Analysis of DNAPL Source-Depletion Costs at 36 Field Sites

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A recent U.S. Environmental Protection Agency (US EPA) expert panel on dense nonaqueous phase liquid (DNAPL) remediation concluded that uncertainty in the costs and benefit of applying source-depletion technologies (i.e., active remediation in source zones) is one key factor that discourages widespread use of these technologies at DNAPL sites (Kavanaugh et al., 2003). To reduce this uncertainty, a detailed evaluation of remediation costs for four active source-depletion technologies was conducted. The source-depletion technologies evaluated were enhanced bioremediation, chemical oxidation, surfactant/cosolvent flushing, and thermal treatments. An extensive review of peer-reviewed literature, conference proceedings, state and federal government agency reports, Internet databases, and technical surveys yielded cost and performance data at 36 full-scale and pilot-scale source-depletion sites. The data indicated that enhanced bioremediation has the lowest median cost per treatment volume of \$29/yd^3 (n = 11), followed by thermal, chemical oxidation, and surfactant/cosolvent at \$88/yd^3 (n = 13), \$125/yd^3 (n = 6), and \$385/yd^3 (n = 6), respectively. Only a slight correlation was observed between treatment size and total treatment cost; however, longer treatment durations correlated to lower treatment costs per volume. Treatment performance appeared to be independent of unit treatment costs. The resulting cost statistics and unit costs can be used to compare the cost of source-depletion projects against the life-cycle cost of long-term plume management techniques such as monitored natural attenuation or plume containment. © 2005 Wiley Periodicals, Inc.

INTRODUCTION

Dense nonaqueous phase liquid (DNAPL) sites pose a unique and difficult challenge to environmental professionals in the remediation of groundwater. Initially, sites with chlorinated solvent-contaminated groundwater were remediated using plume management techniques, with pump-and-treat systems being the most common selection. Most reports indicate that pump-and-treat systems have been ineffective at treating contaminated groundwater even after years of groundwater pumping (National Research Council [NRC], 1999; Pankow & Cherry, 1996). An increased understanding of the ineffectiveness of pump-and-treat systems came during the 1990s (US EPA, 1989). More comprehensive site characterization and evaluation led to an understanding that many of these sites contained DNAPL source mass, even in cases where DNAPL is not directly encountered (US EPA, 1993). Capillary forces act to restrict the mobility of nonaqueous phase contaminants in the subsurface, meaning that mass transfer limits advective flushing of an aqueous phase contaminant through a pump-and-treat strategy. The presence of DNAPL, whether in the residual or pooled form, can provide a continuous and long-

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term source of contaminant for a groundwater plume with a life span of several decades to centuries, depending upon the type of contaminant (Lowe et al., 1999).

As the understanding of DNAPL sites increased, new technologies were developed and used to address the cleanup of DNAPL sites. Technologies such as air sparging, enhanced bioremediation, chemical oxidation, surfactant flushing, cosolvent flushing, reactive barriers, and thermal treatments have been developed and tested in laboratory, pilot, and full-scale demonstrations (NRC, 1999). These technologies can reduce the remediation time frames to achieve groundwater constituent assessment levels over pump-and-treat systems because they directly treat the DNAPL source material. Unfortunately, there is still a great deal of uncertainty in the costs and benefits of these technologies compared with nonactive remediation approaches, and this uncertainty has discouraged their widespread use in the treatment of sites with a DNAPL source zone (Kavanaugh et al., 2003). To address this knowledge gap, a U.S. Environmental Protection Agency (US EPA) expert panel on DNAPL remediation identified the need for a survey of DNAPL source-depletion projects to provide actual information on costs and benefits (Kavanaugh et al., 2003).

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This article presents the findings from a project funded by the Strategic Environmental Research and Development Program (SERDP) to develop a source remediation cost and performance database for DNAPL source-depletion remediation technologies. Four active remediation technologies were chosen for the cost and performance database: (1) enhanced bioremediation, (2) chemical oxidation, (3) surfactant/cosolvent flushing, and (4) thermal treatment. Peer-reviewed literature, federal and state agency reports, Internet Web sites, and a detailed survey were used to gather information on sites that used one of these four active remediation technologies to address DNAPL source zone contamination. Over 60 sites were evaluated for both cost and performance data, with 36 sites providing enough information on project costs. This article provides a detailed summary of cost information.

DATA COLLECTION METHODS

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

Over 60 sites were reviewed. Collected performance data included concentration reduction and/or percentage of DNAPL mass removed, size (volume and area treated), and cost data. The cost data incorporated whether actual project costs or estimated total costs were reported for full-scale implementation of a source-depletion technology. A total of 36 sites across the United States had sufficient performance, size, and cost data for the evaluation. The following is a breakdown of these 36 field sites based on the implemented source-depletion technology: (1) 11 enhanced bioremediation sites, (2) 13 chemical oxidation sites, (3) six surfactant/cosolvent flushing sites, and (4) six thermal sites. Of the 36 field sites, 26 source-depletion projects were classified as "full-scale" applications of the technology compared to 10 "pilot-scale" projects. Exhibits 2 and 3 provide a summary of the sites and include treatment volume, total cost, and cost per volume in both cost per cubic yard and cost per acre.

Peer-Reviewed Literature	*Environmental Science and Technology* *Groundwater* *Groundwater Monitoring and Remediation* *Journal of Contaminant Hydrology* *Surfactants and Cosolvents for NAPL Remediation: A Technology Practices Manual* **Battelle Conference Proceedings**
Agencies	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
Survey/Web sites	SERDP survey CLU-IN Web site, www.clu-in.org

Note: SERDP = Strategic Environmental Research and Development Program.

Exhibit 1. Summary of resources used during remediation technology research

EVALUATION OF COST INFORMATION

A breakdown of the total treatment cost versus the treatment volume for each of the remediation technologies is provided in Exhibit 4. For the four technologies, a linear regression was applied to each data set, and R^2 values for the trend lines were used to evaluate the best fit of the data. Thermal treatment demonstrated the strongest correlation ($R^2 = 0.9684$) between increased total cost and increased treatment volume, followed by enhanced bioremediation ($R^2 = 0.38$). Both chemical oxidation and surfactant/cosolvent technologies demonstrated lesser but similar correlations ($R^2 = 0.1316$ and 0.2401, respectively). Exhibit 3 provides a summary of total project costs. For chemical oxidation and surfactant/cosolvent technologies, costs were generally between \$100,000 and \$2.6 million. Enhanced bioremediation demonstrated the widest range of total costs (\$20,000 to \$35.4 million), followed by thermal technology total project costs (\$138,000 to \$20.0 million).

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

Lower costs for enhanced bioremediation are probably related to the cheaper unit cost of enhanced bioremediation amendments (electron donor). Costs reported for molasses

Site No.	Site Name	Site Location	Scale	Treatment Size (yd³)	Total Cost ($)	Cost per Volume ($/yd³)
Enhanced Bioremediation Sites						
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
Chemical Oxidation Sites						
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
Surfactant/Cosolvent Sites						
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[1]	Laramie, WY	Pilot	5,000	500,000	100
S-06	Alameda NAS	Alameda, CA	Pilot	NA	NA	66
Thermal Sites						
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

Note: NA = Data not available.

[1] Total project cost and volume reported as an estimate in site literature.

Exhibit 2. Summary of remediation technology sites

Technology	Total Project Costs		
	Minimum	**Median**	**Maximum**
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
Total	**$20,000**	**$440,000**	**$35,410,000**

Note: Site S-06 did not report total project costs and is not included in this summary.

Exhibit 3. Summary of total project costs for enhanced bioremediation, chemical oxidation, surfactant/cosolvent, and thermal technologies

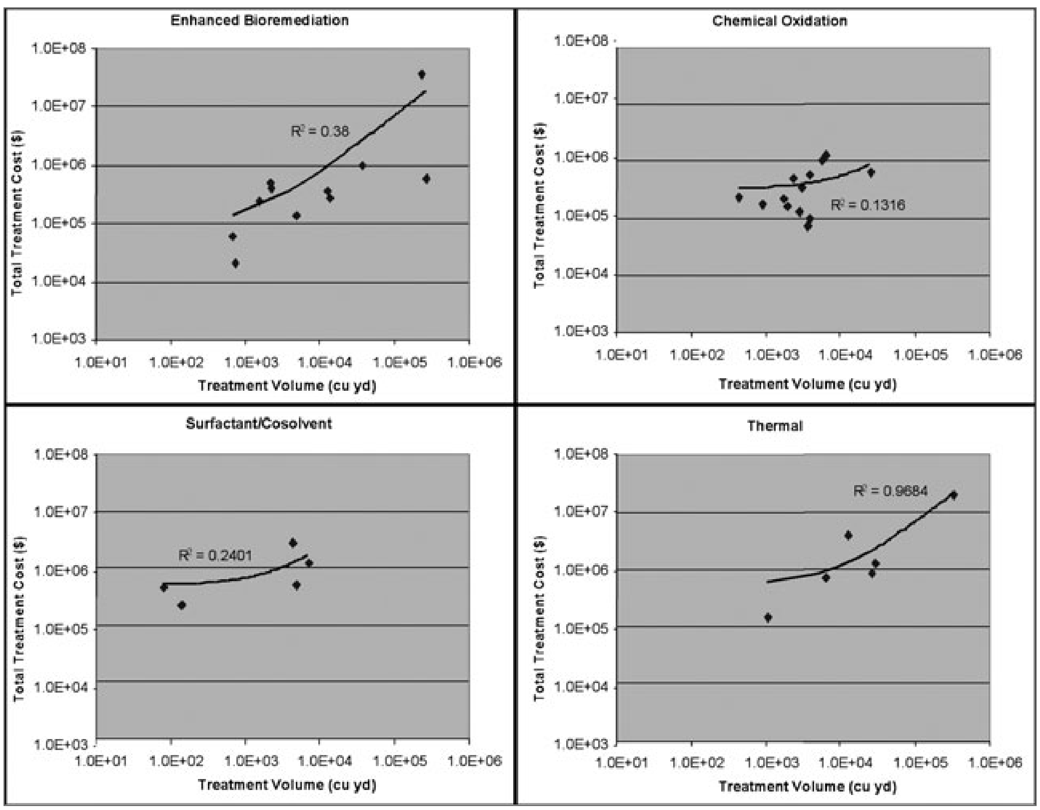
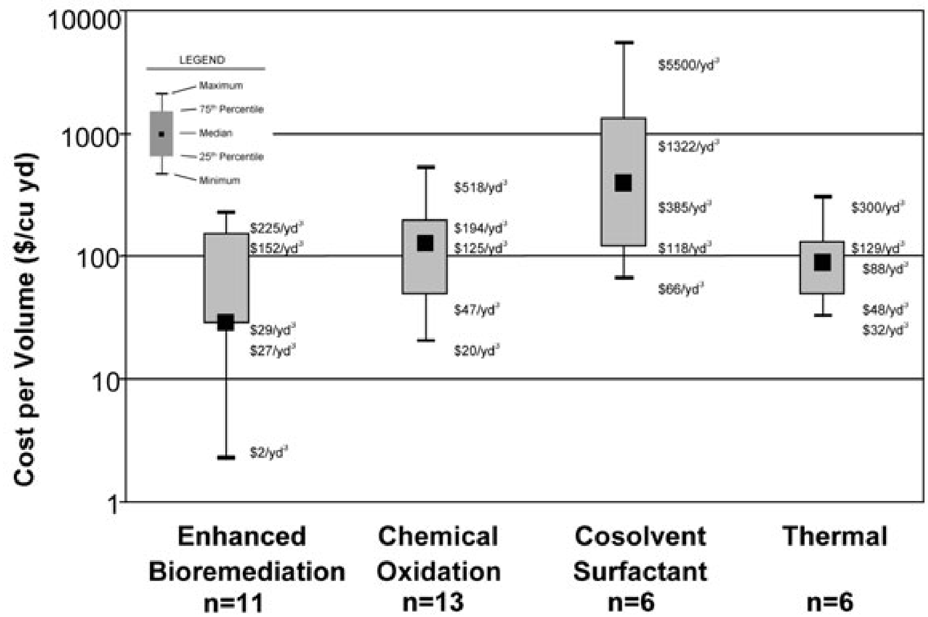


Exhibit 4. Total treatment cost for enhanced bioremediation, chemical oxidation, surfactant/cosolvent, and thermal technologies versus treatment volume

(~$0.50/lb), are cheaper than surfactants (~$1.30/lb) and chemical oxidants (potassium permanganate ~$1.50 /lb to $2.00/lb; Ramsburg & Pennell, 2001; US EPA, 1999). However, some enhanced bioremediation treatment sites use slow-release electron donors, which have a unit cost of $5/lb to $7/lb (Air Force Center for Environmental Excellence [AFCEE], 2004). The use of less substrate (in pounds), direct-push technologies for delivery, or larger well spacing are possible factors that result in lower costs for sites using slow-release electron donors. In the case of both chemical oxidation and surfactant source-



n = number of sites with reported data.

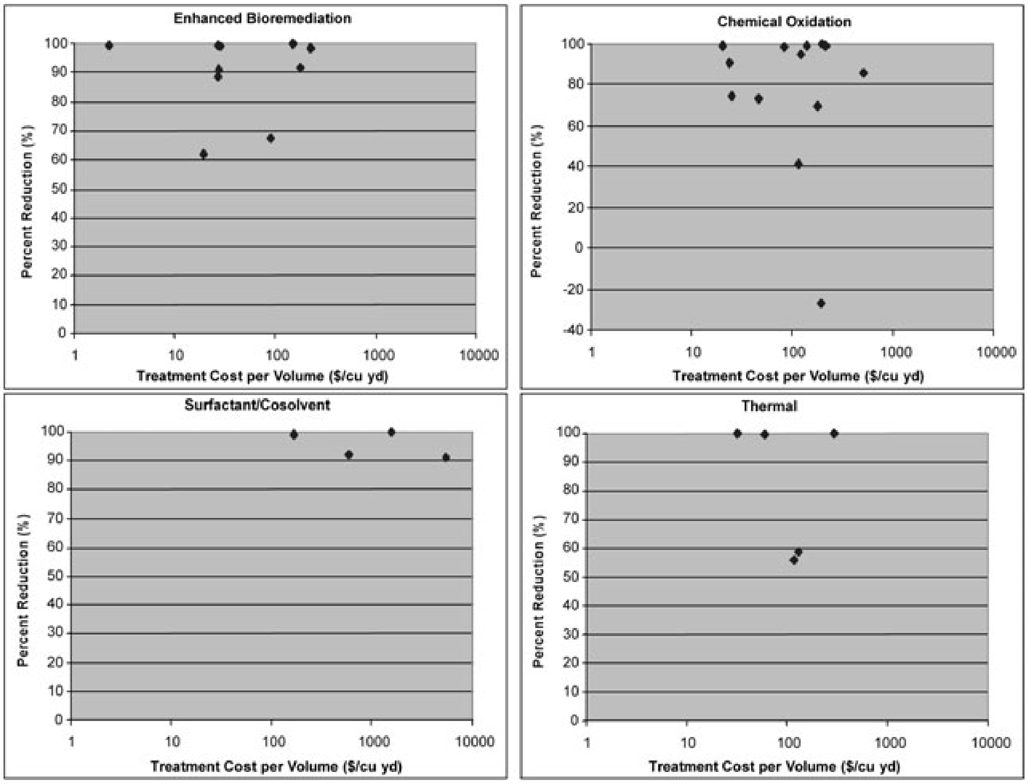
Exhibit 5. Whisker plots of minimum, median, maximum, 25th, and 75th percentiles of cost per volume data

depletion sites, often pore volumes (on the order of thousands to tens of thousands of gallons of amendment) are injected (Lowe et al., 1999).

EVALUATION OF PERFORMANCE VERSUS COST

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

Cost and performance were compared to determine if sites that had a higher cost per volume also had a higher percent reduction in source zone concentration. This is essentially asking the question that if more money is spent per volume treated, is better performance achieved? Exhibit 6 demonstrates the percent reduction of the remediation technologies versus the cost per volume for each site, with a total of 34 sites represented in the four graphs. The data from Exhibit 6 illustrate that the technology performance appears to be independent of the cost spent per volume. In particular, there were 14 sites that demonstrated performance of 99 percent or greater concentration reduction, and the median cost per volume of those sites was $\$146/yd^3$. In comparison, there were seven sites that demonstrated performance of 70 percent or less concentration re-



Note: Performance data was not reported for sites S-05 and S-06 in Exhibit 2.

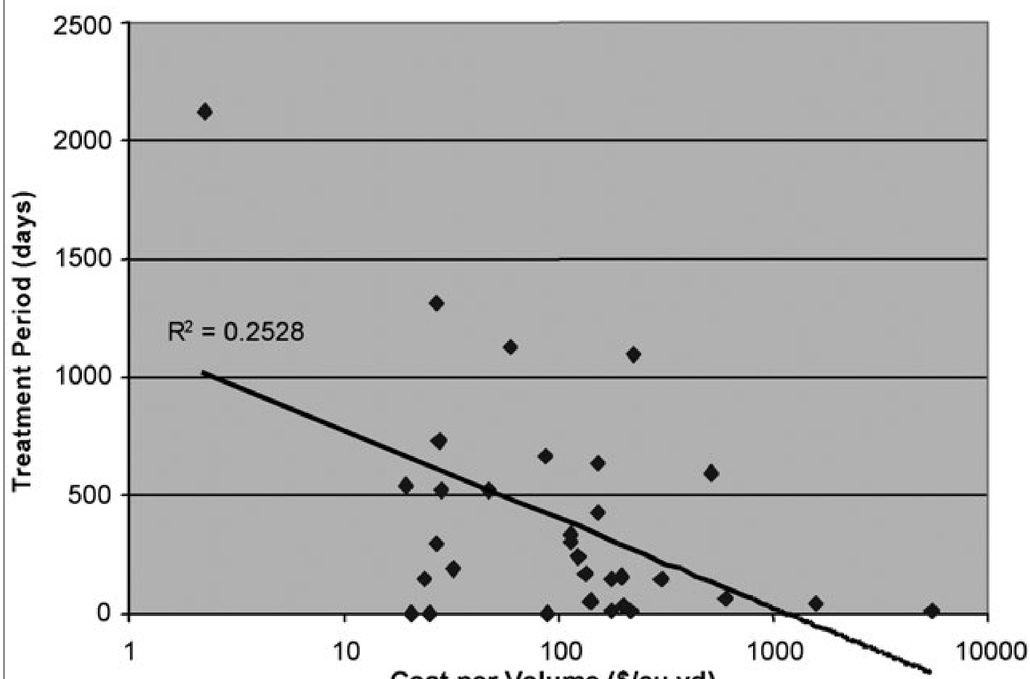
Exhibit 6. Performance as percent concentration reduction versus treatment cost per volume for the four remediation technologies

duction, and the median cost per volume of those sites was $116/yd^3. The minimum cost of sites demonstrating 99 percent or greater concentration reduction was site B-02 at $2/yd^3, while the maximum cost was site S-04 at $1,563/yd^3. The minimum cost of sites demonstrating 70 percent or less percent concentration reduction was site B-04 at $20/yd^3, and the maximum cost was for site C-01 at $194/yd^3. Site C-01 also exhibited the poorest performance demonstrating an *increase* of 26.6 percent in constituent concentration with a cost of $194/yd3. Site S-01 had the highest cost per volume at $5,500/yd^3 and demonstrated a 91.2 percent reduction in constituent concentration. Conversely, site B-02 had the lowest cost per volume at $2/yd^3 and demonstrated a 99.6 percent reduction in constituent concentration.

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

EVALUATION OF TREATMENT DURATION AND COST

In addition to performance data, treatment duration was evaluated to determine if a correlation between longer treatment time frames and increased cost per volume for



Note: Treatment duration was not reported for sites S-02, S-05, S-06, and T-06 in Exhibit 2.

Exhibit 7. Treatment duration versus treatment cost per volume

source-depletion technologies existed. A total of 32 sites had treatment duration data available, and the median value for the 32 sites was 210 days. Treatment duration versus treatment cost per volume data is provided in Exhibit 7. From Exhibit 7, there is a slight correlation ($R^2 = 0.2528$) between cost per volume and treatment duration. The site with the longest treatment duration (over 2,100 days), site B-02, also had the lowest cost per volume treated ($2/yd^3). Six sites had treatment durations of less than one week, and these sites exhibited a range of treatment costs per volume between $20/yd^3 and $5,500/yd^3, with a median of $135/yd^3. There were 12 sites with treatment durations of greater than one year, and these sites exhibited a range of treatment costs per volume between $2/yd^3 and $518/yd^3, with a median cost per volume of $54/yd^3.

Finally, several sites have reported information comparing the cost of pump-and-treat technologies versus active remediation technologies. In particular, the Visalia, California, thermal treatment site (site T-03) reported that using a pump-and-treat system to remediate a wood-treatment site source zone would cost approximately $110/yd^3 compared to $60/yd^3 using thermal treatment (US DOE, 2000). However, the report also stated that pump-and-treat would have a cheaper life-cycle cost for sites with treatment volumes greater than 0.5–1.0 million cubic yards. The Visalia pump-and-treat system is based on the system operating for a period of 30 years and a net-present value calculation with a 3.8 percent discount rate. A pilot-scale treatment test using surfactant technology was performed at the Bachman Road site in Oscoda, Michigan (site S-04), and the site reported that full-scale implementation of surfactant treatment would cost between $382,000 and $443,000 as compared to using pump-and-treat, which would cost $1.2 million (Ramsburg & Pennell, 2001). Note that both of the cost estimates for the Visalia and Bachman Road sites did not include any costs for management of the plume after source depletion, even though target concentration levels were not achieved at either site. Based on cost data from this project, median source-depletion technology costs vary between $29/yd^3 and $385/yd^3, which compares favorably with the reported costs of pump-and-treat of $78/yd^3 to $200/yd^3 (Lowe et al., 1999).

CONCLUSIONS

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

- A slight correlation exists between increased total treatment cost and increased treatment volume.
- Enhanced bioremediation had the lowest median treatment cost per volume at $29/yd^3.
- Surfactant/cosolvent treatment had the highest median treatment cost per volume at $385/yd^3.
- Lower unit cost for enhanced bioremediation sites may be related to cheaper cost of amendments and smaller volumes of amendments applied to treatment of the sites.
- Technology performance is independent of cost spent per volume.
- There is a slight correlation between shorter treatment durations versus increased cost per volume.
- Several sites have reported cheaper cost per volume and/or total treatment costs using active remediation technologies versus pump-and-treat systems.

Data from this cost evaluation will be available as part of a Web-based Decision Support System (available from www.gsi-net.com in late 2005), which will allow users to select certain site criteria and view site performance and cost data based on selected site criteria. Site managers can use the unit cost data to develop planning-level cost estimates for different source-depletion technologies. In addition, the statistical distributions of remediation costs presented in the database can also be used in cost studies that rely on Monte Carlo simulations or other statistical tools.

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