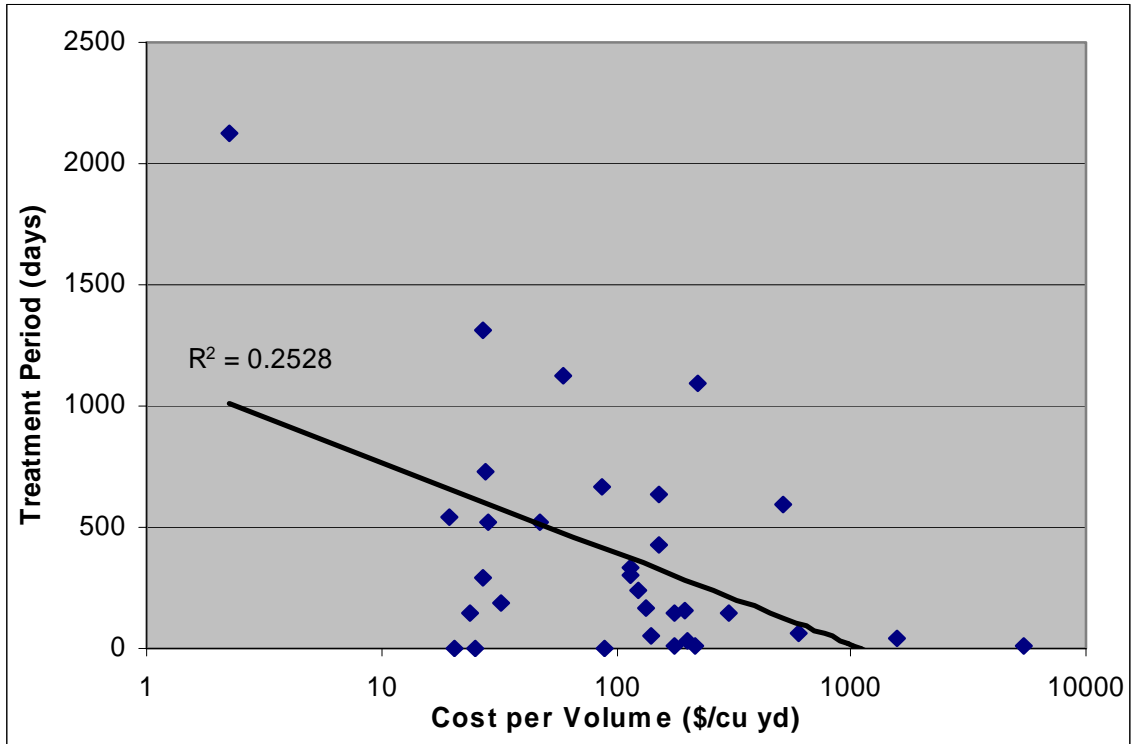
**Exhibit 4. Total Treatment Cost for Enhanced Bioremediation, Chemical Oxidation, Surfactant/Cosolvent, and Thermal Technologies versus Treatment Volume.**



**Exhibit 5. Whisker Plots of Minimum, Median, Maximum, 25<sup>th</sup>, and 75<sup>th</sup> Percentiles of Cost per Volume Data.** n = number of sites with reported data



**Exhibit 6. Performance as Percent Concentration Reduction versus Treatment Cost per Volume for the Four Remediation Technologies.** Note that performance data was not reported for sites S-05 and S-06 on Exhibit 2.



**Exhibit 7. Treatment Duration versus Treatment Cost per Volume.** Note that treatment duration was not reported for sites S-02, S-05, S-06, and T-06 on Exhibit 2.

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**Charles J. Newell,**<sup>1</sup> Ph.D., is a Vice President of Groundwater Services, Inc. He has co-authored three EPA publications, five environmental decision support software systems, numerous technical articles, and two books: *Natural Attenuation of Fuels and Chlorinated Solvents* and *Ground Water Contamination: Transport and Remediation*. His professional expertise includes site characterization, groundwater modeling, non-aqueous phase liquids, risk assessment, natural attenuation, bioremediation, non-point source studies, software development, and long-term monitoring projects.

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