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Cost Analyses for Selected Groundwater Cleanup Projects:
Pump and Treat Systems and Permeable Reactive Barriers

SUMMARY

Groundwater contamination is present at many Superfund and RCRA corrective action sites. Groundwater cleanup technologies, such as pump-and-treat (P&T) systems and permeable reactive barriers (PRBs), are being used at a number of those sites. Information about the costs of groundwater cleanup technologies and factors that affect those costs may be valuable to site managers, technology developers and users, and others involved in groundwater remediation efforts to identify and evaluate those technologies for new and ongoing projects. This report presents the results of an analysis, performed by the U.S. Environmental Protection Agency (EPA), of costs for groundwater cleanup incurred at 48 sites (the 32 P&T sites and 16 PRB sites listed in Exhibit 1). The report is based on data in case studies prepared by EPA and other members of the Federal Remediation Technologies Roundtable (FRTR) and by the Remediation Technologies Development Forum (RTDF), and supplements EPA's analysis of 28 groundwater remediation projects (*Groundwater Cleanup: Overview of Operating Experience at 28 Sites, September 1999, EPA 542-R-99-006*).

The analysis of the 48 sites found that there is a significant amount of variability in the costs of groundwater cleanups and that many of the factors that affect costs are site-specific. However, the following overall conclusions can be drawn:

- The types of contaminant groups in the groundwater affect the capital costs of a P&T system. In general, capital costs and annual operating costs were lower for sites at which chlorinated solvents are present, alone or with other volatile organic compounds (VOCs), than for sites at which other combinations of contaminants (such as VOCs with metals) are present. For sites at which complex combinations are present, it generally was necessary to use more complex aboveground treatment systems.
- The types of above-ground treatment affect the annual operating costs of a P&T system. For P&T sites at which chlorinated solvents are present, alone or with other VOCs, and at which air stripping or granular activated carbon (GAC) treatment only are used, annual operating costs were lower than for sites at which the same contaminants are present but a wider variety of treatment technologies are used. The additional treatment technologies sometimes require additional labor and use of both chemicals and energy.
- For the sites in this analysis, the capital costs for PRBs generally were lower than those for P&T systems. Decisions about whether a PRB or P&T system would be less expensive for a given site generally are based on total life-cycle costs for each type of system (including total capital and operating costs); such site-specific factors as hydrogeology, contaminant type, extent of contamination, and remedial goals often are considered in making such decisions. In addition, PRBs may not be technically feasible at all sites.

The FRTR includes senior executives of eight agencies that have an interest in exchanging information about remediation technologies. Primary members include the U.S. Departments of Defense, Energy, and the Interior, and EPA. Other participants include the Nuclear Regulatory Commission, the National Aeronautics and Space Administration, the Tennessee Valley Authority, and the U.S. Coast Guard. Information about the Roundtable is available through the FRTR's web site at <*www.frtr.gov*>. Information about the P&T sites was obtained from FRTR case studies.

The RTDF includes members representing industry, government, and academia who have an interest in identifying steps government and industry can take together to develop and improve the environmental technologies needed to address their mutual cleanup problems in the safest, most cost-effective manner possible. Information about the RTDF is available through the RTDF's web site at <*www.rtdf.org*>. Information about PRB sites was obtained primarily from an RTDF report; limited information was obtained from FRTR and other sources.

- Economies of scale were observed when the P&T system treats relatively large volumes of groundwater. For systems treating more than 20 million gallons of groundwater per year, capital and annual operating costs per volume of groundwater treated per year appear to be lower than those costs for systems treating less than 20 million gallons per year.

CRITERIA FOR SELECTING SITES FOR ANALYSIS

Exhibit 2 provides a description of P&T and PRB technologies. In selecting sites for this analysis, the available FRTR and RTDF case studies were screened using the following criteria:

- The P&T or PRB system was operated on a full-scale basis (rather than as a pilot-scale or field demonstration).
- For P&T sites, information was available about the capital cost, the annual average operating cost, and the amount of groundwater treated per year of system operation; for PRB sites, information was available about the capital cost.
- For P&T sites, aquifer cleanup goals (not containment-only goals) had been established.

For the analysis, 48 sites were identified (32 P&T sites and 16 PRB sites, including one site at which a PRB replaced a P&T system), as shown in Exhibit 1.

EXHIBIT 1. ALPHABETICAL LIST OF SELECTED SITES

Site Name	
P&T Sites (32)	
Amoco Petroleum Pipeline, Michigan	Mystery Bridge at Highway 20 Superfund Site, DOW/DSI,
Baird and McGuire Superfund Site, Massachusetts	Odessa Chromium I Superfund Site, OU 2, Texas
Bofors Nobel Superfund Site, OU 1, Michigan	Odessa Chromium IIS Superfund Site, OU 2, Texas
City Industries Superfund Site, Florida	Old Mill Superfund Site, Ohio
Des Moines TCE Superfund Site, OU 1, Iowa	SCRDI Dixiana Superfund Site, South Carolina
Former Firestone Facility Superfund Site, California	Site A (confidential Superfund site), New York
Former Intersil, Inc. Site, California*	Sol Lynn/Industrial Transformers Superfund Site, Texas
French Limited Superfund Site, Texas	Solid State Circuits Superfund Site, Missouri
Gold Coast Superfund Site, Florida	Solvent Recovery Services of New England, Inc. Superfund Site,
JMT Facility RCRA Site (formerly Black & Decker), New York	Sylvester/Gilson Road Superfund Site, New Hampshire
Keefe Environmental Services Superfund Site, New Hampshire	Twin Cities Army Ammunition Plant Superfund Site (TCAAP),
King of Prussia Technical Corporation Superfund Site, New	United Chrome Superfund Site, Oregon
LaSalle Electrical Superfund Site, Illinois	U.S. Aviex Superfund Site, Michigan
Libby Groundwater Superfund Site, Montana	U.S. Department of Energy (DOE) Kansas City Plant, Missouri
McClellan Air Force Base Superfund Site, OU B/C California	U.S. DOE, Savannah River site, A/M Area, South Carolina
Mid-South Wood Products Superfund Site, Arkansas	Western Processing Superfund Site, Washington
PRB Sites (16)	
Aircraft Maintenance Facility, Oregon	Industrial Site, Northern Ireland
Caldwell Trucking, New Jersey	Industrial Site, South Carolina
Federal Highway Administration Facility, Colorado	Kansas City Plant, Missouri
Former Drycleaning Site, Germany	Lowry Air Force Base, Colorado
Former Intersil, Inc. Site, California*	Marzone Inc./Chevron Chemical Company, Georgia
Former Manufacturing Site, New Jersey	Nickel Rim Mine Site, Ontario, Canada
Industrial Site, Kansas	U.S. Coast Guard Support Center, North Carolina
Industrial Site, New York	Y-12 Site, Oak Ridge National Laboratory, Tennessee

*Both a PRB and a P&T system were operated at the former Intersil site.

EXHIBIT 2. SELECT GROUNDWATER TREATMENT TECHNOLOGIES

Pump and Treat (P&T)

P&T involves extracting contaminated groundwater through recovery wells or trenches and treating the groundwater by *ex situ* (aboveground) processes, such as air stripping, carbon adsorption, biological reactors, or chemical precipitation. Variables in the design of a typical P&T system include:

- The number and pumping rate of groundwater extraction points (determined by such factors as the extent of contamination and the productivity of the contaminated aquifer)
- The *ex situ* treatment processes employed (determined by such factors as system throughput and the contaminants that require remediation)
- The discharge location for the effluent from the treatment plant (determined by such factors as location of the site and regulatory requirements)

Additional information about the fundamentals of P&T technology can be found in *Design Guidelines for Conventional Pump-and-Treat Systems*.

Permeable Reactive Barriers (PRBs)

A PRB is an *in situ* (below-ground) treatment zone of reactive material that degrades or immobilizes contaminants as groundwater flows through it. PRBs are installed as permanent, semi-permanent, or replaceable units across the flow path of a contaminated plume. Natural gradients transport contaminants through strategically placed media. The media degrade, sorb, precipitate, or otherwise remove groundwater contaminants. The choice of the reactive media for a PRB is based on the specific organic or inorganic contaminant to be remediated. Most PRBs installed to date use zero-valent iron (Fe^o) as the reactive medium for converting contaminants to nontoxic or immobile species. Other applications under development use limestone, organic carbon, or bone char phosphate. The hydrogeologic setting at the site also is crucial; PRBs are best applied to shallow, unconfined aquifer systems in unconsolidated deposits, as long as the reactive material is more conductive than the aquifer.

Most PRBs are installed in one of two basic configurations: funnel-and-gate or continuous trench, although other techniques such as hydrofracturing also are used. The funnel-and-gate system employs impermeable walls to direct the contaminated plume through a gate, or treatment zone, that contains the reactive media. In a continuous trench configuration, a trench is installed across the entire path of the plume and is filled with reactive media. Most PRBs installed to date have had depths of 50 feet (ft) or less. PRBs having depths of 30 ft or less can be installed with a continuous trencher, while those installed at depths between 30 and 70 ft require a more innovative installation method, such as biopolymers. Installation of PRBs at depths greater than 70 ft is more challenging.

IMPORTANT DATA CONSIDERATIONS

Several important considerations related to the data and results presented in this report are listed below:

- The sites selected are not a statistically representative sample of groundwater remediation projects; rather, they present a range of the types of systems that are used to clean up groundwater at Superfund and RCRA corrective action sites.
- Cost data were provided by EPA remedial project managers (RPMs), site owners, or vendors; include both actual and estimated costs of groundwater cleanup; and were not verified independently by EPA.
- Groundwater cleanup has been completed at only two of the 32 P&T sites and is ongoing at the other P&T sites. For the 30 P&T sites where remediation is ongoing, the costs presented in this report do not necessarily represent the total cost of cleaning up groundwater at the site.
- Because groundwater cleanup is ongoing at most of the sites and the total time necessary to complete cleanup is not known, this report presents the average annual operating costs rather than the total operating costs incurred during site remediation. Likewise, no net present value (NPV) was calculated for the remedial costs because additional costs will be incurred at sites at which remediation is ongoing, and the length of time each system will operate in the future is not known. Rather, costs are presented as unit costs (cost per year or cost per 1,000 gallons). The unit costs are described in more detail later in this report.
- The costs for PRB and P&T systems presented in this report may include costs for source control remedies (such as slurry walls) employed at the sites, when the source control was an integrated part of the groundwater cleanup. Exhibits 10 and 11 present the components included in the costs for each of the sites included in this analysis.

METHODOLOGY FOR EVALUATING THE COSTS OF P&T AND PRB TECHNOLOGIES

Total capital and total annual operating costs were provided in the individual case studies by EPA RPMs, site owners, and vendors. For this analysis, the following methodology was used to calculate unit costs and adjusted costs for the 48 sites.

Unit Costs

There are several ways in which unit costs can be calculated for groundwater remediation systems. The following three types of unit costs were used in this analysis:

- ***Average operating cost per year of operation:*** This value was calculated by dividing the total operating cost to date by the number of years represented by that cost. Several factors affect the average operating cost per year, including throughput of the system, the treatment processes required to treat the extracted groundwater, and the operating efficiency of the system. Because a breakdown of annual operating costs by year was not available for most of the sites, the change in operating costs over the life of a site's remediation system could not be evaluated.

- ***Capital cost per 1,000 gallons of groundwater treated per year:*** This value represents the relative costs of installing remedial systems of various capacities, and is influenced by such factors as:

  - the complexity of the aquifer (which affect the size and complexity of the system needed to extract the contaminated groundwater)

  - the types of contaminants targeted for treatment at the site (which affect the components of the treatment plant needed to remove the contaminants)

  - the water and air discharge limits for the particular site (which affect the treatment plant components needed)

  - restoration goals (which affect the time frame for cleanup)

- ***Average annual operating cost per 1,000 gallons of groundwater treated per year:*** This value represents the relative costs of operating systems of various capacities and complexities. Similar to the capital cost per 1,000 gallons of groundwater treated per year, this unit cost is highly dependent on such site-specific factors as the complexity of the aquifer, the types of contaminants targeted for treatment, the water and air discharge limits, and the restoration goals.

Adjusted Costs

Remediation costs for the selected sites were adjusted for the location of the site (location adjustment) and for the years in which costs were incurred (inflation adjustment). Those adjustments are described below and in Appendix A to this report. Appendix A presents the equations used to adjust the total capital and total annual operating costs; gives equations used to calculate the average annual operating costs; and shows example calculations for one of the sites.

- ***Location adjustment:*** Costs were adjusted for location by multiplying the costs provided for each site by an Area Cost Factor (ACF) Index published by the U.S. Army Corps of Engineers in PAX Newsletter No. 3.2.1, dated March 31, 1999 and available at <*http://www.hq.usace.army.mil/cemp/e/es/pax/paxtoc.htm*>.

- ***Inflation adjustment:*** The inflation factor used for this analysis was based on the Construction Cost Index published by Engineering News Record. The most current year that had an annual average inflation adjustment factor available at the time of preparing this report was for 1999. Costs were adjusted to year 1999 dollars by multiplying the costs provided for each site by an inflation adjustment factor for the year in which the costs were incurred. For capital cost time adjustment, the inflation adjustment factor for the actual year that the costs were incurred was used. For annual operating cost time adjustment, the inflation adjustment factor for the median year of all years over which the costs were incurred was used. The Construction Cost Index is available at *http://www.enr.com/cost/costcci.asp*.

RESULTS AND CONCLUSIONS

This analysis considered six main factors that affect the cost of P&T and PRB technology applications (discussed in reference 1): (1) characteristics or properties of contaminants present, (2) system design and operation, (3) source control, (4) hydrogeologic setting, (5) extent of contamination, and (6) remedial goals. The analysis found that the costs varied significantly between sites and that many of the factors that affect costs are site-specific. In addition, the amount of information available about each of the factors varied by site. For the analysis, general conclusions were identified about the effect of a factor when information related to that factor was available for five or more sites.

Exhibits 3 through 9 present the results of the cost analysis for the 48 sites, with detailed data for each site summarized in Exhibits 10 and 11 for P&T and PRB sites, respectively. Exhibit 3 provides an overall summary of the remedial cost and unit cost data for the 48 sites included in the analysis, while Exhibits 4 through 9 present 25th percentile, 50th percentile (median), 75th percentile, and average costs, based on the types of contaminants present, the technologies used, and the volume of groundwater treated each year. General conclusions about the effect of contaminant property factors and system design and operation factors are presented below.

EXHIBIT 3. SUMMARY OF REMEDIAL COST AND UNIT COST DATA FOR 48 SITES

Cost Category	P&T Sites (32 Sites)				PRB Sites (16 Sites)			
	25th Percent.	Median	75th Percent.	Average	25th Percent.	Median	75th Percent.	Average
Years of system operation (with data available)	4	5	8	6	NC	NC	NC	NC
Average volume of groundwater treated per year (1,000 gallons per year)	7,000	30,000	100,000	120,000	NC	NC	NC	NC
Total capital cost ($)[1]	1,700,000	2,000,000	5,900,000	4,900,000	440,000	680,000	1,000,000	730,000
Average operating cost per year ($ per year)[1]	180,000	260,000	730,000	770,000	NC[2]	NC[2]	NC[2]	NC[2]
Capital cost per volume of groundwater treated per year ($/1,000 gallons per year)[1]	23	78	350	280	NC	NC	NC	NC
Average annual operating cost per volume of groundwater treated per year ($/1,000 gallons per year)[1]	5	16	41	32	NC	NC	NC	NC

Source: FRTR and RTDF; refer to Exhibit 1 for a list of sites.

1 All reported costs were adjusted for site locations and years in which costs were incurred, as described in the text.

2 Two of the case studies at PRB sites (Intersil and USCG) included annual operating costs for the PRB systems. Those costs are presented in Exhibit 11.

NC = Not calculated; insufficient data available.

Contaminant property factors:

Contaminant properties affect the cost of groundwater remediation systems. These properties define (1) the relative ease with which contaminants can be removed from the extracted groundwater (by *ex situ* treatment technologies), (2) the steps that are required to treat the groundwater, and (3) the complexity of the mixture of contaminants. Sites analyzed on the basis of contaminant property factors included sites contaminated with chlorinated solvents, alone or with other VOCs, and sites at which other combinations of contaminants were present. On the basis of site-specific data, the following conclusions can be made about contaminant property factors:

- The type of contaminant groups in the groundwater affects both the capital and the annual operating cost of a P&T system, as shown in Exhibit 4. For sites with chlorinated solvents alone or with other VOCs (such as ethers or ketones), capital costs were lower than those for sites with other combinations of contaminants (such as chlorinated solvents, BTEX, metals, PCBs, or PAHs). The median capital cost for P&T systems removing chlorinated solvents, alone or with other VOCs, is $1,900,000, as compared with a median capital cost of $7,400,000 for P&T systems removing other combinations of contaminants. The type of contaminant groups in the groundwater has similar effects on the annual operating cost of a P&T system. Sites at which chlorinated solvents, alone or with other VOCs, were present had lower annual operating costs than sites at which other combinations of contaminants were present. The median annual operating cost for P&T systems removing chlorinated solvents alone, or with other VOCs, is $12 per 1,000 gallons treated, as compared with a median annual operating cost of $39 per 1,000 gallons treated for P&T systems removing other combinations of contaminants.

EXHIBIT 4. COST COMPARISON OF P&T SYSTEMS THAT TREAT VARIOUS CONTAMINANT GROUPS

Contaminant Group	Cost Range			Average Cost	Number of Sites
	25th Percentile	Median	75th Percentile		
Total Capital Cost[2]					
Chlorinated solvents, alone or with other VOCs	$1,200,000	$1,900,000	$4,400,000	$3,600,000	18
Other combinations of contaminants (solvents, BTEX, metals, PCBs or PAHs)[1]	$4,300,000	$7,400,000	$15,000,000	$8,900,000	9
Average Annual Operating Cost per 1,000 Gallons Treated[2,3]					
Chlorinated solvents, alone or with other VOCs	$3	$12	$40	$26	18
Other combinations of contaminants (solvents, BTEX, metals, PCBs or PAHs)[1]	$10	$39	$61	$53	9

1 The costs of P&T systems that treat only metals or only BTEX are not included in this exhibit because data were available for only three such systems. General conclusions were developed about the effect of a factor when information about that factor was available for five or more sites.

2 All reported costs were adjusted for site locations and years in which costs were incurred, as described in the text.

3 The average volume of groundwater treated per year for the 18 sites at which chlorinated solvents, alone or with other VOCs, were present and the nine sites at which a combination of contaminants were present are 160,000,000 and 65,000,000 gallons, respectively.

- The type of above-ground treatment affects the annual operating cost of a P&T system. For sites contaminated with chlorinated solvents, alone or with other VOCs, Exhibit 5 compares the annual operating costs of treatment systems using air stripping or GAC only with annual operating costs of treatment systems using a wider variety of treatment technologies. For P&T sites for which remedial cleanup goals had been established for chlorinated solvents, alone or with other VOCs, and using air stripping or GAC treatment only, annual operating costs were lower than those for sites for which remedial cleanup goals had been established for the same contaminants but at which other combinations of treatment technologies, such as biological treatment or filtration, were used. The median average annual operating cost for P&T systems removing chlorinated solvents with air stripping or GAC only is $3 per 1,000 gallons treated. The median average annual operating cost for P&T systems removing the same contaminants with other combinations of treatment technologies is $40 per 1,000 gallons treated. At sites for which remedial cleanup goals had been established for chlorinated solvents, alone or with other VOCs, treatment technologies besides air stripping or GAC may be necessary because other substances present in the groundwater may inhibit the effectiveness of the air stripping or GAC units. For example, at Sol Lynn, the initial treatment system included an air stripper and GAC unit only. However, an iron filter was added to the treatment train to minimize fouling of the packing of the air stripper. Such additional treatment technologies may require additional labor and use of chemicals or electricity.

EXHIBIT 5. ANNUAL OPERATING COST COMPARISON OF VARIOUS P&T TECHNOLOGIES AT SITES CONTAMINATED WITH CHLORINATED SOLVENTS, ALONE OR WITH OTHER VOCs

Treatment Technology	Average Annual Operating Cost per 1,000 Gallons Treated[1,2]			Number of Sites
	25th Percentile ($)	Median ($)	75th Percentile ($)	
AS and/or GAC treatment only	2	3	12	11
Other combination of treatment technologies (see Exhibit 10)	28	40	41	7
All sites with chlorinated solvents, alone or with other VOCs	3	12	40	18

[1] All reported costs were adjusted for site locations and years when costs were incurred, as described in the text.
[2] The average volume of groundwater treated per year for the 11 sites at which air stripping (AS) or granular activated carbon (GAC) was used, the 7 sites at which other combinations of treatment technologies were used, and the 18 sites at which chlorinated solvents alone or with other VOCs, were present are 260,000,000; 19,000,000; and 160,000,000 gallons, respectively.

System design and operation factors:

The cost of a groundwater remediation system is affected by a number of factors including the type of treatment technologies used to remediate the site, the adequacy of a system design to remediate the site, system downtime, system optimization efforts, the amount and type of monitoring performed, and the use of multiple primary treatment technologies (for example, P&T and an *in situ* technology). On the basis of site-specific data, the following conclusions can be made about system design and operation factors:

- For the sites included in the analysis, the total capital costs for PRBs generally were lower than those for P&T systems. As demonstrated in Exhibit 6, the 75th percentile of total capital costs for the 16 PRB projects ($1,000,000) was less than the 25th percentile of total capital costs for the 32 P&T projects ($1,700,000). The data included in the analysis show that the total capital cost of a very large PRB may approach the total capital cost of a small P&T system. In addition, the median total capital cost for the 32 P&T projects is $2,000,000; the median total capital cost for the 16 PRB projects is $680,000. Decisions about whether a PRB or P&T system would be less expensive for a given site generally are based on total life-cycle costs for each type of system; such site-specific factors as hydrogeology, contaminant type, extent of contamination, and remedial goals should be considered in making those decisions. Further, PRBs may not be feasible at every site; therefore, a comparison of P&T and PRB systems may not be appropriate for a given site.

EXHIBIT 6. CAPITAL COST COMPARISON OF P&T AND PRB SYSTEMS

Technology	Capital Cost Range[1]			Average Capital Cost[1] ($)	Number of Sites
	25th Percentile ($)	Median ($)	75th Percentile ($)		
P&T	1,700,000	2,000,000	5,900,000	4,900,000	32
PRBs	440,000	680,000	1,000,000	730,000	16

[1] All reported costs were adjusted for site locations and years when costs were incurred, as described in the text

- Two of the case studies at PRB sites included annual operating costs for the PRB systems. The adjusted annual operating costs for the PRBs at those sites are $75,000 at the U.S. Coast Guard site and $120,000 at the Intersil site. The annual operating costs included in the analysis are those for relatively new PRB systems, and operating costs included monitoring costs only; maintenance was not required during the period of operation for which data were available. As a PRB system ages, maintenance of the system may be required, including replacement of the exhausted reactive medium and other repairs of the PRB system. Decisions about whether a PRB or a P&T system would be less expensive would include an analysis of total life-cycle costs for each type of system. Again, such site-specific factors as hydrogeology, contaminant type, extent of contamination, and remedial goals should be considered in making those decisions.

- Economies of scale were observed when relatively large volumes of groundwater were treated annually by a P&T system. For sites at which more than 20 million gallons of groundwater per year are treated, the capital and annual operating costs per volume of groundwater treated per year appear to be lower than at sites where 20 million gallons or less are treated per year. As Exhibit 7 shows, the median capital costs per volume of groundwater treated per year for P&T sites at which 20 million gallons or less are treated per year and for those at which more than 20 million gallons are treated per year are $440 per 1,000 gallons per year and $24 per 1,000 gallons per year, respectively. The data show a similar trend in annual operating costs per volume of groundwater treated per year. The median average annual operating costs per volume of groundwater treated per year for P&T sites at which 20 million gallons or less are treated per year and for those at which more than 20 million gallons are treated per year are $42 per 1,000 gallons per year and $5 per 1,000 gallons per year, respectively.

  Exhibits 8 and 9 show the distribution of the unit capital costs and the average annual operating costs for the P&T sites included in the analysis, respectively, as a function of volume of groundwater treated per year. For sites at which more than 20 million gallons per year are treated, operating and capital costs are lower than costs for sites at which 20 million gallons or less per year are treated. Unit costs vary more for sites at which 20 million gallons or less per year are treated than for sites at which 20 million or more gallons per year are treated. Because of the variability in the costs, these data are not intended for use in making estimates of costs for other sites.

EXHIBIT 7. COMPARISON OF UNIT TREATMENT COST FOR P&T SITES WITH VOLUME TREATED PER YEAR

Size of Treatment System Size (1,000 gallons/year)	Cost Range			Average Cost	Number of Sites
	25th Percentile	Median	75th Percentile		
Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 gallons/year)[1]					
≤ 20,000	$200	$440	$730	$580	14
> 20,000	$14	$24	$62	$49	18
Average Annual Operating Cost Per Volume of Groundwater Treated Per Year ($/1,000 gallons)[1,2]					
≤ 20,000	$33	$42	$64	$62	14
> 20,000	$3	$5	$7	$10	18

1 All reported costs were adjusted for site locations and years when costs were incurred, as described in the text.
2 The average volume of groundwater treated per year for the 14 sites treating 20 million gallons or less of groundwater annually and the 18 sites treating more than 20 million gallons of groundwater annually are 7,800,000 and 200,000,000 gallons, respectively.

Other Factors - Source control, hydrogeology, extent of contamination, and remedial goals also can have a significant effect on remediation costs; however, insufficient data were available to develop quantitative conclusions about the effects of those factors on the costs for the sites included in the analysis.[1] Several site-specific examples are presented below to demonstrate how each of those factors increase or decrease costs for a particular site. The examples listed below compare remediation costs for P&T sites at which the groundwater is contaminated with chlorinated solvents, alone or with other VOCs. The examples also are presented in Exhibits 10 and 11, which include costs and information about the factors that affect the costs for all 48 sites included in the analysis.

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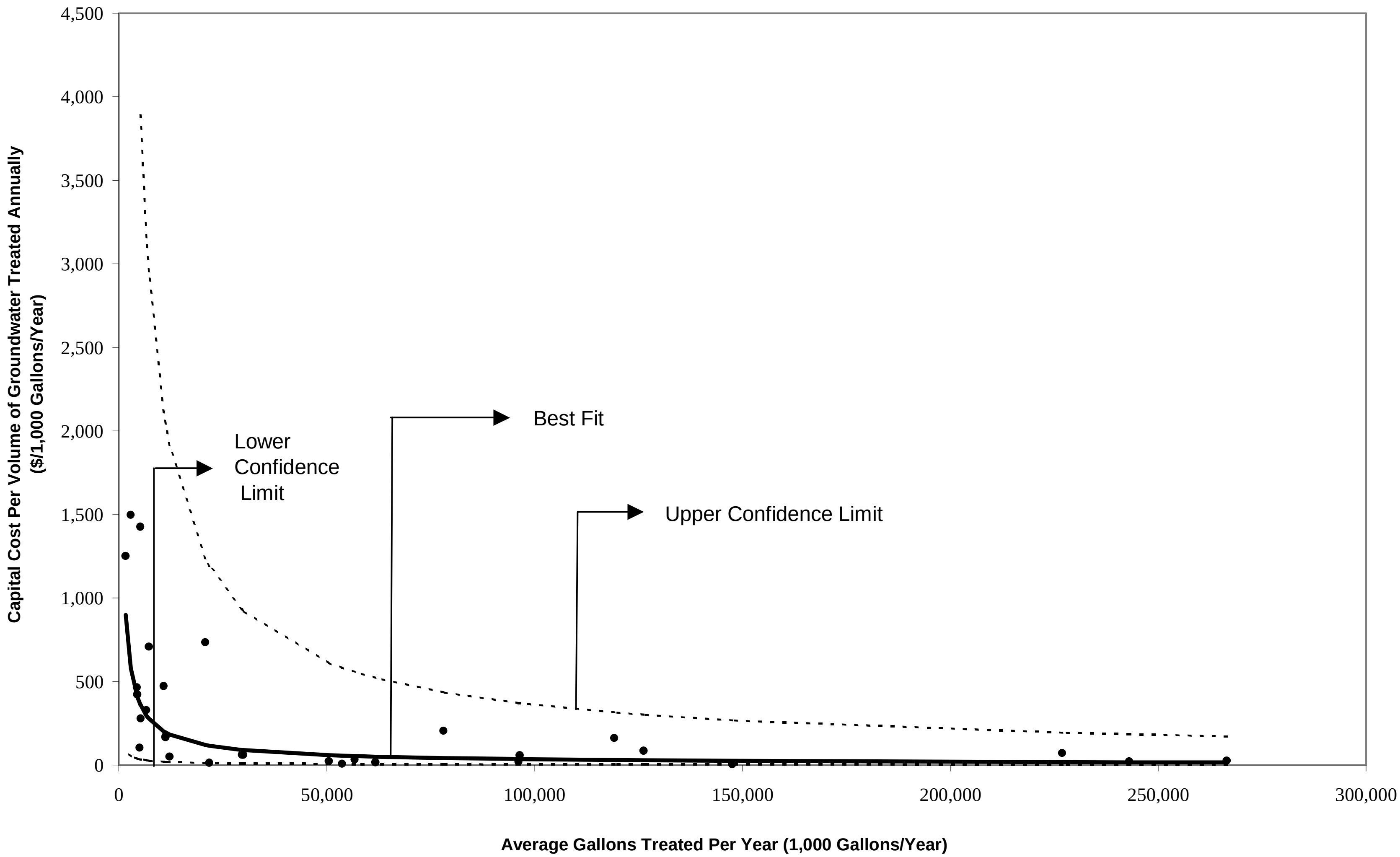
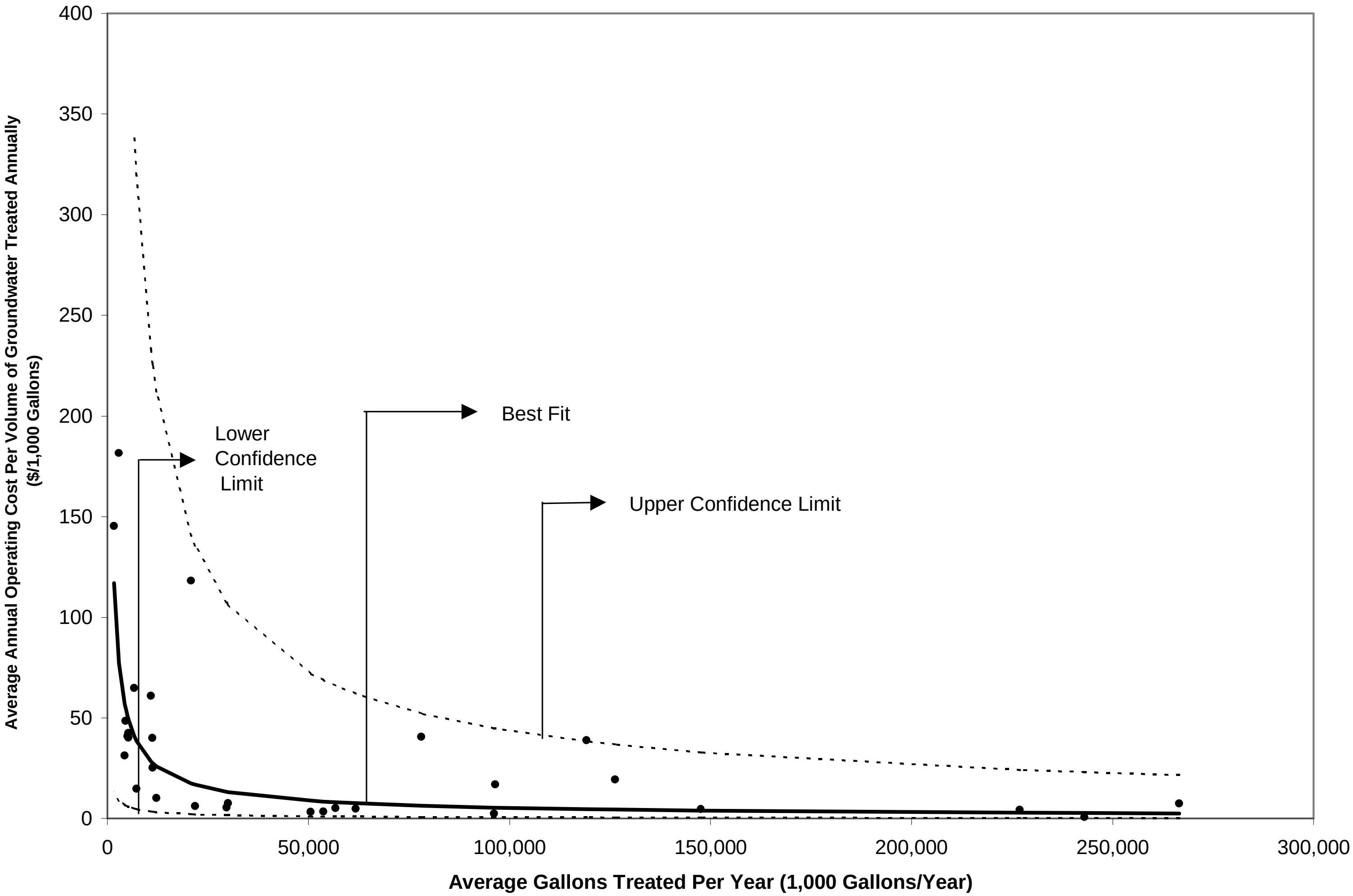
1 *There are several tools available that are used to estimate the costs for use of groundwater (and other) cleanup technologies, and that address these types of factors. Tools include products such as RACER and RS Means®. Additional information on these products is available through the RACER and RS Means® web sites, at <www.talpart.com/products/racer/racerabout.html> and <www.rsmeans.com>, respectively.*

EXHIBIT 8. CAPITAL COST FOR PUMP AND TREAT SYSTEMS AS A FUNCTION OF QUANTITY TREATED PER YEAR



1. All reported costs were adjusted for site locations and years when costs were incurred, as described in the text.
2. This chart shows a solid line based on a best fit of the available data for the 32 P&T sites, and dashed lines for the upper and lower confidence intervals using a 95% degree of confidence. The lines were drawn based on the results from a statistical analysis of the available data, using SAS JMP software; the specific methodology used to draw the lines is described more fully in the EPA report titled "Year 2000 Remediation Technology Cost Compendium" (under preparation by EPA's Technology Innovation Office). This chart shows an expanded view of the data points within the ranges shown, and does not include several sites that are treating more than 300,000 gallons per year.

EXHIBIT 9. ANNUAL OPERATING COST FOR PUMP AND TREAT SYSTEMS AS A FUNCTION OF QUANTITY TREATED PER YEAR



1. All reported costs were adjusted for site locations and years when costs were incurred, as described in the text.
2. This chart shows a solid line based on a best fit of the available data for the 32 P&T sites, and dashed lines for the upper and lower confidence intervals using a 95% degree of confidence. The lines were drawn based on the results from a statistical analysis of the available data, using SAS JMP software; the specific methodology used to draw the lines is described more fully in the EPA report titled “Year 2000 Remediation Technology Cost Compendium” (under preparation by EPA’s Technology Innovation Office). This chart shows an expanded view of the data points within the ranges shown, and does not include several sites that are treating more than 300,000 gallons per year.

Source control factors:

The method, timing of application, and success of source controls in mitigating contact of non-aqueous phase liquids (NAPLs) or other sources of contaminants, such as highly contaminated soil, with groundwater affect the cost of groundwater remediation systems. At several sites, efforts were made to remove NAPL or isolate the NAPL from contact with the groundwater. Such efforts often involved significant capital expenditures. For example, at Western Processing, both dense non-aqueous phase liquids (DNAPLs) and light non-aqueous phase liquids (LNAPLs) were observed in the groundwater. A slurry wall was constructed around the site to contain the plume and NAPLs and help achieve the cleanup goals in a limited amount of time. Capital costs for construction of the slurry wall were approximately $1.8 million.

Hydrogeologic factors:

The cost of groundwater remediation systems is affected by the properties of the aquifer. These properties include hydraulic connection of aquifers that allows for contamination of more than one aquifer, aquifer flow parameters, influences of adjacent surface water bodies on the aquifer system, and influences of adjacent groundwater production wells on the aquifer system. The following example illustrates a specific case in which hydrogeological factors affected the cost of the groundwater remediation technology implemented at the site. At JMT, the hydraulic conductivity in the contaminated bedrock aquifer was relatively low (0.65 feet per day). To increase the hydraulic conductivity, controlled blasting was carried out to create an artificial fracture zone, which served as an interceptor drain in the bedrock around the extraction well. While that approach increased the capital cost of the system, it allowed effective extraction of the groundwater from the bedrock aquifer by one well screened in the new fracture zone.

Extent of contamination factors:

The magnitude of the contaminated groundwater plume, including the area and depth of the plume and the concentration of contaminants within the plume, affect the cost of groundwater remediation systems. Typically, groundwater contamination that is limited in area and depth is easier and cheaper to remediate than the same mass of contaminant when it extends deeper and spreads out over a larger area. This factor affects the size of the extraction and treatment system and the complexity of the system in terms of the quantity of groundwater to be extracted from the aquifer and treated *ex situ*. For example, at Gold Coast, the initial areal extent of the contaminated plume was estimated to be 0.87 acre, and the initial volume of the plume was estimated to be less than 3 million gallons. The site was remediated at a total cost of less than $800,000.

Remedial goal factors:

Regulatory factors affect the design of a remedial system or the period of time it must be operated. These factors include aquifer restoration or treatment system performance goals, and specific system design requirements (such as disallowing reinjection of treated groundwater or specifying the treatment technology to be used). For example, at Western Processing, a P&T system, consisting of more than 200 groundwater extraction points pumping approximately 265 gpm, was installed. After approximately seven years of operation, an ESD was issued to change the focus of remediation efforts from restoration to containment. Because of that change, the system was modified to a system pumping approximately 80 gpm, which significantly reduced operating costs for the system.

NOTICE AND DISCLAIMER

This report was prepared by EPA's Technology Innovation Office with support provided under Contract Number 68-W-99-003. Information in this report is derived from a variety of references (including personal communications with experts in the field), some of which have been peer-reviewed. This report has undergone EPA and external review by experts in the field. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. For more information about this report, please contact: Linda Fiedler, U.S. EPA, Technology Innovation Office, Ariel Rios Building, 1200 Pennsylvania Ave., N.W. (MS 5102G), Washington, D.C., 20460; (703) 603-7194; e-mail: *fiedler.linda@epa.gov*.

EXHIBIT 10. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED P&T SITES

Site Name and Location	Contaminants With Remedial Cleanup Goals [1]	Remediation Technology [2]										Years of Operation/Status [3,4]	Gallons Treated Per Year (1,000 Gallons)	Adjusted Capital Cost (Reported Capital Cost) [5]	Adjusted Av.Ann. Oper. Cost (Reported Av. Ann. Oper. Cost) [5,6]	Adjusted Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons/Year) [5]	Adjusted Av. Ann. Oper. Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons) [5,6]	Cost Highlights
		P&T (with *ex situ* treatment)[7]					AS	FPR	ISB	PRB	VCB							
		BIO	GAC	PHYS/CHEM	OXID	STRIP												
CHLORINATED SOLVENTS ALONE OR WITH OTHER VOCs																		
French, Ltd., TX	benzene, toluene, chloroform, 1,2-DCA, VC	●	●	●					●		●	3.9/A	78,000	$16,000,000 ($15,000,000)	$3,200,000 ($3,300,000)	$200	$41	Oversight costs were high because this is a large system. Costs include those for P&T, ISB, and two VCBs. *Ex situ* metals treatment was added after it was determined that the biological treatment unit failed to sufficiently remove metals. Costs for VCBs are included in the capital costs because they were an integral part of containing the groundwater plume.
TCAAP, MN	1,2-DCE, 1,1,1-TCA, TCE, PCE					●						4.9/O	1,400,000	$12,000,000 ($8,000,000)	$810,000 ($590,000)	$8.4	$0.58	Complex hydrogeology (multilayer aquifer system) increased remediation costs.
Firestone, CA	1,1-DCE, TCE, PCE, 1,1-DCA, benzene, toluene, xylene		●			●						6.8/C	270,000	$6,900,000 ($4,100,000)	$2,000,000 ($1,300,000)	$26	$7.3	Frequent modifications to system increased costs. Cost of analysis and data management were high.
McClellan AFB, OU B/C, CA	None, primary contaminants of concern are TCE, cis-1,2-DCE, PCE, 1,2-DCA					●						6.8/O	96,000	$5,600,000 ($4,000,000)	$1,600,000 ($1,200,000)	$58	$17	Frequent modifications to system increased costs. Excess treatment capacity required internal groundwater recycling to sustain efficient treatment; this raised operating costs. Small system, unit costs reflect economies of scale. The *ex situ* treatment system originally included biological treatment. This unit operation was discontinued after influent ketone levels fell below detection limits. A second smaller groundwater treatment system was installed at the site in 1991; costs for this system are not included.
U.S. DOE, Savannah River, SC	TCE, PCE, 1,1,1-TCA					●						8.3/O	240,000	$5,200,000 ($4,100,000)	$170,000 ($150,000)	$21	$0.71	Complex hydrogeology and presence of DNAPLs increased remediation costs.
Des Moines, IA	TCE					●						8.8/O	550,000	$2,200,000 ($1,600,000)	$140,000 ($110,000)	$3.9	$0.25	Large treatment system; unit costs reflect economies of scale.
Old Mill, OH	TCE, PCE, 1,2-DCE, ethylbenzene		●			●						7.8/O	1,700	$2,100,000 ($1,600,000)	$240,000 ($210,000)	$1,300	$150	Modifications to the system increased capital costs by 22 percent. Relatively small volume of groundwater treated annually; increased unit cost relative to larger systems.

EXHIBIT 10. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED P&T SITES (CONTINUED)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1]	Remediation Technology [2]: P&T (with *ex situ* treatment)[7]: BIO	P&T: GAC	P&T: PHYS/CHEM	P&T: OXID	P&T: STRIP	AS	FPR	ISB	PRB	VCB	Years of Operation/Status [3,4]	Gallons Treated Per Year (1,000 Gallons)	Adjusted Capital Cost (Reported Capital Cost) [5]	Adjusted Av.Ann. Oper. Cost (Reported Av. Ann. Oper. Cost) [5,6]	Adjusted Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons/Year) [5]	Adjusted Av. Ann. Oper. Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons) [5,6]	Cost Highlights
Sol Lynn, TX	TCE		●	●		●						3.0/S	4,000	$2,000,000 ($2,100,000)	$130,000 ($150,000)	$460	$31	Complex hydrogeology increased capital costs. An iron filter was added to the *ex situ* treatment train to minimize fouling in the air stripper packing.
U.S. Aviex, MI	1,1,1-TCA, 1,2-DCA, DEE, 1,1-DCE, TCE, PCE, BTEX					●						3.4/O	96,000	$1,900,000 ($1,400,000)	$230,000 ($180,000)	$20	$2.4	Optimization of interim P&T system before final remedy reduced costs. All contaminants with remedial cleanup goals except diethyl ether are chlorinated solvents or BTEX. All contaminants are VOCs, as reflected in the relatively simple *ex situ* treatment system.
U.S. DOE, Kansas City, MO	None, contaminants of greatest concern at the site are PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, and VC.				●							5.8/O	11,000	$1,900,000 ($1,400,000)	$450,000 ($360,000)	$170	$40	Remediation costs was high for the following reasons: frequent fouling of the extraction wells required well treatment/redevelopment; and initial oxidation system was undersized and was replaced with larger system.
Keefe, NH	PCE, TCE, 1,1-DCE, benzene, 1,2-DCA			●		●						4.1/O	11,000	$1,900,000 ($1,600,000)	$280,000 ($240,000)	$170	$25	Optimization of the system pumping rates increased mass removal efficiency.
SCRDI Dixiana, SC	PCE, TCE, 1,1,1-TCA, 1,1-DCE, 1,1,2-TCA, 1,1,2,2-PCA, chloroform, carbon tetrachloride, benzene, dichloromethane					●						4.6/O	4,500	$1,900,000 ($1,800,000)	$220,000 ($220,000)	$420	$48	PRP made major modifications to the remedial system, which increased costs. Relatively low contaminant concentration resulted in lower remediation costs. *Ex situ* treatment system originally included a metal media filter unit before the original air stripper. The metal removal unit was discontinued when the original packed-column air stripper was replaced with a shallow stacked tray air stripper.
JMT, NY	TCE, cis-1,2-DCE, TCA, VC					●						9.6/O	5,200	$1,400,000 ($880,000)	$220,000 ($150,000)	$280	$42	Modifications of treatment system increased capital costs 35 percent; system consisted of one extraction well, which reduced remediation costs.
City Industries, FL	1,1-DCA, 1,1-DCE, MC, VC, PCE, TCE, 1,1,1-TCA, benzene, toluene, ethylbenzene, acetone, MEK, MIBK, phthalates, cis-1,2-DCE, trans-1,2-DCE					●						3.0/O	51,000	$1,200,000 ($1,200,000)	$160,000 ($170,000)	$23	$3.2	Optimized pump rates; biofouling of air stripper increased system downtime and likely increased remediation costs. All contaminants with remedial cleanup goals except acetone, MEK, MIBK, and phthalates are chlorinated solvents or BTEX. All contaminants are VOCs, as reflected in the relatively simple *ex situ* treatment system.

EXHIBIT 10. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED P&T SITES (CONTINUED)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1]	Remediation Technology [2]: P&T (with *ex situ* treatment)[7]: BIO	P&T: GAC	P&T: PHYS/CHEM	P&T: OXID	P&T: STRIP	AS	FPR	ISB	PRB	VCB	Years of Operation/Status [3,4]	Gallons Treated Per Year (1,000 Gallons)	Adjusted Capital Cost (Reported Capital Cost) [5]	Adjusted Av.Ann. Oper. Cost (Reported Av. Ann. Oper. Cost) [5,6]	Adjusted Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons/Year) [5]	Adjusted Av. Ann. Oper. Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons) [5,6]	Cost Highlights
Solid State, MO	TCE					●						4.2/O	62,000	$1,000,000 ($930,000)	$300,000 ($280,000)	$17	$4.9	Capital costs do not include costs for installation of four deep extraction wells installed as part of RI/FS.
Intersil (P&T), CA	TCE, cis-1,2-DCE, VC, Freon 113®					●				●		7.2/D	5,000	$510,000 ($320,000)	$200,000 ($140,000)	$100	$41	Groundwater extraction system was expanded after three years of operation, likely increasing operating costs. Costs for the PRB are not included.
Mystery Bridge, WY	trans-1,2-DCE, cis-1,2-DCE, TCE, PCE, 1,1,1-TCA, 1,1-DCE					●						3.6/O	54,000	$340,000 ($310,000)	$180,000 ($170,000)	$6.3	$3.4	Low concentrations in groundwater result in lower remediation costs.
Gold Coast, FL	MC, 1,1-DCA, trans-1,2-DCE, TCE, PCE, toluene					●	●					3.7/C	22,000	$290,000 ($250,000)	$130,000 ($120,000)	$13	$6.2	Optimized extraction wells resulted in lower remediation costs; P&T system required less than four years to clean up site. Costs for the AS are not included.
BTEX ONLY																		
Site A, NY	BTEX					●	●		●			2.3/O	6,700	$2,200,000 ($1,400,000)	$430,000 ($290,000)	$330	$65	Use of skid-mounted modular equipment reduced capital costs. The capital cost includes the cost of SVE wells because this cost could not be separated from the groundwater system costs.
Amoco, MI	None, contaminants of concern are BTEX and MTBE		●					●				5.7/O	150,000	$470,000 ($300,000)	$700,000 ($480,000)	$3.2	$4.7	Leasing GAC and GAC system provided flexibility to modify treatment system, likely reducing remediation costs. Costs for AS are not included.
METALS ONLY																		
United Chrome, OR	Cr			●								8.6/O	7,200	$5,100,000 ($3,300,000)	$110,000 ($74,000)	$710	$15	Modular treatment system used initially, reducing costs.
Odessa I, TX	Cr			●								4.2/O	30,000	$1,900,000 ($2,000,000)	$220,000 ($250,000)	$62	$7.5	ROD required that ferrous iron be produced onsite electrochemically, limiting number of appropriate vendors and increasing capital costs.
Odessa II, TX	Cr			●								4.1/O	30,000	$1,800,000 ($1,900,000)	$160,000 ($180,000)	$62	$5.4	ROD required that ferrous iron be produced onsite electrochemically, limiting number of appropriate vendors and increasing capital costs.

EXHIBIT 10. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED P&T SITES (CONTINUED)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1]	Remediation Technology [2]										Years of Operation/Status [3,4]	Gallons Treated Per Year (1,000 Gallons)	Adjusted Capital Cost (Reported Capital Cost) [5]	Adjusted Av.Ann. Oper. Cost (Reported Av. Ann. Oper. Cost) [5,6]	Adjusted Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons/Year) [5]	Adjusted Av. Ann. Oper. Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons) [5,6]	Cost Highlights
		P&T (with *ex situ* treatment)[7]					AS	FPR	ISB	PRB	VCB							
		BIO	GAC	PHYS/CHEM	OXID	STRIP												
OTHER COMBINATIONS OF CONTAMINANTS																		
Western Processing, WA	Cd, Cr, Cu, Ni, Pb, Zn, Hg, Ag, cyanide, trans-1,2-DCE, cis-1,2-DCE					●					●	8.2/O	120,000	$19,000,000 ($14,000,000)	$4,600,000 ($3,600,000)	$160	$39	Remediation cost was high for the following reasons: large complex system with over 200 vacuum well points was initially used, 24-hour oversight was required; frequent maintenance was required to control iron precipitate buildup; treatment system originally included metals precipitation, oxidation, air stripping, and granular activated carbon treatment. In 1995, remedial goal was changed from aquifer restoration to plume containment; metals precipitation, oxidation, and granular activated carbon treatment were subsequently discontinued. The capital cost includes the cost of a slurry wall because it is an integral part of containing the groundwater plume.
Bofors Nobel, OU 1, MI	Remedial goals set for analine, 2-chloroaniline, selected purgeable halocarbons, and selected purgeable aromatics. Key specific contaminants are benzene, benzidine, 2-chloroaniline, 1,2-DCE, TCE, 3,3-dichlorobenzidene, aniline, VC.		●		●	●						3.1/O	230,000	$16,000,000 ($12,000,000)	$970,000 ($770,000)	$70	$4.3	Preventative maintenance program ensured uninterrupted operation of extraction system, which likely reduced remediation costs. A metals precipitation unit that was operated during the first two years of system operation was taken out of service after it was determined to be unnecessary.
Baird and McGuire, MA	BTEX, acenaphthene, naphthalene, 2,4-dimethyl phenol, dieldrin, chlordane, Pb, As		●	●		●						3.8/O	21,000	$15,000,000 ($11,000,000)	$2,500,000 ($2,000,000)	$730	$120	Operating costs increased due to the need to monitor for a wide range of contaminants and for several full-time operators to be onsite. Originally, *ex situ* system included biological treatment. This step was eventually discontinued. Historical data indicate that sufficient organic removal rates are attained without the use of biological treatment.

EXHIBIT 10. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED P&T SITES (CONTINUED)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1]	Remediation Technology [2]: P&T (with *ex situ* treatment)[7]: BIO	GAC	PHYS/CHEM	OXID	STRIP	AS	FPR	ISB	PRB	VCB	Years of Operation/Status [3,4]	Gallons Treated Per Year (1,000 Gallons)	Adjusted Capital Cost (Reported Capital Cost) [5]	Adjusted Av.Ann. Oper. Cost (Reported Av. Ann. Oper. Cost) [5,6]	Adjusted Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons/Year) [5]	Adjusted Av. Ann. Oper. Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons) [5,6]	Cost Highlights
Sylvester/ Gilson Road, NH	MC, chloroform, MEK, toluene, phenols, Se, methyl methacrylate, 1,1,1-TCA, trans-1,2-DCA, 1,1-DCA, chlorobenzene, 1,1,2-TCA, VC, benzene	●		●		●					●	9.5/E	130,000	$11,000,000 ($7,200,000)	$2,400,000 ($1,800,000)	$85	$19	Remediation cost was high for the following reasons: several full-time operators were on site 24 hours per day, high costs for fuel oil to operate the vapor incinerator used for air emission control.
LaSalle, IL	PCBs, TCE, 1,2-DCE, 1,1,1-TCA, VC, 1,1-DCA, PCE		●			●						4.4/O	5,200	$7,400,000 ($5,300,000)	$210,000 ($160,000)	$1,400	$40	Complex mixture of contaminants and DNAPL contributed to elevated capital costs. Relatively small volume of groundwater treated annually; increased unit cost relative to larger systems.
Solvent Recovery Service, CT	None, contaminants at the site include TCE, cis-1,2-DCE, 1,1,1-TCA, PCBs, Ba, Cd, Ch, Pb, Mn		●	●	●						●	3.0/O	11,000	$5,100,000 ($4,400,000)	$660,000 ($580,000)	$470	$61	Presence of DNAPL contributed to elevated capital and operating costs. The capital cost includes the cost of a sheet pile wall because it was an integral part of containing the groundwater plume.
Libby, MT	napthalene, acenaphthene, fluorene, anthracene, pyrene, fluoranthene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene, indeno(1,2,3-cd)pyrene, As, benzene, PCP	●							●			5.3/O	3,000	$4,300,000 ($3,000,000)	$520,000 ($400,000)	$1,500	$180	Chemical costs (e.g., hydrogen peroxide) were high for *in situ* bioremediation; monitoring, sampling, and analysis costs were high at the beginning of the project. Relatively small volume of groundwater treated annually; increased unit cost relative to larger systems.
King of Prussia, NJ	1,1-DCA, trans-1,2-DCE, 1,1,1-TCA, TCE, PCA, PCE, benzene, toluene, ethylbenzene, Be, Cr, Cu, Ni, Cd, Hg,, Zn		●	●		●						2.7/O	57,000	$1,800,000 ($2,000,000)	$290,000 ($330,000)	$32	$5.1	Electrochemical treatment to remove metals from the groundwater increased costs.

EXHIBIT 10. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED P&T SITES (CONTINUED)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1]	Remediation Technology [2]										Years of Operation/Status [3,4]	Gallons Treated Per Year (1,000 Gallons)	Adjusted Capital Cost (Reported Capital Cost) [5]	Adjusted Av.Ann. Oper. Cost (Reported Av. Ann. Oper. Cost) [5,6]	Adjusted Capital Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons/Year) [5]	Adjusted Av. Ann. Oper. Cost Per Volume of Groundwater Treated Per Year ($/1,000 Gallons) [5,6]	Cost Highlights
		P&T (with *ex situ* treatment)[7]					AS	FPR	ISB	PRB	VCB							
		BIO	GAC	PHYS/CHEM	OXID	STRIP												
MSWP, AR	PCP, Cr, As, benzo(a)anthracene, benzo(a)pyrene, benzo(b+k)fluoranthene, chrysene		●									8.3/O	12,000	$600,000 ($470,000)	$120,000 ($110,000)	$49	$10	Use of fabric filters increased operating life of GAC units and therefore reduced remediation costs. During a slowdown in plant operations, an additional carbon treatment system was operated briefly to treat metal-contaminated groundwater from one extraction well. Before and after this slowdown, the water from this well was used as makeup water for plant operations.

Source: FRTR case studies of ongoing and completed groundwater remediation projects.
[1]Contaminant Key: As = arsenic, Ba = barium, Be = beryllium, BTEX = benzene, toluene, ethylbenzene, and xylenes, Cd = cadmium, Cr = chromium, Cu = copper, DCA = dichloroethane, DCE = dichloroethene, DEE = diethyl ether, MC = methylene chloride, MEK = methyl ethyl ketone, MIBK = methyl isobutyl ketone, Mn = manganese, MTBE = methyl tert butyl ether, NH-SVOLs = nonhalogenated semivolatiles, Ni = nickel, PAH = polycyclic aromatic hydrocarbons, Pb = lead, PCA = tetrachloroethane, PCB = polychlorinated biphenyls, PCE = tetrachloroethene, PCP = pentachlorophenol, TCA = tetrachloroethane, TCE = tetrachloroethene, VC = vinyl chloride, Zn = zinc.
[2]Remediation Technology Key: AS = air sparging, BIO = biological treatment, FPR = free product recovery, GAC = granular activated carbon adsorption, ISB = *in situ* bioremediation, PHYS/CHEM = physical or chemical removal of metal, OXID = Oxidation, PRB = permeable reactive barrier, STRIP = air stripping, VCB = vertical containment barrier.
[3]If cost data are not available for the entire period of treatment system operation, then the number of years for which cost data are available is presented.
[4]Status Key: A = monitored natural attenuation, C = complete, D = P&T discontinued, PRB ongoing, E = shut down pending explanation of significant difference, O = ongoing, S = shut down pending study.
[5]All reported costs were adjusted for site locations and years when costs were incurred, as described in the text. All unadjusted (reported) costs are presented in parentheses. Adjusted costs are not presented in parentheses.
[6]Av. Ann. Oper. Cost = Average Annual Operating Cost
[7]The *ex situ* treatment systems presented in these columns include the treatment units in operation at the time that the case studies were prepared (for systems with and ongoing status) or the treatment units most recently in operation before system shutdown (for systems with any status other than ongoing).

EXHIBIT 11. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED PRB SITES

Site Name and Location	Contaminants[1]	Adjusted Cap. Cost[2] (Reported Cap. Cost)	Cost Components: Design	Construction	Materials	Reactive Media	Engineering	Haz. Waste T&D	Unspecified	Installation Date	Installation Method[3]	Number of PRBs/Gates	PRB Location or Function	Reactive Media Material[4]	Reactive Media Dimensions: Total Mass	Width	Length	Depth	Cost Highlights
CHLORINATED SOLVENTS																			
Kansas City Plant, MO	1,2-DCE, VC	$1,600,000 ($1,500,000) Design = $200,000 Other = $1,300,000	●	●	●	●		●		Apr. 1998	CT	1	Top half of trench	2 ft Fe^o, 4 ft sand	370 tons of iron	6 ft	130 ft	13-27 ft[9]	Contractor had difficulty using 1-pass deep trenching machine (wet, heavy clay). Resorted to conventional sheet pile construction. This likely increased remediation costs.
													Bottom half of trench	100% Fe^o				27-33 ft	
Caldwell Trucking, NJ	TCE	$1,400,000 ($1,120,000)	●	●	●	●				Apr. 1998	HF	2	Permeation infill	Fe^o	250 tons	3 in	150 ft	15-50 ft	Permeation infill wall cost $531,000
													Hydrofrace	Fe^o		3 in	90 ft	15-50 ft	Hydrofrace wall cost $791,000
Former Manf. Site, NJ	1,1,1-TCA; PCE; TCE; DNAPL	$1,100,000 ($875,000) Design = $180,000 Iron = $360,000* Other = $560,000	●	●	●	●				Sept. 1998	DE, CT, SPC	1	DNAPL excavation	1:1 Fe^o/ sand	720 tons of iron	5 ft	127 ft	25 ft	Below grade sewer line permitted water to enter excavation. Therefore, subaqueous excavation was required for that portion of the wall, increasing remediation costs.
													Top 4 to 7 ft of CT[9]	3:2 Fe^o/ sand					
													Bottom 7 to 21 ft of CT[9]	4:1 Fe^o/ sand					
FHA Facility, CO	TCA; 1,1-DCE; TCE; cis-1,2-DCE	$1,100,000 ($1,000,000) Iron = $210,000[9] Other = $890,000	●	●	●	●				Oct. 1996	F&G	4	All 4 PRBs	Fe^o	476 tons of iron*	varies	Each gate is 40 ft wide	25 ft[9]	1,040-ft funnel section. Use of multiple gates increased remediation costs.
Industrial Site, NY	TCE, cis-1,2-DCE, VC	$1,000,000 ($797,000) Iron = $360,000[9] Other = $640,000		●	●	●				Dec. 1997	CT	2	Main trench	Fe^o	742 tons	1 ft	370 ft	18 ft	Capital cost includes cost of site improvements to allow access by the trenching equipment.
													Upgradient trench			1 ft	10 ft	NR	

EXHIBIT 11. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED PRB SITES (CONTINUED)

Site Name and Location	Contaminants [1]	Adjusted Cap. Cost [2] (Reported Cap. Cost)	Cost Components: Design	Construction	Materials	Reactive Media	Engineering	Haz. Waste T&D	Unspecified	Installation Date	Installation Method [3]	Number of PRBs/Gates	PRB Location or Function	Reactive Media Material [4]	Reactive Media Dimensions: Total Mass	Width	Length	Depth	Cost Highlights
Intersil, CA[5]	TCE, cis-1,2-DCE, VC, Freon 113®	$760,000 ($600,000)[10] Iron = $170,000* Other = $590,000		●	●	●				Feb. 1995	F&G	1	NA	Fe^o	220 tons	4 ft	36 ft	11-31 ft	Two slurry walls: 300 ft and 235 ft long. Average annual operating costs are $120,000[10].
Aircraft Facility, OR	TCE	$710,000 ($600,000)							●	Mar. 1998	F&G	2	Gate 1	Fe^o	324 tons of iron[9]	Two 9-in thick layers	50 ft	to 24-34 ft	2-ft. thick funnel walls, 650-ft. long funnel.
													Gate 2	Fe^o, sand		3 ft	60 ft	to 24-34 ft	
Lowry Air Force Base, CO	TCE	$600,000 ($530,000)	●	●	●	●				Dec. 1995	F&G	1	NA	Fe^o	NR	5 ft	10 ft	0-17 ft	Two 14-ft. sheet piling funnel walls
Industrial Site, N. Ireland	TCE; cis-1,2-DCE	$580,000[6] ($375,000)		●[9]	●	●	●			Dec. 1995	F&R	1	NA	Fe^o	NR	Vessel has 4-ft diam.	Vessel has 4-ft diam.	33-49 ft	Two 100-ft. bentonite/cement slurry walls
Industrial Site, KS	TCE; 1,1,1-TCA	$400,000 ($400,000) Iron = $50,000* Other = $350,000		●[9]	●	●				Jan. 1996	F&G	1	NA	Fe^o	70 tons	3 ft	20 ft	0-30 ft	Two 490-ft. bentonite slurry walls
Industrial Site, SC	TCE, cis-1,2-DCE, VC	$360,000 ($400,000) Design = $45,000 Iron = $130,000* Other = $180,000	●	●	●	●				Nov. 1997	CT	1	NA	Fe^o, sand (1:1 ratio)	400 tons of iron	1 ft	375 ft[9]	0-29 ft	Installation of PRB system being performed in two phases; costs reflect both phases.

EXHIBIT 11. SUMMARY OF COST AND TECHNICAL INFORMATION FOR SELECTED PRB SITES (CONTINUED)

Site Name and Location	Contaminants [1]	Adjusted Cap. Cost [2] (Reported Cap. Cost)	Cost Components							Installation Date	Installation Method [3]	Number of PRBs/Gates	PRB Location or Function	Reactive Media Material [4]	Reactive Media Dimensions				Cost Highlights
			Design	Construction	Materials	Reactive Media	Engineering	Haz. Waste T&D	Unspecified						Total Mass	Width	Length	Depth	
Former Dryclean Site, Germany	PCE; 1,2-DCE	$160,000 ($123,000) Design = $39,000 Other = $120,000	●	●		●				June 1998	CW	1	NS	1:1 mass ratio Fe°/ gravel	69 tons	2-3 ft	33 ft	10 - 33 ft[7]	The mandrel construction method was chosen because it was determined to be easier and less expensive than continuous sheet piling construction.
													NS	IS	85 tons		41 ft		
METALS AND INORGANICS																			
Nickel Rim Mine Site, Canada	Ni, Fe, Sulfate	$43,000 ($30,000)	●	●	●	●				Aug. 1995	C&F	1	NA	OC/ pea gravel	NR	12 ft	50 ft	14 ft deep	12-in clay cap covers PRB to prevent surface water and oxygen entry. Coarse sand buffer zones installed up and downgradient.
COMBINATION OF CONTAMINANTS																			
Y-12 Site, Oak Ridge National Lab, TN	U, Tc, HNO3	$900,000 ($1,000,000)	●	●	●	●				Nov. 1997	CT	1	NS	100% iron	80 tons iron	2 ft	26 ft	22-30 ft	Did not excavate into confining unit; this may result in lower remediation costs and may permit the groundwater to bypass the reactive media.
													NS	100% gravel	NR		199 ft		
										Dec. 1997	F&R	5	All 5 reactors	iron	NR	NR	NR	NR	
Marzone Inc., GA	alpha-HCB, beta-HCB, DDD, DDT, xylene, EB, lindane, methyl parathion	$650,000 ($750,000) Design = $200,000 Other = $450,000	●	●	●	●				Aug. 1998	F&G	1	NA	AC	0.9 tons	NR	400 ft	NR	System flushing required every 3-4 weeks to reinitiate flow; resulting in higher than anticipated operating costs.
U.S. Coast Guard Support Center, NC[8]	Cr^{+6}, TCE	$460,000 ($500,000)[10] Design = $160,000 Iron = $150,000 Other = $150,000	●	●	●	●				June 1996	CT	1	NA	Fe°	450 tons	2 ft	150 ft	3-24 ft	Total trench is 225 ft long. The exact location of the 26-ft iron portion is unspecified.

Primary Source: EPA, Office of Solid Waste and Emergency Response. 1999. *Field Applications of In Situ Remediation Technologies: Permeable Reactive Barriers*. EPA 542-R-99-002. June.

Additional Sources: Fax Transmittal from Mr. Robert Puls, EPA to Susan Guenther, TTEMI. March 8, 2000. Comments on Exhibit 10: Summary of Cost and Technical Information for Selected Permeable Reactive Barrier Sites.
EPA. 1998. *Remediation Case Studies: Innovative Groundwater Treatment Technologies*. Volume 11. EPA 542-R-98-015. September.

[1] Contaminant Key: As = arsenic, HCB = hexachlorobenzene, Cd = cadmium, Cu = copper, Cr^{+6} = hexavalent chromium, DCE = dichloroethene, DDD = dichlorodiphenyldichloroethane, DDT = dichlorodiphenyltrichloroethane, DNAPL = dense nonaqueous-phase liquid, EB = ethylbenzene, Fe = Iron, HNO3 = nitric acid, Ni = Nickel, Pb = lead, PCE = tetrachloroethene, Tc = technetium, TCA = trichloroethane, TCE = trichloroethene, U = uranium, VC = vinyl chloride, Zn = zinc.

[2] All reported capital costs were adjusted for site locations and years when costs were incurred, as described in the text. All unadjusted (reported) costs are presented in parentheses. Adjusted costs are not presented in parentheses.

[3] Installation Method Key: C&F = cut and fill, CT = continuous trencher, CW = continuous wall, DE = dense nonaqueous-phase liquid (DNAPL) extraction, F&G = funnel and gate, F&R = funnel and reaction vessel, HF = hydraulic fracturing, SPC = Sheet piling construction.

[4] Reactive Media Material Key: AC = activated carbon, AFO = amorphous ferric oxyhydroxide, Fe^{o} = zero-valent iron, IS = iron sponge (wood shavings or chips impregnated with hydrated iron oxide), LM = limestone, OC = organic carbon (municipal/leaf compost and wood chips), PO_4 = bone char phosphate.

[5] Adjusted average annual operating costs for Intersil are $120,000. Information was obtained from EPA 542-R-98-015.

[6] An adjustment factor for Northern Ireland is not available. Therefore, an adjustment factor for the United Kingdom was used.

[7] The lower boundary of the continuous wall was not reported. However, the aquifer extends to 33 ft.

[8] Adjusted average annual operating costs for the U.S. Coast Guard Support Center are $78,000. Information was obtained from EPA 542-R-98-015.

[9] Information provided by Mr Robert Puls, EPA.

[10] Information obtained from EPA 542-R-98-015.

NA = Not applicable, NR = Not reported, NS = Not specified

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APPENDIX A. COST EQUATIONS AND EXAMPLE CALCULATIONS

The equations used to normalize the total capital and total annual operating costs and to calculate the average annual operating costs are presented below.

Adjusted Total Capital Cost	=	(Total Capital Cost)(ACF)(IF)
Adjusted Total Annual Operating Cost	=	(Total Annual Operating Cost)(ACF)(IF)
Average Annual Operating Cost	=	(Adjusted Total Annual Operating Cost)/(# of Years)

Example calculations are presented below for the Former Firestone Superfund Site, which is one of the 32 P&T sites included in the analysis. The site is located in Salinas, California (California ACF = 1.15). The groundwater treatment system at the Former Firestone Superfund Site was installed in 1985 (IF = 1.44). Annual costs were incurred from 1986 to 1992, for a total of 6.8 years. 1989 was used as the median year in which annual costs were incurred (IF = 1.31). The total unadjusted capital cost and total annual operating cost for the site are $4,100,000 and $8,800,000, respectively.

Adjusted Total Capital Cost	=	($4,100,000)(1.15)(1.44)	=	$6,900,000
Adjusted Total Annual Cost	=	($8,800,000)(1.15)(1.31)	=	$13,000,000
Average Annual Operating Cost	=	($13,000,000)/(6.8)	=	$2,000,000

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