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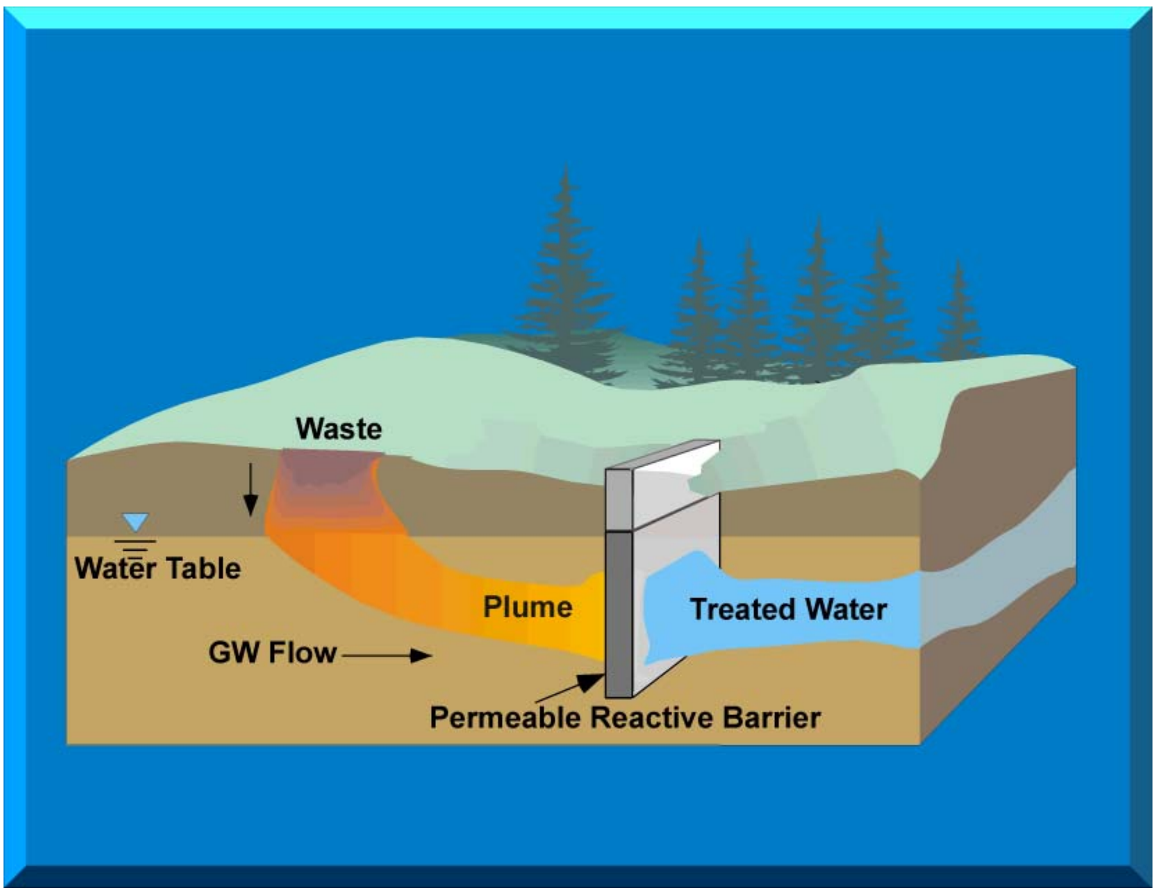
Economic Analysis of the Implementation of Permeable Reactive Barriers for Remediation of Contaminated Ground Water



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Economic Analysis of the Implementation of Permeable Reactive Barriers for Remediation of Contaminated Ground Water

by

Robert M. Powell and Patricia D. Powell
Powell & Associates Science Services
Las Vegas, Nevada 89123

Robert W. Puls
Subsurface Protection and Remediation Division
National Risk Management Research Laboratory
Ada, Oklahoma 74820

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Project Officer
David S. Burden
Subsurface Protection and Remediation Division
National Risk Management Research Laboratory
Ada, Oklahoma 74820

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

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Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

Permeable reactive barriers are no longer perceived as a new or unproven in situ technology for ground-water remediation. They are now recognized as a standard remedial option for site owners and remedial project managers to consider when trying to decide which remedial technology is best suited for effective cleanup at hazardous waste sites. This document provides information about the costs of applying this technology and should be useful in arriving at these difficult decisions. The report summarizes cost data from 22 sites across the United States where permeable reactive barriers have either been installed or were to be installed. While it is difficult to assemble comprehensive cost data on new and developing technologies, every effort was made to obtain the most complete data set possible. The information presented should be helpful in guiding technology selection at hazardous waste sites where ground water has been seriously impacted.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Stephen G. Schmelling, Acting Director
Subsurface Protection and Remediation Division
National Risk Management Research Laboratory

Abstract

This report presents an analysis of the cost of using permeable reactive barriers to remediate contaminated ground water. When possible, these costs are compared with the cost of pump-and-treat technology for similar situations. Permeable reactive barriers are no longer perceived as an innovative remediation technology but are rapidly maturing and may be considered as a standard remediation technology, similar to pump-and-treat.

PRB cost information was obtained from a variety of sources, including reports, surveys, and interviews. Costs were broken out into four general categories: site characterization, design, construction, and operation and maintenance. Subcategories within these four further detailed the costs.

A novel approach to comparing treatment costs for PRBs is proposed and used. It relies on describing costs per the quantity of water that actually needs to be treated rather than the typical P&T approach of dollars per gallon that enter the treatment system whether contaminated or not.

Cost comparisons indicate that, depending upon the situation, implementing a PRB can either be more or less expensive than a P&T in terms of capital expenditures, but that routine operation and maintenance costs favor the PRBs. However, a major unknown with regard to implementing PRBs is the potential need for replacement or rejuvenation of the reactive media.

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SI Conversion Factors

	Multiply	English (US) Units	by	Factor	to get	Metric (SI) Units
Area:		1 ft^2		0.0929		m^2
		1 in^2		6.452		cm^2
Flow rate:		1 gal/min		6.31×10^{-5}		m^3/s
		1 gal/min		0.0631		L/s
		1 MGD		43.81		L/s
Length:		1 ft		0.3048		m
		1 in		2.54		cm
Mass:		1 lb		453.59		g
		1 lb		0.45359		kg
Volume:		1 ft^3		28.316		L
		1 ft^3		0.028317		m^3
		1 gal		3.785		L
		1 gal		0.003785		m^3
Temperature:		$^oF - 32$		0.55556		^oC
Concentration:		1 gr/ft^3		2.2884		g/m^3
		1 gr/gal		0.0171		g/L
		1 lb/ft^3		16.03		g/L
Pressure:		1 lb/in^2		0.07031		kg/cm^2
		1 lb/in^2		6894.8		$Newton/m^2$
Heating value:		Btu/lb		2326		Joules/kg
		Btu/scf		37260		Joules/scm

1. Introduction

During the past decade there have been numerous investigations into innovative remedial technologies that could supplement or, preferably, entirely replace standard pump-and-treat (P&T) technologies for the treatment of contaminated ground water. These technologies have consisted of in situ treatments that can either transform the contaminants into innocuous breakdown products or detoxify and immobilize them in the subsurface, hence minimizing or eliminating their biospheric impacts.

Among the most promising of these innovative technologies are permeable reactive barriers (PRBs). Rather than serving to constrain plume migration, PRBs are designed as conduits for the contaminated ground-water flow. As contaminated water passes through the reactive zone of the PRB, the contaminants are either immobilized or chemically transformed to a more desirable (e.g., less toxic, more readily biodegradable, etc.) state. Therefore, a PRB is a barrier to contaminants, but not to ground-water flow. A permeable reactive subsurface barrier has been defined as:

> "...an emplacement of reactive materials in the subsurface designed to intercept a contaminant plume, provide a flow path through the reactive media, and transform the contaminant(s) into environmentally acceptable forms to attain remediation concentration goals downgradient of the barrier." (Powell et al., 1998)

During the past ten years, PRB technologies have been investigated at all scales, from batch and column studies to full field-scale implementations, and tested for efficacy with a variety of contaminants. They have proven highly effective and seen extensive implementation for the dechlorination of chlorinated hydrocarbons and the reductive precipitation of chromate (Cr^{6+} as CrO_4^{2-}), in particular.

To date, more than 40 PRBs have been installed in the field to restore ground-water quality. Because of this a track record for these systems is beginning to be established; therefore, it is now time to move PRB systems from the "innovative" technology list into the toolbox of standard technologies that are routinely considered for remediation. With this move comes the need to develop effective means of measuring cost versus performance of these systems relative to the other standard technologies, such as P&T.

Some cost analyses of individual PRB systems have been done and in some cases compared to either P&T systems already in operation at the site (O' Hannesin, 1998) or proposed (U.S. DOD, 1999; Gavaskar et al., 2000) for the site. The intent of this document is to further document PRB costs and assess cost-effectiveness versus standard P&T technologies. Twenty separate PRB sites were used for the study, along with estimates for full-scale implementations at two pilot sites. The sites vary significantly in many respects, making a direct comparison between them for total cost potentially misleading. In addition to site-specific differences, such as hydrology and geology, some PRBs are pilot-scale studies, some are full-scale remediations, and some of each of these two types have been used for PRB research purposes. Costs have been broken down into as much level of detail as is available. This was done in an attempt to better understand what sorts of factors and considerations lead to an increase or a decrease in the overall costs relative to the same component at other sites. This breakdown also helps in the comparison of the PRB implementations at these sites to actual or potential P&T systems located within the same contaminated milieu. Assumptions for these analyses included ongoing remediation for a period of 30 years (for both the PRB and the P&T remediations), with replacement of the reactive media within the PRBs at ten-year intervals (based on reactive inorganic ground-water constituents). Potential alternatives to replacement are discussed later in this document.

The cost detail for the PRBs was broken down into four general categories: (1) site characterization, (2) design, (3) construction, and (4) operation and maintenance. A fifth cost category would be needed when PRBs are used to remediate radionuclides; i.e., the disposal of spent reactive materials. This is not a focus of this document. Within each of these general categories, cost was broken down into as much detail as was available from the published information and the contacts for the sites. However, for several of the sites the information was either not available or not forthcoming. In some instances, concern was expressed that the information was confidential and the client would not want it to be released. In others, it seems that the information was simply never considered at a finer level of detail than these four broad categories. Some site contacts did not respond to our information requests. In these circumstances other sources were sought, and occasionally located. Nevertheless, less detailed information is available for some of the sites than is desirable from the standpoint of a comprehensive cost analysis.

Comparisons to (P&T) systems that were either implemented at or considered for these PRB sites are presented. Some P&T data from other reports are also used as comparators to the PRB costs. The PRB and P&T unit values (e.g., dollars per 1000 gallons treated) are developed and compared in a way that seems more appropriate for the PRB technology than has been done in earlier reports.

In brief, it was found that the PRB implementations were sometimes more and sometimes less expensive to construct than P&T systems. When periodic reactive media maintenance costs were excluded, the PRB systems were found considerably cheaper to maintain for the same level of effectiveness or better. However, the lack of information, in particular on the longevity of reactive media in PRB systems, along with no proven maintenance methods other than replacement, cause PRB cost estimates to be potentially highly inaccurate.

2. Purpose of the Report

Long considered the standard for ground-water remediation, P&T technologies have come under increasing scrutiny during the past decade. Although still useful under appropriate circumstances, e.g., effecting some cleanup or containment of contaminant hot-spots, such as free product, the limitations of pumping and treating ground water often render it an imperfect technology for addressing contaminant plumes. These limitations have been addressed elsewhere in general (Keely, 1989; NRC, 1994) and in the context of the usefulness of PRBs specifically (Powell and Powell, 1998). However, there is a wealth of information available, including cost and design data, for P&T systems and it is both logical and inevitable that they are considered as possible remedial actions for sites with contaminated ground water.

However, due to a heightened awareness of P&T technology limitations, it became increasingly important to evaluate methods that were not subject to, or rendered ineffective by, these same factors. Slightly over a decade ago, researchers at the University of Waterloo (Gillham, 1995) developed a technology that overcame many of the P&T limitations; i.e., using permeable barriers of reactive media in the subsurface to intercept contaminant plumes. During the ensuing decade, PRB technology has been thoroughly investigated both in laboratory and field settings and is being successfully used at many contaminated sites. Initially, many believed that PRB technology would be much cheaper than P&T both in capital costs and annual operation and maintenance (O&M) costs. As the number of installations has grown, it has become increasingly apparent that the capital costs of PRB installation are very dependent upon site characteristics and plume dimensions. This is in addition to an added level of site characterization that is usually needed to ascertain proper placement and design of the PRB. In several instances, it has been found that capital costs of PRB installation exceed actual capital costs, or estimates, for P&T systems.

Nonetheless, even with higher capital costs, PRBs have been assumed to have much lower O&M costs than P&T systems. Recently, however, the lower O&M costs have also been questioned. One report from U.S. EPA compared ground-water cleanup costs at 28 sites, including three sites with PRB installations (U.S. EPA, 1999a). This report seems to indicate that both the PRB capital costs and O&M costs, expressed as unit costs, are actually in the middle to high end of the cost range relative to P&T systems. Such reports have caused concerns about whether the cost savings of PRB systems are as important as once believed (RTDF, 2000). This is particularly so now that the potential need for periodic reactive media replenishment or replacement has become known.

This report has been developed to further document PRB costs and attempt to determine the factors that have caused PRB O&M costs to equal or exceed those of P&T systems as they are being reported, even when media maintenance is not being considered in those reports. It was found that both the capital and O&M costs of PRB systems vary widely, due to differences in site characteristics. However, it appears that reported unfavorable O&M comparisons (exclusive of media maintenance) with P&T are largely due to the methods being used for the unit comparisons. Additionally, there are other intangible benefits to using PRB technology that do not often show up in cost comparisons.

3. PRB Sites Evaluated

Table 1 provides some basic information about the PRB sites that were the subjects of this study. It provides the type of PRB, in a general sense, whether the installation was a continuous trench, a funnel-and-gate system (F&G), or installed using hydraulic fracturing of bedrock. However, it should be noted that there are numerous methods for creating a continuous trench. These include the use of continuous trenching machines; the use of mandrels that are filled with reactive media, driven into the subsurface (where one drive overlaps the previous to maintain continuity) then removed; the installation of sheet pilings on either side of a zone to be trenched and filled; the use of guar gum gels to support open trenches; and many others. Additionally, the choice of impermeable materials to use for the funnel sections of F&G installations, as well as the means of installing the gates, can also vary widely. Information about such procedures at these sites is generally available elsewhere (http://www.rtdf.org/; U.S. EPA, 1999b) and these techniques are not the focus of this report. It is important to realize, however, that costs can be significantly affected by the PRB installation procedures chosen.

Table 1 also provides information about the reactive media installed at these sites, the tonnage that was used and the contaminants being treated. Zero-valence state iron, i.e., iron metal (ZVI, Fe(0), or Fe^0), is the most commonly used reactive media to date in PRB installations and is incorporated into 19 of the 20 sites included in this report. Zero-valent iron has been shown to be extremely effective for degrading chlorinated hydrocarbons, causing the PCE -> TCE -> DCE -> VC -> C_2H_2 reductive dechlorination series of reactions to occur rapidly in response to electrons provided by the iron. The mechanisms and intermediate transitional species of these reactions, as well as the fact that they do not generally occur with 100% stepwise dechlorination, are still being studied and are beyond the scope of this document, but have been discussed in other publications (Powell et al., 1998; Roberts et al., 1996). ZVI is also extremely effective for reductively precipitating Cr(VI) as chromate (CrO_4^{2-} or $HCrO_4^-$) to Cr(III) and immobilizing it in the subsurface (Powell

Table 1. Basic PRB Site Information

Site	PRB Type	Reactive Material	Mass, Tons	Treated Contaminants	PRB Scale	On-Site P&T?	Research Site?
USCG Support Center	Trench	Fe(0)	450	TCE; Cr(VI)	Full-scale	Estimated	Yes
Intersil Site	F&G	Fe(0)	220	TCE; c-1,2-DCE; VC; Freon 113	Full-scale	Yes	No
Watervliet Arsenal	Trench	Fe(0)	166	PCE; TCE; cDCE; tDCE; VC	Pilot-scale	Estimated	No
Moffett Federal Airfield	F&G	Fe(0)	75	TCE; 1,2-DCE; PCE	Pilot-scale	0	Yes
Somersworth Landfill SF Site	Trench	Fe(0)	3552	PCE; TCE; cDCE; VC	Full-scale	Estimated	No
Dover AFB, DE	F&G	Fe(0)	59	PCE; TCE; DCE	Pilot-scale	0	Yes
Kansas City Plant, MO	Trench	Fe(0)	650	TCE; 1,2-DCE; VC	Full-scale	Yes	No
Aircraft Maintenance, OR	F&G	Fe(0)	324	PCE, TCE	Full-scale	No	No
Caldwell Trucking, NJ	Hydr. Frac./Perm. Infill	Fe(0)	250	TCE	Full-scale	ND	No
Former Manufacturing, Fairfield, NJ	Trench	Fe(0)	720	1,1,1-TCA; PCE; TCE	Full-scale	Estimated	No
Industrial Site, Coffeyville, KS	F&G	Fe(0)	70	TCE; 1,1,1-TCA	Full-scale	ND	No
Industrial Site, NY	Trench	Fe(0)	742	TCE; cDCE; VC	Full-scale	Estimated	No
Industrial Site, SC	Trench	Fe(0)	400	TCE; cDCE; VC	Full-scale	ND	No
Nickel Rim, Ontario	Trench	Organic Matter	425	Ni; Fe; SO4	Full-scale	No	No
Cape Canaveral, FL	Trench	Fe(0)	205	TCE; DCE; VC	Pilot-scale	ND	Yes
MMR CS-10 Plume, MA	Hydr. Frac./Perm. Infill	Fe(0)	49	PCE; TCE	Pilot-scale	ND	No
Pease AFB, NH	Trench	Fe(0)	360	TCE; cis-1,2-DCE; VC	Full-scale	ND	No
Vancouver, Canada	Trench	Organic Matter	0	Cu, Zn, Cd, Ni	Pilot-scale	ND	No
Warren AFB Spill Site 7, WY	Trench	Fe(0)	1750	TCE, DCE, VC	Full-scale	ND	No
London, Ontario	Trench	Oxygen furnace slag	400	Phosphate	Full-scale	ND	No
Moffett, Full-Scale Est.	F&G	Fe(0)	2518	TCE; 1,2-DCE; PCE	Full-scale	Estimated	No
Dover, AFB Full-Scale Est.	F&G	Fe(0)	108	PCE; TCE; DCE	Full-scale	Estimated	No

et al., 1995; Blowes et al., 1997). It should be realized that many of the sites reporting the use of ZVI have mixed it with pea gravel or sand to maintain high hydraulic conductivity in the PRB and to accommodate construction methods. Others have included pyrite or other materials to effect some sort of chemical modification prior to or during the reactions with the ZVI. Information about these modifications is also generally available elsewhere. Of the 20 PRB sites, three of them are exclusively treating metals and/or inorganic compounds, and they are using organic matter (to remediate Ni, Fe, sulfate) or oxygen furnace slag (to remediate phosphate).

A factor influencing the apparent costs of a site is whether or not a full-scale or a pilot-scale PRB technology is implemented. Fourteen of the sites included in this study are operating full-scale PRB implementations. Six are pilot-scale systems that are, or have been, operated, and two are estimates of full-scale systems based on the results of the pilot-scale PRBs at the sites. It was decided to include the two full-scale estimates in this analysis because they have been very thoroughly planned and analyzed for cost, apparently better than many of the operating systems. They are also based on the results of pilot tests at the same site that give the estimates an added degree of credibility. Another factor that could influence the costs is whether or not the PRB was used merely as a remedial technology or whether active PRB research was conducted at the site. Most of the sites have had some additional effort made towards understanding the usefulness and effectiveness of the PRB installations, beyond that usually done for a toolbox remedial technology. Four of the sites are clearly identified as research sites. At these locations activities far beyond the scope of a traditional remedial application were carried out in order to better understand PRB technology.

4. Information Acquisition and Methodology

Information was gleaned from several sources in the process of compiling information for this report. These sources included the Internet, published reports, contacts for the specific sites, and a visit to PRB technology license vendors such as the University of Waterloo and EnviroMetal Technologies, Inc., in Waterloo, Ontario, Canada.

4.1. Online and print information sources

A large amount of information about PRB technology in general, as well as site-specific applications of the technology, is now available on the Internet. These sources include those established by federal and state government, specifically for providing information on remediation techniques, as well as other private and corporate sites. Among the better resources are:

The Groundwater Remediation Technologies Analysis Center (http://www.gwrtac.org/)

The Remediation Technologies Development Forum (http://www.rtdf.org/)

The Hazardous Waste Clean-up Information Web Site (http://www.clu-in.org/)

The Federal Remediation Technologies Roundtable (http://www.frtr.gov/)

Internet data were also searched and mined using Sherlock® technology (Apple Computer, Inc.) to locate less obvious sources of information. Much of the detailed PRB and site information available on the Internet is available in Portable Document Format® (PDF, Adobe, Inc.) and many documents of this sort were downloaded and searched for site information with a particular focus on cost.

Numerous books and reports about PRB systems have been published by EPA, DOE, DOD and other governmental bodies as well as private entities during the past several years. Many of these were also obtained and searched for materials and information relevant to the content of this report.

4.2. Telephone contacts

The RTDF website provides PRB site summaries that briefly describe the implementation and cost of PRB installations. These summaries typically include contact information for the sites. Contacts were attempted for all of the sites included in this report via either telephone or email, usually both, or by visitation. Unfortunately, several of the contacts did not respond to our inquiries, limiting information about their sites to what has been published. Those who did respond generally provided valuable information that was unattainable via other methods.

4.3. Emailed forms

Detailed information acquisition forms were emailed to all site contacts. These were provided for their use in responding to our queries about their PRB sites. The level of detail requested in these forms was very high and it was not anticipated that a single site contact would have answers for all the questions that were asked. These forms were accompanied by an explanation of the purpose of the questionnaire and the importance of the contact's information for accomplishing the goals of this report. The contacts were also informed of our awareness that they would probably not be able to answer all of the questions. An example of this form is found in Appendix A of this report. Although several contacts returned the form, few of them filled it out at even the most basic level of costs (e.g., subtotals for site characterization, design, construction, operation and maintenance). Several provided only the cost of the reactive media along with a total cost or total construction cost. However, a few of the contacts fully completed the forms. We are grateful for the efforts of all those who responded, especially those who attempted to fully complete the forms.

4.4. Vendor visits

In order to acquire more information about the PRB systems and their costs, visits were made to the University of Waterloo and EnviroMetal Technologies, Inc. (ETI), both in Waterloo, Ontario, Canada. These entities are the patent-holders and licensers of the PRB technology as it applies to ZVI for remediation of organic compounds and certain PRB technologies for inorganic contaminants, such as trace metals. A great deal of site-specific information was obtained during these visits as well as leads on additional PRB manuscripts and contacts.

4.5. Information quality

During the investigation of PRB information for this report it was often found to be very difficult to categorize cost data in a consistent manner across sites, based upon the information obtained. Different sites often had very different approaches to organizing their cost information and occasionally seemed to have very little information at all that could be made public. In addition to such difficulties, we found numerous inconsistencies between reported costs and characteristics for the same site and typographical errors in the tables and text of some documents. We have attempted to confirm the correct values for such inconsistencies but, in a document of this kind, it is impossible to verify that all the values used in the tables and analyses are 100% accurate. To compensate for variability in cost category reporting we have attempted, whenever possible, to divert site costs into categories that seemed appropriate for a comparison of this type. We strongly urge site managers to develop standardized cost reporting techniques that allow better, more readily comparable and accessible cost information, perhaps following the guidelines that have been recently recommended by the Federal Remediation Technologies Roundtable (FRTR - U.S. EPA, 1998).

4.6. Information storage and organization

The nature of this project required the acquisition and storage of large quantities of information that had to be updated as better or more complete information was obtained. To manage this information, six custom databases were developed using FileMaker Pro® (FileMaker, Inc.). These six included databases for (1) site information, (2) site contacts, (3) captured information references, (4) site characterization, (5) design/construction/licensing, and (6) monitoring/O&M. These databases were relational, with the relationships linked via the PRB site name. Many of the calculations were done within the databases, allowing automatic updating whenever new values were entered into the databases. Scripts were then written in FileMaker® to automatically export chosen sets of database records to Edition files. Microsoft Excel® (Microsoft, Inc.) was then "subscribed" to these Editions, and was automatically updated whenever new data were entered into the databases and the exporting scripts run. Tables and graphs were generated within Excel® and imported into Microsoft Word® as linked objects for the final output. This approach speeded data throughput and should have minimized typographical errors since data were entered, almost exclusively, into FileMaker Pro® and carried all the way through to the final tables and charts as described.

4.7. Cost parameter breakdown

Although an attempt was made to determine PRB costs to a greater level of detail, practical considerations required that, in general, costs be subtotaled into four major cost categories whenever possible. These categories are site characterization, design, construction, and O&M (to include monitoring costs). In addition to these categories, the tables in this report include stated costs and the approximate cost to establish the PRB and operate it during its first year. An attempt was made to acquire PRB licensing costs but these were confidential or unobtainable for most of the sites. The rule-of-thumb for the licensing cost is 15% of the cost of reactive media and construction for the University of Waterloo technologies (John Vogan, ETI, personal communication). This can vary due to several factors, including PRB size.

Costs for P&T systems were not broken down into categories beyond total cost and annual O&M cost. This information is available elsewhere and a reiteration was neither desired nor necessary for purposes of this document. An attempt was made, however, to ascertain which of the PRB sites (a) had P&T systems installed either previously or concurrently or (b) had estimated P&T costs as part of the remedial feasibility studies. Of the 22 sites included in this report, two have had onsite P&T systems and seven have had P&T estimates made at the sites.

5. Economic Data for the Permeable Reactive Barrier Sites

5.1. Stated versus calculated costs for the PRB sites

Stated costs for 21 of the 22 PRB sites discussed in this document are provided in Table 2. The "Stated Costs" are the costs that have been typically reported to the public via web sites, reports, presentations and manuscripts. Stated costs for 15 of the sites are from the publication "Field Applications of In Situ Remediation Technologies: Permeable Reactive Barriers" (U.S. EPA, 1999b) and the corresponding RTDF web site (http://www.rtdf.org). These are referred to in Table 2, simply as RTDF. The sources for the stated costs for the remaining sites, when available, are also referenced in Table 2.

In addition to stated costs, a "Calculated Approximate 1st Year Cost" was developed for this report. This cost includes, to our ability to determine and/or obtain them, the costs of all PRB-related activities required to get the system into the ground and operate it for its first year. To obtain the approximate 1st year cost the following cost categories were summed:

1. Site characterization costs
2. Design costs
3. Construction costs
4. Initial license and report fees
5. Monitoring equipment costs
6. Annual monitoring costs
7. Annual reporting costs
8. Costs of monitoring wells added for the PRB
9. Other initial monitoring/sampling costs
10. Other annual O&M costs

Table 2. PRB Stated Costs and Sources

Site	Stated Cost Source	Stated PRB Cost
USCG Support Center	RTDF	$ 500,000
Intersil Site	RTDF	$ 1,000,000
Watervliet Arsenal	RTDF	$ 387,000
Moffett Federal Airfield	RTDF	$ 540,000
Somersworth Landfill SF Site	O'Hannesin, 1998	$ 2,100,000
Dover AFB, DE	RTDF	$ 800,000
Kansas City Plant, MO	RTDF	$ 1,500,000
Aircraft Maintenance, OR	RTDF	$ 600,000
Caldwell Trucking, NJ	RTDF	$ 1,120,000
Former Manufacturing, Fairfield, NJ	RTDF	$ 875,000
Industrial Site, Coffeyville, KS	RTDF	$ 400,000
Industrial Site, NY	RTDF	$ 797,000
Industrial Site, SC	RTDF	$ 400,000
Nickel Rim, Ontario	RTDF	$ 30,000
Cape Canaveral, FL	RTDF	$ 809,000
MMR CS-10 Plume, MA	RTDF	$ 160,000
Pease AFB, NH	Gavaskar et al., 2000	$ 300,000
Vancouver, Canada	Personal Comm.	$ 25,000
Warren AFB Spill Site 7, WY	Heneman et al., 2000	$ 2,350,000
London, Ontario	NA	$ -
Moffett, Full-Scale Est.	U.S. DOD, 1999	$ 4,910,942
Dover, AFB Full-Scale Est.	Gavaskar et al., 2000	$ 947,000

It should be noted that values for many of these cost categories were not available for several of the sites, therefore the 1st year value is the sum of fewer of these categories. In many cases, the overall cost is still the same or very close, because the sites simply did not break down costs into subcategories. For example, some sites included characterization in the design costs or the design costs in the construction category.

Table 3 provides the stated cost, the calculated approximate 1st year cost, the difference between the two, the calculated construction cost (calculated from data obtained) and the difference between the stated cost and the construction cost. The data for stated cost, 1st year cost and construction cost, are graphically depicted in Figure 1. For some sites, 1st year cost amounted to a significantly higher dollar amount than the stated cost for the PRB site. In a few of these instances, these stated costs were closer to the values for "Calculated Construction Cost" (discussed in a later section of this report) which would exclude many of the other PRB costs. This illustrates that caution is warranted when stated costs are accepted unequivocally without regard to what is included in these costs. This further supports the need for standardized cost reporting techniques (FRTR - U.S. EPA, 1998).

For three of the sites we were simply unable to obtain any cost breakdown data and have only the stated costs available. These sites were:

1. Caldwell Trucking, New Jersey
2. Massachusetts Military Reservation, CS-10 Plume, Massachusetts
3. Vancouver, Canada

5.2. PRB site characterization costs

The site characterization database and the information request form contained entries for ten categories of site characterization costs. However, site characterization costs seemed to be the most poorly tracked cost information across the studied sites. Of the 11 sites for which a total site characterization cost was obtained, only three reported any breakdown and these reported only one site characterization category besides "other." Therefore, no table of site characterization breakdowns is included in this report.

5.3. PRB design costs

Five categories of PRB design costs were sought for this study. These were:

1. Tests, data, and statistical analysis costs
2. Modeling costs

Table 3. Calculated PRB Costs Relative to Stated PRB Costs

Site	Stated PRB Cost	Calculated Approximate 1st Yr. Cost	Stated Cost Minus 1st Yr. Cost	Calculated Construction Cost	Stated Cost Minus Construction
USCG Support Center	$ 500,000	$ 1,070,000	$ (570,000)	$ 500,000	$0
Intersil Site	$ 1,000,000	$ 1,005,000	$ (5,000)	$ 656,000	$344,000
Watervliet Arsenal	$ 387,000	$ 387,000	$ -	$ 274,000	$113,000
Moffett Federal Airfield	$ 540,000	$ 742,375	$ (202,375)	$ 377,375	$162,625
Somersworth Landfill SF Site	$ 2,100,000	$ 2,515,000	$ (415,000)	$ 2,100,000	$0
Dover AFB, DE	$ 800,000	$ 739,000	$ 61,000	$ 358,000	$442,000
Kansas City Plant, MO	$ 1,500,000	$ 1,490,000	$ 10,000	$ 1,240,000	$260,000
Aircraft Maintenance, OR	$ 600,000	$ 1,135,000	$ (535,000)	$ 700,000	($100,000)
Caldwell Trucking, NJ	$ 1,120,000	$ -		$ -	-
Former Manufacturing, Fairfield, NJ	$ 875,000	$ 900,000	$ (25,000)	$ 725,000	$150,000
Industrial Site, Coffeyville, KS	$ 400,000	$ 400,000	$ -	$ 400,000	$0
Industrial Site, NY	$ 797,000	$ 1,000,000	$ (203,000)	$ 1,000,000	($203,000)
Industrial Site, SC	$ 400,000	$ 400,000	$ -	$ 356,000	$44,000
Nickel Rim, Ontario	$ 30,000	$ 120,000	$ (90,000)	$ 35,000	($5,000)
Cape Canaveral, FL	$ 809,000	$ 760,150	$ 48,850	$ 729,250	$79,750
MMR CS-10 Plume, MA	$ 160,000	$ -		$ -	-
Pease AFB, NH	$ 300,000	$ 1,250,000	$ (950,000)	$ 550,000	($250,000)
Vancouver, Canada	$ 25,000	$ -		$ -	-
Warren AFB Spill Site 7, WY	$ 2,350,000	$ 2,350,000	$ -	$ 2,350,000	$0
London, Ontario	$ -	$ 29,700		$ 26,700	-
Moffett, Full-Scale Est.	$ 4,910,942	$ 4,983,220	$ (72,278)	$ 4,618,122	$292,820
Dover, AFB Full-Scale Est.	$ 947,000	$ 1,095,000	$ (148,000)	$ 582,000	$365,000

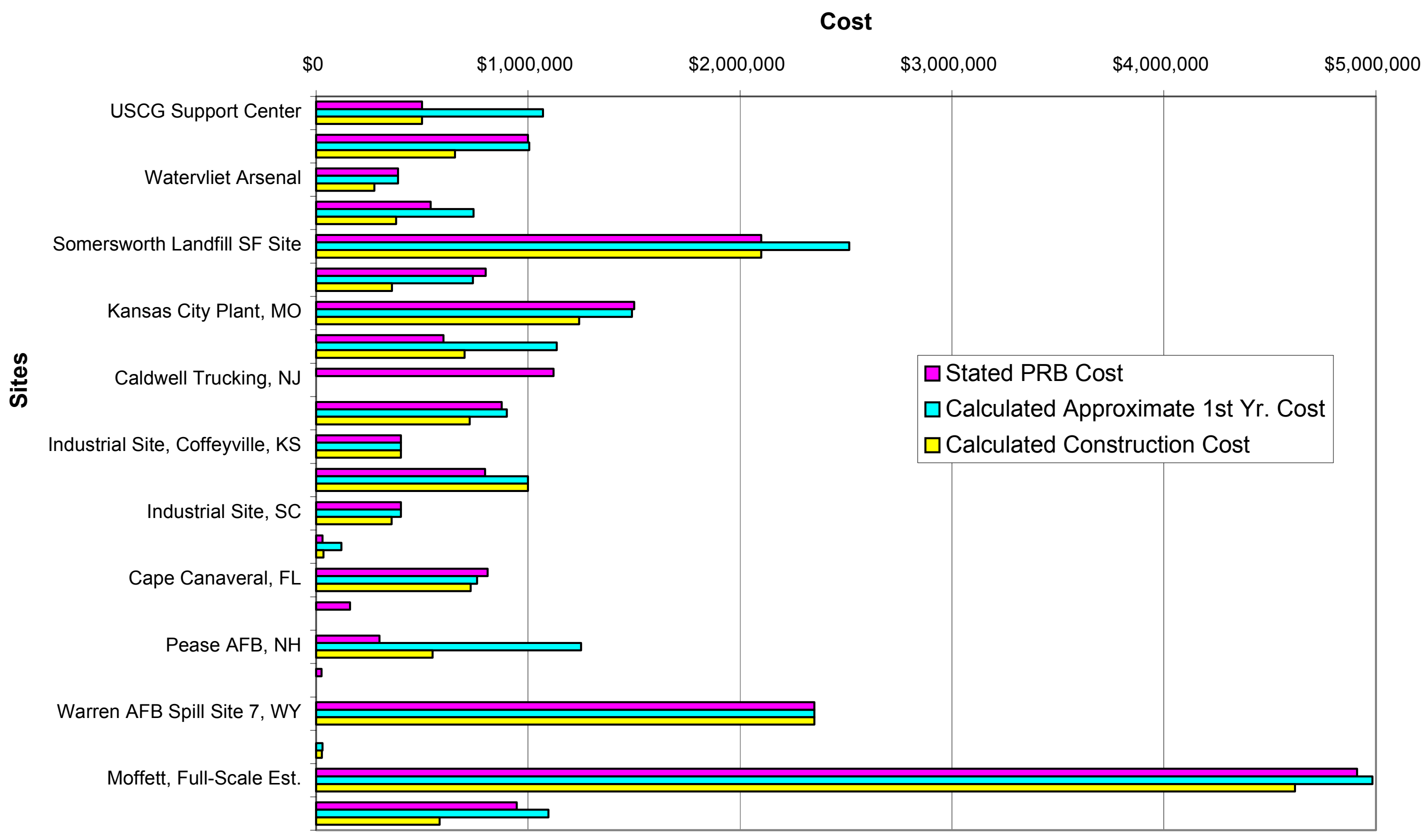

Figure 1. Bar plot of Stated Cost, Calculated Approximate 1st Year Cost, and Calculated Construction Cost for the PRB sites.

3. Alternatives comparison costs
4. Design plans/architectural drawing costs
5. Other design costs

In the design section of the database, the "other" field was used to contain data listed by the sites as "other design costs" as well as for containerizing the "total design cost" when that was all that was reported. The "Design Total" field provided the summation of all the other categories including "other." This approach was also used in the other sections of the databases. Design costs were obtained, or calculated, for 14 of the 22 sites in this study, although only eight of them had information broken down into one or more specific categories besides "other." Table 4 provides information on the design cost breakdown for the PRB sites. Figures 2 and 3 show the percentage breakdown for design costs from the two sites having data in multiple categories, USCG Support Center, North Carolina, and Somersworth Landfill, New Hampshire, respectively.

5.4. PRB construction costs

Construction costs were sought for the sites in ten categories. These were:

1. Reactive media costs
2. Funnel costs
3. Gate costs
4. Trenching costs
5. Mobilization costs
6. Equipment costs
7. Health and safety costs
8. Installation/labor costs
9. Materials disposal costs
10. Other construction costs

Some level of construction cost breakdown was obtained for 13 of the 22 sites. Table 5 provides this information. Eleven of the sites have data in two or more construction categories beyond "other."

Table 4. Design Cost Breakdown for the PRB Sites

Site	Tests/Stats	Modeling	Alternatives Comparison	Plans/ Drawings	Other	Design Total
USCG Support Center	$ 25,000	$ 10,000	$ -	$ 35,000	$ 75,000	$ 145,000
Intersil Site	$ -	$ -	$ -	$ 100,000	$ 154,000	$ 254,000
Watervliet Arsenal	$ -	$ -	$ -	$ -	$ 113,000	$ 113,000
Moffett Federal Airfield	$ 75,000	$ -	$ -	$ -	$ 100,000	$ 175,000
Somersworth Landfill SF Site	$ 100,000	$ 40,000	$ 100,000	$ 100,000	$ -	$ 340,000
Dover AFB, DE	$ 100,000	$ -	$ -	$ -	$ 100,000	$ 200,000
Kansas City Plant, MO	$ -	$ -	$ -	$ -	$ 100,000	$ 100,000
Aircraft Maintenance, OR	$ -	$ 15,000	$ 10,000	$ -	$ 10,000	$ 35,000
Caldwell Trucking, NJ	$ -	$ -	$ -	$ -	$ -	$ -
Former Manufacturing, Fairfield, NJ	$ -	$ -	$ -	$ -	$ 150,000	$ 150,000
Industrial Site, Coffeyville, KS	$ -	$ -	$ -	$ -	$ -	$ -
Industrial Site, NY	$ -	$ -	$ -	$ -	$ -	$ -
Industrial Site, SC	$ -	$ -	$ -	$ -	$ 44,000	$ 44,000
Nickel Rim, Ontario	$ 30,000	$ -	$ -	$ -	$ -	$ 30,000
Cape Canaveral, FL	$ 30,900	$ -	$ -	$ -	$ -	$ 30,900
MMR CS-10 Plume, MA	$ -	$ -	$ -	$ -	$ -	$ -
Pease AFB, NH	$ -	$ -	$ -	$ -	$ 200,000	$ 200,000
Vancouver, Canada	$ -	$ -	$ -	$ -	$ -	$ -
Warren AFB Spill Site 7, WY	$ -	$ -	$ -	$ -	$ -	$ -
London, Ontario	$ -	$ -	$ -	$ -	$ -	$ -
Moffett, Full-Scale Est.	$ 75,000	$ -	$ -	$ 100,000	$ -	$ 175,000
Dover, AFB Full-Scale Est.	$ 50,000	$ -	$ -	$ -	$ 100,000	$ 150,000

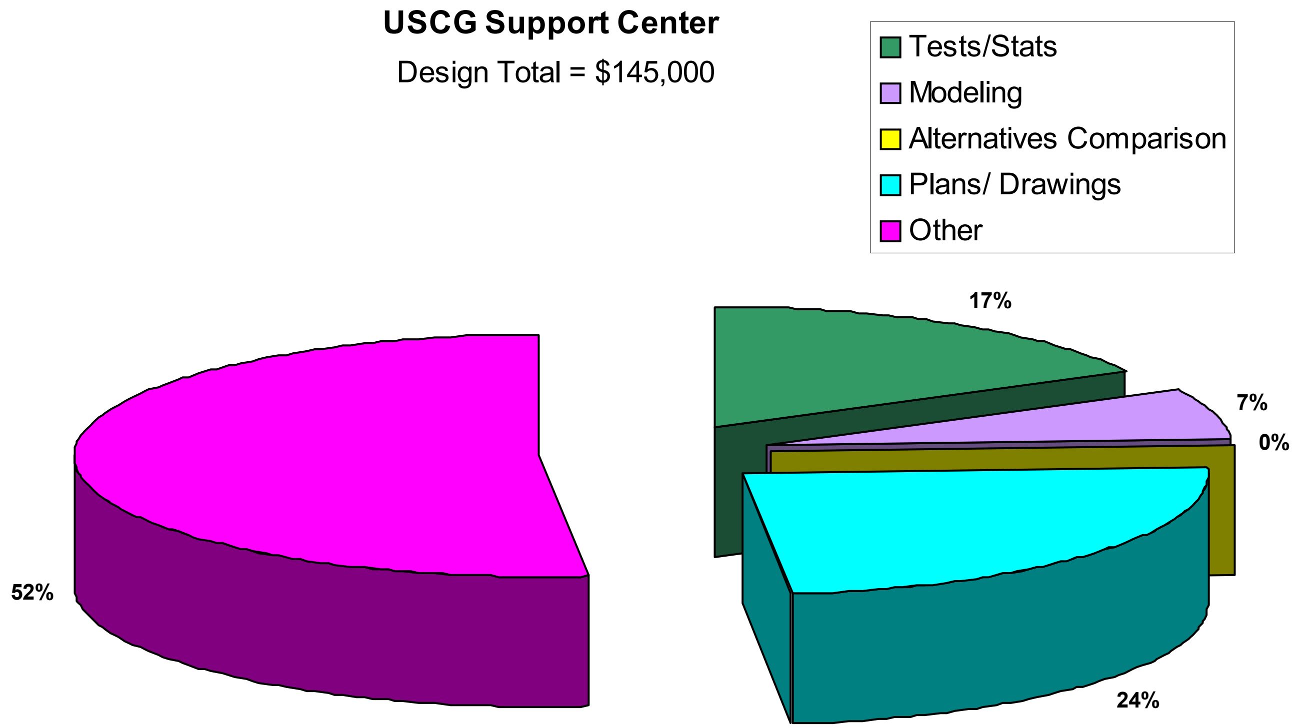

Figure 2. PRB design cost breakdown for USCG Support Center, North Carolina.

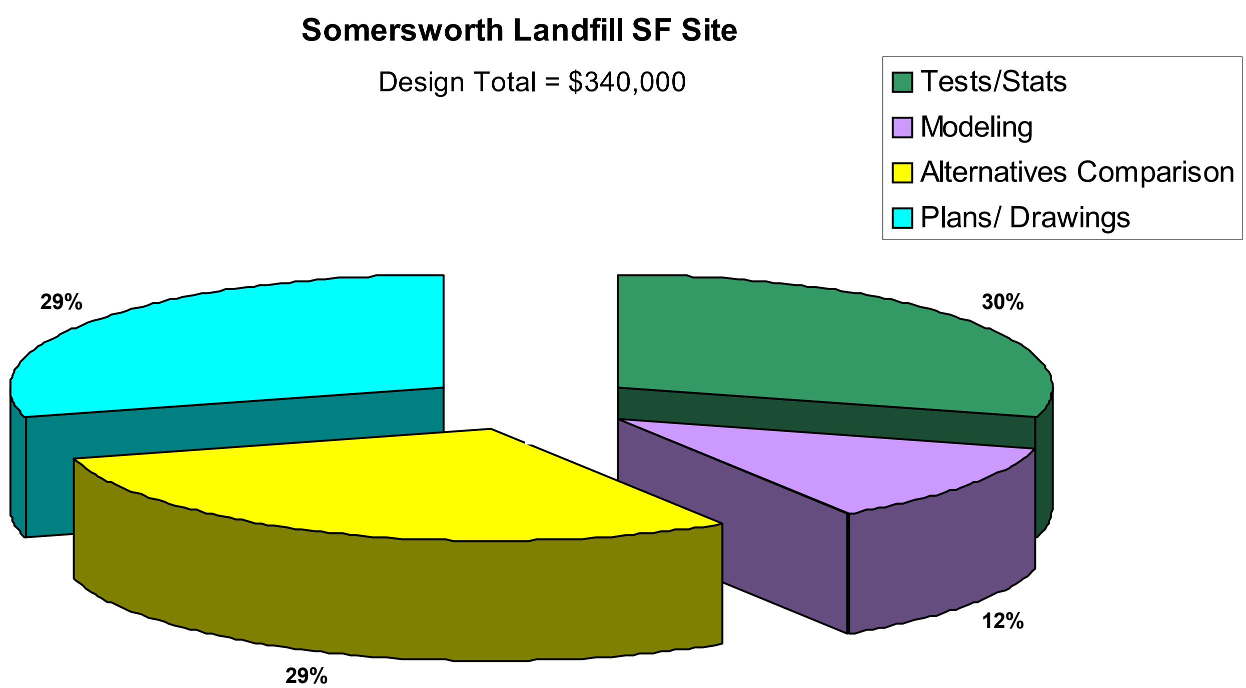

Figure 3. PRB design cost breakdown for Somersworth Landfill, New Hampshire.

Table 5. Construction Cost Breakdown for the PRB Sites

Site	Reactive Media	Funnels	Gates	Trench	Mobilization	Equipment	Health & Safety	Installation & Labor	Materials Disposal	Other	Construction Total
USCG Support Center	$ 200,000	$ -	$ -	$ 150,000	$ -	$ -	$ -	$ -	$ 150,000	$ -	$ 500,000
Intersil Site	$ 170,000	$ 178,000	$ 100,000	$ -	$ -	$ -	$ -	$ 75,000	$ 50,000	$ 65,000	$ 638,000
Watervliet Arsenal	$ 87,360	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 169,640	$ 257,000
Moffett Federal Airfield	$ 39,375	$ 60,000	$ 100,000	$ -	$ -	$ -	$ -	$ -	$ -	$ 133,000	$ 332,375
Somersworth Landfill SF Site	$ 1,200,000	$ -	$ -	$ 750,000	$ 150,000	$ -	$ -	$ -	$ -	$ -	$ 2,100,000
Dover AFB, DE	$ 47,000	$ 51,000	$ 133,000	$ -	$ 38,000	$ -	$ -	$ -	$ 10,000	$ 17,000	$ 296,000
Kansas City Plant, MO	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 220,000	$ 980,000	$ 1,200,000
Aircraft Maintenance, OR	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 650,000	$ -	$ 50,000	$ 700,000
Caldwell Trucking, NJ	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Former Manufacturing, Fairfield, NJ	$ 359,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 366,000	$ 725,000
Industrial Site, Coffeyville, KS	$ 50,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 350,000	$ 400,000
Industrial Site, NY	$ 358,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 642,000	$ 1,000,000
Industrial Site, SC	$ 133,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 223,000	$ 356,000
Nickel Rim, Ontario	$ 15,000	$ -	$ -	$ -	$ -	$ -	$ -	$ 15,000	$ -	$ 5,000	$ 35,000
Cape Canaveral, FL	$ -	$ -	$ -	$ -	$ 115,000	$ -	$ -	$ 614,250	$ -	$ -	$ 729,250
MMR CS-10 Plume, MA	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Pease AFB, NH	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 500,000	$ 500,000
Vancouver, Canada	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Warren AFB Spill Site 7, WY	$ 600,000	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,400,000	$ -	$ 200,000	$ 2,200,000
London, Ontario	$ 8,000	$ -	$ -	$ 6,700	$ 4,000	$ -	$ -	$ 5,000	$ -	$ -	$ 23,700
Moffett, Full-Scale Est.	$ 881,300	$ 1,156,164	$ 966,610	$ 557,812	$ 39,693	$ -	$ 271,047	$ -	$ 404,359	$ 295,137	$ 4,572,122
Dover, AFB Full-Scale Est.	$ 48,000	$ 102,000	$ 266,000	$ -	$ 60,000	$ -	$ -	$ -	$ -	$ 44,000	$ 520,000

5.5. Major cost/capital cost component summaries

Table 6 summarizes and totals the cost categories of site characterization, design, and construction for the PRB sites. Figure 4 illustrates these major cost components for sites with data in more than one category. In terms of true “capital costs,” per our understanding of Federal Remediation Technologies Guidelines (FRTR - U.S. EPA, 1998), the capital cost would exclude site characterization but would include licensing fees for the technology and reports to, and interactions with, regulatory agencies. Table 7 includes these costs, for the few sites where the data could be obtained, along with the design, construction, and total capital cost summation. It should be noted that the capital costs in Table 7, and displayed graphically in Figure 5, are calculated from the design and construction costs which are themselves calculated from cost subcategories detailed in Tables 4 (design) and 5 (construction). Because of this there are no capital cost entries for the three sites for which cost breakdowns could not be obtained. It is possible that the “Stated Costs” for these sites are equivalent to the capital costs but, in the absence of additional information, these were not included in the table.

5.6. Operation and maintenance at the PRB sites

Annual operation and maintenance (O&M) costs were calculated or obtained from 10 of the 22 sites. O&M cost categories included:

1. Annual monitoring costs
2. Annual reporting costs
3. Other annual O&M costs

In addition to these annual costs, it is anticipated that the reactive media may require periodic replenishment or replacement in these PRB systems. Recent speculation has suggested periods of five to 10 years for the replenishment/ replacement cycle during a 30-year lifetime. When the reactive media is iron metal, this cycle may be at about 10-year intervals, although this could vary based upon ground-water chemistry and other site factors. The interval for replacing organic matter-based PRBs may be shorter, based upon recent results from the Nickel Rim site in Ontario (D. Blowes, personal communication). Because of reactive media maintenance or replacement, the annual O&M cost for PRBs might have a periodic jump relative to the routine annual O&M costs. This cost should be figured into the O&M future cost scenario when comparing PRBs to other technologies, such as P&T. Typically, PRBs will have relatively low annual O&M, including only monitoring and reporting costs, relative to more active remediation technologies. This is due to the passive nature of most PRB installations that rely on the natural hydraulic gradient of the ground water to move the contaminants through the reaction zone. P&T systems, on the other hand, are comprised of a number of actively working components, including pumps, valves, treatment trains, etc., that require ongoing maintenance, parts replacement, etc.

Because most PRB sites have been in the ground for less than five years, media maintenance costs remain a matter of great speculation. Research is ongoing to determine means of replenishing the media in situ, rather than fully replacing the media. Column and field investigations on iron-media PRBs have shown that the upgradient surface of the reactive zone is the most likely region for failure to occur, a direct result of the ongoing remedial reactions. If failure occurs it will probably be due to the formation of precipitates on the iron surfaces and in the voids between the iron granules. These precipitates can both lower the reactivity of the iron and reduce ground-water flow through the PRB. Since these depleted/altered/precipitated regions seem to extend for only a few centimeters into the PRB, at sites currently studied, the most likely mode for failure is flow blockage. This could cause diversion of contaminated waters over, under and around the PRB, reducing its remedial effect. These effects have been graphically illustrated and described (Powell et al., 1998). However, recent geochemical modeling studies, using site ground-water characteristics, have indicated only about 15% porosity reduction over a lifetime of 20 years (J. Vogan, personal communication; RTDF PRB Workshop). Should this prove accurate then, theoretically, iron maintenance might not be necessary over a 30 year PRB lifetime for some systems.

Various techniques are being proposed for replenishing and/or disrupting precipitate–cemented PRB surfaces in situ (M. Duchene, ETI, personal communication). Among these are:

1. Jetting the upgradient face of the PRB with water under high pressure;
2. Using solid-stem augers to agitate the upgradient face of the PRB;
3. Using ultrasound to break-up the precipitate on the upgradient face; and
4. Using a pressure wave hydraulic pulse method to break-up the precipitate.

These methods hope to avoid the actual replacement of the media that, in most cases, would be much more expensive. With the exception of ultrasound, field trials of these possible rejuvenation methods have not been completed and it can only be stated that these methods may prove to be successful.

Table 6. Major Cost Components for the PRB Sites

Site	Site Characterization	Design	Construction	Total
USCG Support Center	$ 150,000	$ 145,000	$ 500,000	$ 795,000
Intersil Site	$ -	$ 254,000	$ 638,000	$ 892,000
Watervliet Arsenal	$ -	$ 113,000	$ 257,000	$ 370,000
Moffett Federal Airfield	$ 100,000	$ 175,000	$ 332,375	$ 607,375
Somersworth Landfill SF Site	$ -	$ 340,000	$ 2,100,000	$ 2,440,000
Dover AFB, DE	$ 165,000	$ 200,000	$ 296,000	$ 661,000
Kansas City Plant, MO	$ 150,000	$ 100,000	$ 1,200,000	$ 1,450,000
Aircraft Maintenance, OR	$ 350,000	$ 35,000	$ 700,000	$ 1,085,000
Caldwell Trucking, NJ	$ -	$ -	$ -	$ -
Former Manufacturing, Fairfield, NJ	$ -	$ 150,000	$ 725,000	$ 875,000
Industrial Site, Coffeyville, KS	$ -	$ -	$ 400,000	$ 400,000
Industrial Site, NY	$ -	$ -	$ 1,000,000	$ 1,000,000
Industrial Site, SC	$ -	$ 44,000	$ 356,000	$ 400,000
Nickel Rim, Ontario	$ 25,000	$ 30,000	$ 35,000	$ 90,000
Cape Canaveral, FL	$ -	$ 30,900	$ 729,250	$ 760,150
MMR CS-10 Plume, MA	$ -	$ -	$ -	$ -
Pease AFB, NH	$ 400,000	$ 200,000	$ 500,000	$ 1,100,000
Vancouver, Canada	$ -	$ -	$ -	$ -
Warren AFB Spill Site 7, WY	$ -	$ -	$ 2,200,000	$ 2,200,000
London, Ontario	$ -	$ -	$ 23,700	$ 23,700
Moffett, Full-Scale Est.	$ 117,820	$ 175,000	$ 4,572,122	$ 4,864,942
Dover, AFB Full-Scale Est.	$ 215,000	$ 150,000	$ 520,000	$ 885,000

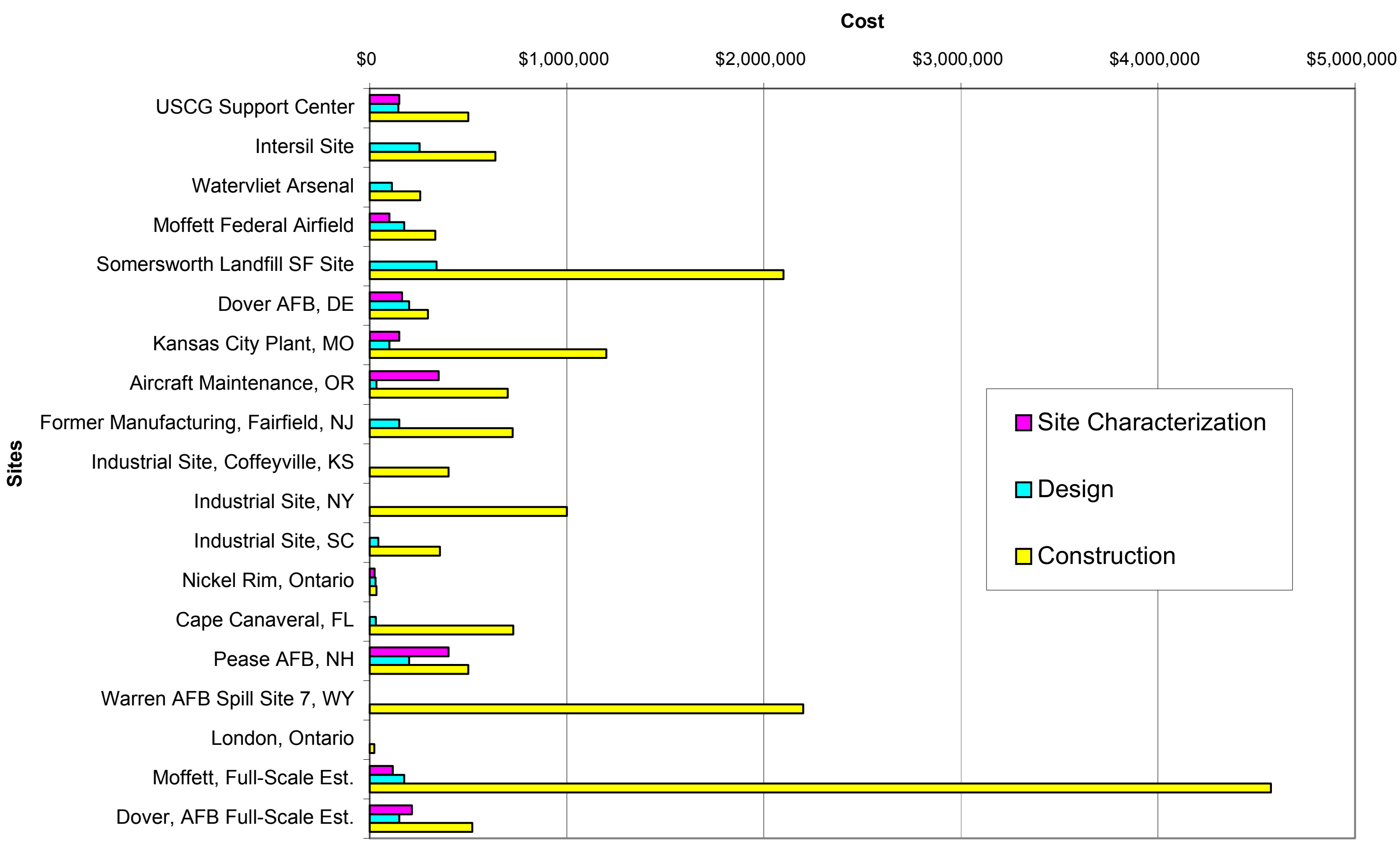

Figure 4. Major cost components for the PRB sites.

Table 7. PRB Site Capital Cost Summary

Site	Design	Construction	PRB License	Initial Reporting	Capital Cost Total
USCG Support Center	$ 145,000	$ 500,000	$ -	$ 190,000	$ 835,000
Intersil Site	$ 254,000	$ 638,000	$ -	$ -	$ 892,000
Watervliet Arsenal	$ 113,000	$ 257,000	$ 17,000	$ -	$ 387,000
Moffett Federal Airfield	$ 175,000	$ 332,375	$ -	$ -	$ 507,375
Somersworth Landfill SF Site	$ 340,000	$ 2,100,000	$ -	$ 75,000	$ 2,515,000
Dover AFB, DE	$ 200,000	$ 296,000	$ -	$ -	$ 496,000
Kansas City Plant, MO	$ 100,000	$ 1,200,000	$ -	$ -	$ 1,300,000
Aircraft Maintenance, OR	$ 35,000	$ 700,000	$ -	$ -	$ 735,000
Caldwell Trucking, NJ	$ -	$ -	$ -	$ -	$ -
Former Manufacturing, Fairfield, NJ	$ 150,000	$ 725,000	$ -	$ -	$ 875,000
Industrial Site, Coffeyville, KS	$ -	$ 400,000	$ -	$ -	$ 400,000
Industrial Site, NY	$ -	$ 1,000,000	$ -	$ -	$ 1,000,000
Industrial Site, SC	$ 44,000	$ 356,000	$ -	$ -	$ 400,000
Nickel Rim, Ontario	$ 30,000	$ 35,000	$ -	$ -	$ 65,000
Cape Canaveral, FL	$ 30,900	$ 729,250	$ -	$ -	$ 760,150
MMR CS-10 Plume, MA	$ -	$ -	$ -	$ -	$ -
Pease AFB, NH	$ 200,000	$ 500,000	$ 50,000	$ -	$ 750,000
Vancouver, Canada	$ -	$ -	$ -	$ -	$ -
Warren AFB Spill Site 7, WY	$ -	$ 2,200,000	$ 150,000	$ -	$ 2,350,000
London, Ontario	$ -	$ 23,700	$ 3,000	$ -	$ 26,700
Moffett, Full-Scale Est.	$ 175,000	$ 4,572,122	$ -	$ -	$ 4,747,122
Dover, AFB Full-Scale Est.	$ 150,000	$ 520,000	$ -	$ -	$ 670,000

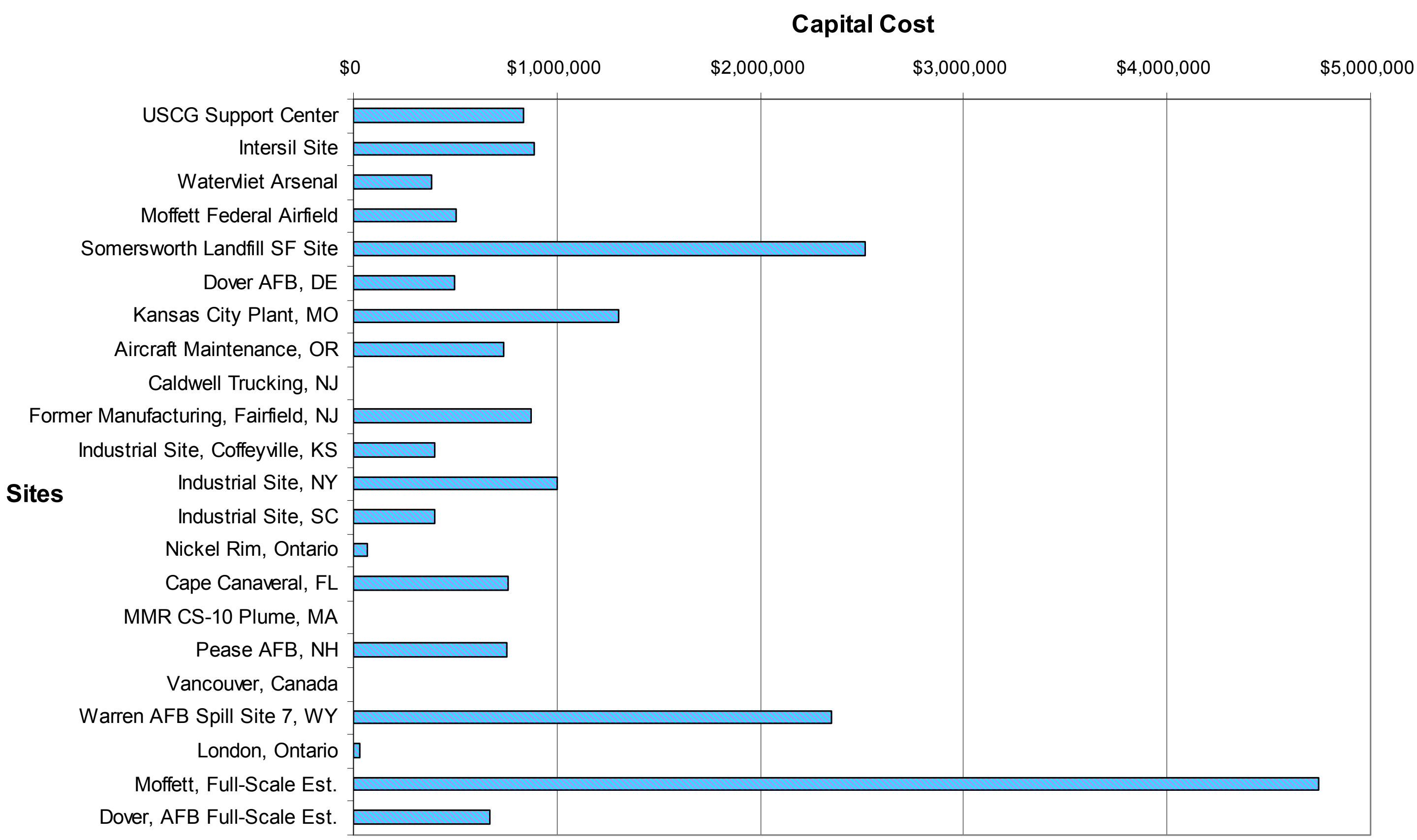

Figure 5. Capital costs of the PRB sites.

We were able to obtain stated media maintenance estimates for only three of the 22 sites in this study. One of these is a functioning PRB site (Intersil) while the other two are estimates for the proposed full-scale implementations at Dover AFB and Moffett Federal Airfield. However, until recently, EnviroMetal Technologies had proposed that, in general, rejuvenation techniques can be evaluated based on a percentage of the original cost of iron metal media (U.S. EPA, 1998). These percentages are 30% for the continuous trench configuration and 20% for the funnel and gate (lower due to its relatively shorter total length; i.e., less face surface area exposure). These O&M and replace/replenish costs are provided in Table 8. It is noted that, of the three sites with estimated replenishment/replacement costs, all are significantly higher than the ETI calculation estimates. However, it is uncertain to us how these estimates have been calculated. It is also noteworthy that the maintenance estimates for the three sites vary widely with respect to their percentage of the original construction costs. These percentages are 35% for Intersil, 5% for Moffett full-scale, and 72% for Dover full-scale. More recently, ETI has estimated O&M using unit costs that are dependent on which of the four rejuvenation techniques is being considered (John Vogan, Mike Duchene, personal communication). In terms of dollars per square foot, these are $3-$15 for jetting, $5-$15 using agitation with solid-stem augers, and $15-$20 for either ultrasound or pressure pulse technology. The ranges in cost tend to depend upon the target depth, auger diameter, etc. These estimates are also included in Table 8, using the cost midpoint for each technique (i.e., $9, $10, and $17.50 per square foot, respectively). Mobilization costs must also be considered and are not included in these cost estimates. ETI notes that both the ultrasound and the pressure pulse technologies offer certain advantages that might offset their higher costs relative to jetting and mechanical agitation. These are:

1. Both use tools that can be placed in conventional two to four inch diameter wells.
2. Both avoid significant spoils generation during use.
3. Both technologies may be used proactively as a form of routine O&M to minimize issues of hydraulic blockage and loss of reactivity before these problems become significant.

It is likely that the actual costs for media maintenance activities will remain largely unknown until some fraction of the PRB sites have begun to fail and undergone a rejuvenation process. It seems reasonable to assume that the longer and deeper the reactive media zones (i.e., higher in media upgradient face, or frontal boundary surface area) the more it will cost to treat/replace the reactive media. Extremely large-scale continuous trench PRBs will probably not fare well in the context of per maintenance cost with F&G configurations. This is because the reactive media itself comprises the entire frontal surface area of the continuous PRB. This will require one of the five replenishment techniques (above) to be carried out along the entire length of the PRB. In the F&G system, only the gate surface areas are exposed, with the gates compensating for the extra needed reactivity by having thicker reaction zones. This results in a much lower length of treatment at the frontal boundary. However, frequency of needed maintenance may be increased with the F&G systems. Whereas continuous trench systems have ground-water flow through them at approximately the natural flow conditions of the aquifer, the F&G systems have greatly increased the flux through the gates by capturing additional water with the funnel sections. Therefore, F&G systems are treating more water per unit time than the continuous trenches, possibly also increasing the rate of precipitate buildup on the frontal boundary of the media. This could lead to an increase in the necessary frequency of maintenance.

Table 9 provides information for the 22 PRB sites in this study with regard to factors that could impact the cost of maintenance. The total lengths, approximate average depths, and calculated cross-sectional surface areas of the systems are provided, as are the same values for the reactive media zones. In the case of continuous trench PRBs these values are, of course, equal. Table 9 also has a column displaying the ratio of the reactive media cross-sectional surface area (Media SA)[1] to that of the entire PRB system (PRB SA). For a standard continuous trench, the ratio is one, whereas the values range from 0.007 to 0.6 for the F&G systems[2]. Although other factors would also affect maintenance costs, it seems reasonable that, for a continuous trench system of the same size as a F&G system, this ratio might be somewhat useful in estimating periodic media maintenance costs. For example, one could compare the Dover full-scale estimate for a F&G system to a hypothetical continuous trench having exactly the same dimensions. These would be 136ft long by 39ft deep, resulting in a frontal surface area of 5304ft^2 for the continuous trench. However, the four 4ft-wide gates, also constructed to a depth of 39ft, have a surface area of only 624ft^2. The ratio between these two values is 0.118, as shown in Table 9. Assuming the cost of surface jetting (for example) the gates is equivalent to 1, the cost of jetting a continuous trench PRB of the same dimensions could be 1/0.118 or 8.5 times the cost, although the trench should need to be serviced proportionally less frequently.

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[1] *Note: This refers to the geometric surface area of the system, i.e., the total facial area of the media and does not include any calculation of the actual surface area of the media granules. That is, the Media SA includes both the frontal surface area occupied by the media granules as well as that of the void spaces between them.*

[2] *Values in Table 9 higher than 1 are for continuous trench PRB systems that have "polishing" PRB trenches downgradient from the initial PRB. These following trenches were not included in the total PRB capture length because their length was encompassed by the length of the upgradient primary PRB.*

Table 8. O&M Costs for the PRB Sites

Site	Annual PRB O&M	PRB Stated Fe Maintenance	ETI Original Fe Maintenance Calc.	ETI Jetting Fe Maintenance Calc.	ETI Auger Agitation Fe Maintenance Calc.	ETI Ultrasound or Pressure Fe Maintenance Calc.
USCG Support Center	$ 85,000	$ -	$ 60,000	$ 32,832	$ 36,480	$ 63,840
Intersil Site	$ 95,000	$ 232,000	$ 34,000	$ 4,536	$ 5,040	$ 8,820
Watervliet Arsenal	$ -	$ -	$ 26,208	$ 25,200	$ 28,000	$ 49,000
Moffett Federal Airfield	$ 90,000	$ -	$ 7,875	$ 2,250	$ 2,500	$ 4,375
Somersworth Landfill SF Site	$ -	$ -	$ 360,000	$ 288,000	$ 320,000	$ 560,000
Dover AFB, DE	$ -	$ -	$ 9,400	$ 2,808	$ 3,120	$ 5,460
Kansas City Plant, MO	$ -	$ -	$ -	$ 35,100	$ 39,000	$ 68,250
Aircraft Maintenance, OR	$ 50,000	$ -	$ -	$ 26,100	$ 29,000	$ 50,750
Caldwell Trucking, NJ	$ -	$ -	$ -	$ 81,000	$ 90,000	$ 157,500
Former Manufacturing, Fairfield, NJ	$ 25,000	$ -	$ 107,700	$ 28,575	$ 31,750	$ 55,563
Industrial Site, Coffeyville, KS	$ -	$ -	$ -	$ 1,980	$ 2,200	$ 3,850
Industrial Site, NY	$ -	$ -	$ -	$ 59,940	$ 66,600	$ 116,550
Industrial Site, SC	$ -	$ -	$ -	$ 84,825	$ 94,250	$ 164,938
Nickel Rim, Ontario	$ 30,000	$ -	$ 4,500	$ 6,300	$ 7,000	$ 12,250
Cape Canaveral, FL	$ -	$ -	$ -	$ 56,700	$ 63,000	$ 110,250
MMR CS-10 Plume, MA	$ -	$ -	$ -	$ 43,200	$ 48,000	$ 84,000
Pease AFB, NH	$ 35,000	$ -	$ -	$ 44,550	$ 49,500	$ 86,625
Vancouver, Canada	$ -	$ -	$ -	$ 5,643	$ 6,270	$ 10,973
Warren AFB Spill Site 7, WY	$ -	$ -	$ -	$ 76,680	$ 85,200	$ 149,100
London, Ontario	$ 3,000	$ -	$ 2,400	$ -	$ -	$ -
Moffett, Full-Scale Est.	$ 72,278	$ 267,538	$ 176,260	$ 63,180	$ 70,200	$ 122,850
Dover, AFB Full-Scale Est.	$ 148,000	$ 421,000	$ 9,600	$ 5,616	$ 6,240	$ 10,920

6. Economic Data for the Pump-and-Treat Sites

6.1. P&T at the PRB sites

Nine of these 22 PRB sites have either had active P&T systems at the site or some aspect of P&T cost estimates made for the site. This information, as well as available construction and O&M cost information, is provided in Table 10. A “0” in the “On-Site P&T” column indicates that the information was not relevant to the pilot-scale because a full-scale estimate was made for both types of systems (Moffett Federal Airfield and Dover AFB). ND in this field means that no data were available. It should be noted that the Somersworth P&T system estimate is extremely high in cost. This cost is from the record of decision (ROD) for the site and due in large part to the planned construction of a slurry wall and an impermeable cap over the site. The ROD amendment now calls for a PRB and a permeable cap, at a total cost of approximately $7,000,000. Due to this, a comparison of Somersworth PRB versus P&T costs is not valid because we have been unable to locate cost data for the P&T excluding the cap.

Table 11 provides a side-by-side comparison of P&T versus PRB construction and O&M costs, including differences in the values (P&T minus PRB). Figure 6 depicts the comparison of the construction costs and Figure 7 the O&M costs. In four of the five valid comparisons (excluding Somersworth Landfill) the PRB system is more expensive to construct than the P&T system and the reverse is true for the remaining site (Watervliet). Whether or not P&T construction will be more or less expensive than a PRB system will be highly site specific. In the case of annual O&M, however, the P&T systems are significantly more expensive than the PRB systems in all five of the valid comparisons.

6.2. P&T at other sites

Although not addressed in detail in this report, P&T data from other sites can illustrate the importance of using comparable unit cost values when evaluating the potential cost-effectiveness of PRB versus P&T installations. This is addressed in Section 7.1 and illustrated in Section 7.3.

Table 9. PRB Information Relevant to Maintenance Costs

Site	Reactive Material	Mass, Tons	PRB Type	Reactive Media Cost	Total PRB Length, ft	Ave. PRB Depth, ft	Total PRB Surface Area, ft^2	Total Reactive Media Length, ft	Ave. Reactive Media Depth, ft	Reactive Media Face Surface Area, ft^2	Ratio, Media SA to PRB SA
USCG Support Center	Fe(0)	450	Trench	$ 200,000.00	152	24	3648	152	24	3648	1.000
Intersil Site	Fe(0)	220	F&G	$ 170,000.00	40	20	800	36	14	504	0.630
Watervliet Arsenal	Fe(0)	165.5	Trench	$ 87,360.00	190	10	1900	280	10	2800	1.474
Moffett Federal Airfield	Fe(0)	75	F&G	$ 39,375.00	50	25	1250	10	25	250	0.200
Somersworth Landfill SF Site	Fe(0)	3552	Trench	$ 1,200,000.00	800	40	32000	800	40	32000	1.000
Dover AFB, DE	Fe(0)	59	F&G	$ 47,000.00	68	39	2652	8	39	312	0.118
Kansas City Plant, MO	Fe(0)	650	Trench	$ -	130	30	3900	130	30	3900	1.000
Aircraft Maintenance, OR	Fe(0)	324	F&G	$ -	650	29	18850	100	29	2900	0.154
Caldwell Trucking, NJ	Fe(0)	250	Hydr. Frac./Perm. Infill	$ -	180	50	9000	180	50	9000	1.000
Former Manufacturing, Fairfield, NJ	Fe(0)	720	Trench	$ 359,000.00	127	25	3175	127	25	3175	1.000
Industrial Site, Coffeyville, KS	Fe(0)	70	F&G	$ 50,000.00	1020	30	30600	20	11	220	0.007
Industrial Site, NY	Fe(0)	742	Trench	$ 358,000.00	370	18	6660	370	18	6660	1.000
Industrial Site, SC	Fe(0)	400	Trench	$ 133,000.00	325	29	9425	325	29	9425	1.000
Nickel Rim, Ontario	Organic Matter	425	Trench	$ 15,000.00	50	14	700	50	14	700	1.000
Cape Canaveral, FL	Fe(0)	205	Trench	$ -	100	45	4500	140	45	6300	1.400
MMR CS-10 Plume, MA	Fe(0)	49	Hydr. Frac./Perm. Infill	$ -	48	100	4800	48	100	4800	1.000
Pease AFB, NH	Fe(0)	360	Trench	$ -	150	33	4950	150	33	4950	1.000
Vancouver, Canada	Organic Matter	0	Trench	$ -	33	19	627	33	19	627	1.000
Warren AFB Spill Site 7, WY	Fe(0)	1750	Trench	$ 600,000.00	568	15	8520	568	15	8520	1.000
London, Ontario	Oxygen furnace slag	400	Trench	$ 8,000.00	0	0	0	0	0	0	NA
Moffett, Full-Scale Est.	Fe(0)	2518	F&G	$ 881,300.00	1100	45	49500	135	52	7020	0.142
Dover, AFB Full-Scale Est.	Fe(0)	108	F&G	$ 48,000.00	136	39	5304	16	39	624	0.118

Table 10. P&T Information for the PRB Sites

Site	On-Site P&T	P&T Construction Cost	Annual P&T O&M
USCG Support Center	Estimated	$ 500,000	$ 200,000
Intersil Site	Yes	$ 325,000	$ 142,158
Watervliet Arsenal	Estimated	$ 834,000	$ -
Moffett Federal Airfield	0	$ -	$ -
Somersworth Landfill SF Site	Estimated	$ 26,000,000	$ 3,400,000
Dover AFB, DE	0	$ -	$ -
Kansas City Plant, MO	Yes	$ -	$ 200,000
Aircraft Maintenance, OR	No	$ -	$ -
Caldwell Trucking, NJ	ND	$ -	$ -
Former Manufacturing, Fairfield, NJ	Estimated	$ 350,000	$ 98,000
Industrial Site, Coffeyville, KS	ND	$ -	$ -
Industrial Site, NY	Estimated	$ -	$ 300,000
Industrial Site, SC	ND	$ -	$ -
Nickel Rim, Ontario	No	$ -	$ -
Cape Canaveral, FL	ND	$ -	$ -
MMR CS-10 Plume, MA	ND	$ -	$ -
Pease AFB, NH	ND	$ -	$ -
Vancouver, Canada	ND	$ -	$ -
Warren AFB Spill Site 7, WY	ND	$ -	$ -
London, Ontario	ND	$ -	$ -
Moffett, Full-Scale Est.	Estimated	$ 1,400,000	$ 695,000
Dover, AFB Full-Scale Est.	Estimated	$ 502,000	$ 219,833

Table 11. Comparison of P&T Costs Versus PRB Costs

Site	P&T Construction Cost	Calc. PRB Construction Cost	P&T Construction Minus PRB Construction	Annual P&T O&M	Annual PRB O&M	Annual P&T Minus PRB O&M
USCG Support Center	$ 500,000	$ 500,000	$ -	$ 200,000	$ 85,000	$ 115,000
Intersil Site	$ 325,000	$ 656,000	$ (331,000)	$ 142,158	$ 95,000	$ 47,158
Watervliet Arsenal	$ 834,000	$ 274,000	$ 560,000	$ -	$ -	$ -
Moffett Federal Airfield	$ -	$ 377,375	$ -	$ -	$ 90,000	$ -
Somersworth Landfill SF Site	$ 26,000,000	$ 2,100,000	$ 23,900,000	$ 3,400,000	$ -	$ -
Dover AFB, DE	$ -	$ 358,000	$ -	$ -	$ -	$ -
Kansas City Plant, MO	$ -	$ 1,240,000	$ -	$ 200,000	$ -	$ -
Aircraft Maintenance, OR	$ -	$ 700,000	$ -	$ -	$ 50,000	$ -
Caldwell Trucking, NJ	$ -	$ -	$ -	$ -	$ -	$ -
Former Manufacturing, Fairfield, NJ	$ 350,000	$ 725,000	$ (375,000)	$ 98,000	$ 25,000	$ 73,000
Industrial Site, Coffeyville, KS	$ -	$ 400,000	$ -	$ -	$ -	$ -
Industrial Site, NY	$ -	$ 1,000,000	$ -	$ 300,000	$ -	$ -
Industrial Site, SC	$ -	$ 356,000	$ -	$ -	$ -	$ -
Nickel Rim, Ontario	$ -	$ 35,000	$ -	$ -	$ 30,000	$ -
Cape Canaveral, FL	$ -	$ 729,250	$ -	$ -	$ -	$ -
MMR CS-10 Plume, MA	$ -	$ -	$ -	$ -	$ -	$ -
Pease AFB, NH	$ -	$ 550,000	$ -	$ -	$ 35,000	$ -
Vancouver, Canada	$ -	$ -	$ -	$ -	$ -	$ -
Warren AFB Spill Site 7, WY	$ -	$ 2,350,000	$ -	$ -	$ -	$ -
London, Ontario	$ -	$ 26,700	$ -	$ -	$ 3,000	$ -
Moffett, Full-Scale Est.	$ 1,400,000	$ 4,618,122	$ (3,218,122)	$ 695,000	$ 72,278	$ 622,722
Dover, AFB Full-Scale Est.	$ 502,000	$ 582,000	$ (80,000)	$ 219,833	$ 148,000	$ 71,833

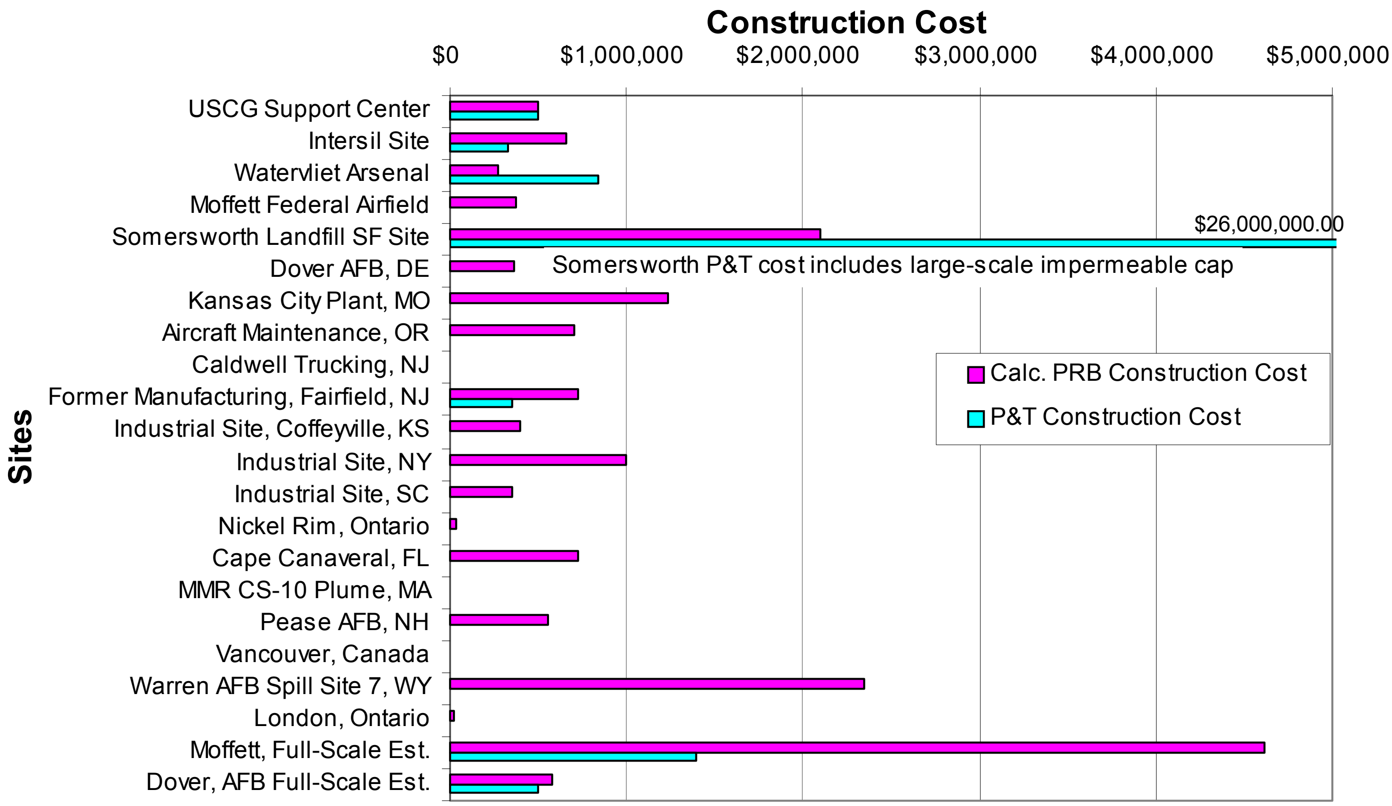

Figure 6. PRB construction costs versus P&T construction costs at the PRB sites.

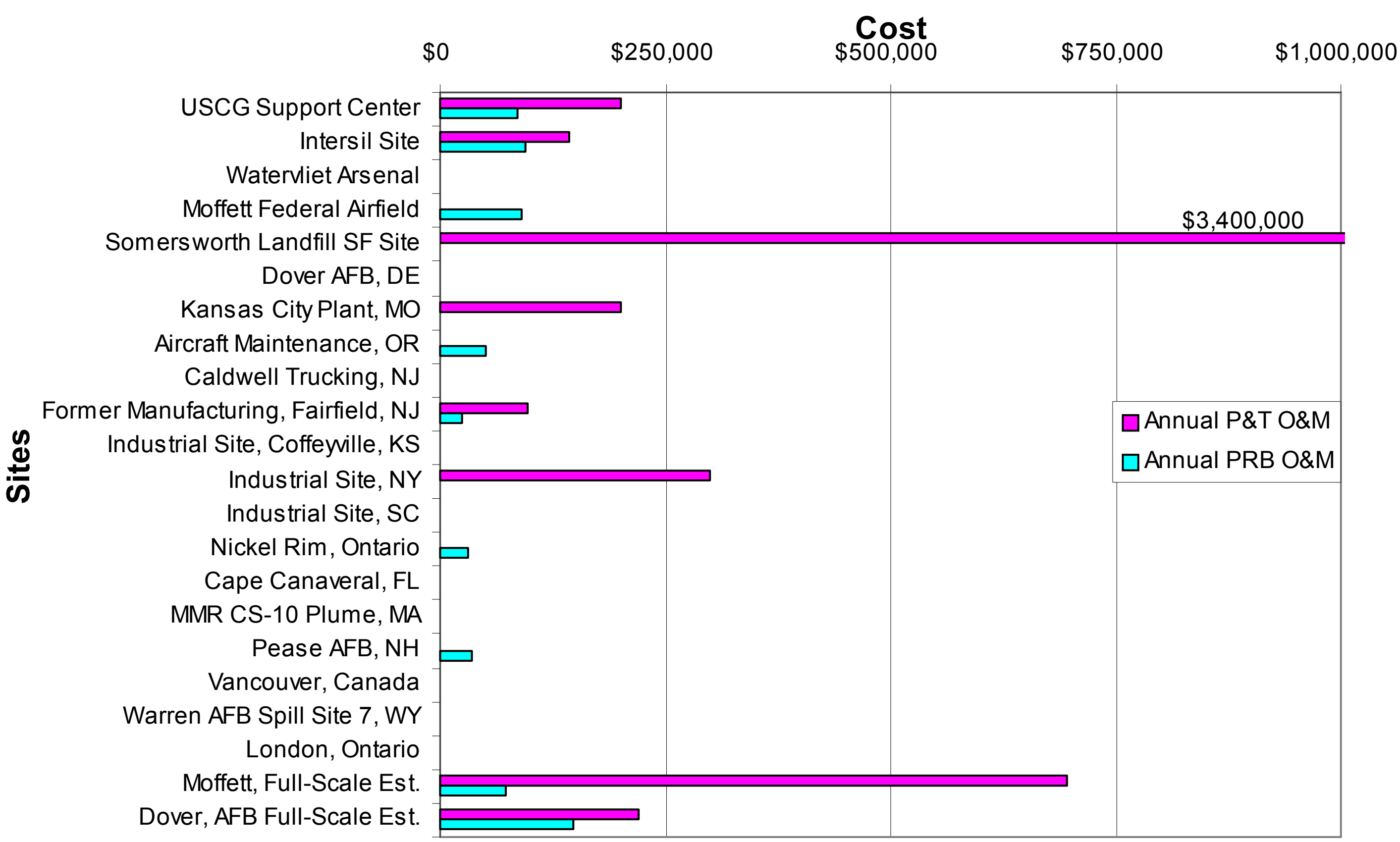

Figure 7. PRB O&M costs versus P&T O&M costs at the PRB sites.

7. Cost Comparison of PRB versus P&T Technologies

7.1. Rationale and approach

As mentioned in Section 2, reports have been published that seem to indicate that PRB systems are no more effective for reducing operation and maintenance costs, on a per unit of treatment basis, than P&T systems. These reports are comparing the technologies based on volume of water treated per unit time. We have examined these reports and data and determined that the method of comparison is causing the discrepancy between low anticipated PRB unit costs and those being reported. The same reports which show a very high O&M unit cost for PRB systems also show extremely low average annual O&M costs for the PRB sites when not expressed as unit costs. Unit costs in these reports were expressed in dollars per 1000 gallons of treated water. This was without regard to whether all the water passing through the P&T systems even needed to be treated. In fact, one of the known problems with P&T systems is that they extract large quantities of ground water for treatment whether it is contaminated or not, often mixing the two as the water is withdrawn from the aquifer. The ratio of contaminated to uncontaminated water entering the P&T system depends on several factors, including the location of the pumping well(s), the rate of pumping, and the time frame during which the system has been operational[3].

Using a unit cost of "dollars per 1000 gallons treated per year" will always skew in favor of the treatment that processes the most water. If a P&T system costs exactly the same as a PRB system (both capital and O&M costs), it will always yield a lower unit cost ($/1000 gal) if its pumping rate exceeds the natural flux rate of water through the PRB. The PRB system, of course, typically depends upon the natural gradient for its contaminated water input. In this report, it is our contention that the excess water treated by a P&T should not be considered when comparing the costs of P&T relative to a PRB. A more logical comparison would be to assume that the PRB system is properly designed and capturing the entire contaminant plume, thus protecting downgradient receptors. One can then use only the annual number of gallons passing through the PRB as the number of gallons that should be treated by either the PRB or the P&T systems. Any additional water treated by the P&T system is superfluous and should not be factored into the calculations. As an illustration:

> Assume a P&T system costs $500,000 in O&M per year. Compare it to a PRB that costs $100,000 in O&M per year. The P&T system treats 1 million gallons per year (gpy), whereas the PRB passes and treats only 100,000 gpy, or 1/10 the volume. Based on the way these figures are currently being calculated in other reports, the P&T would cost only $500/1000 gallons whereas the PRB comes in at $1000/1000 gallons, or twice the cost. However, the PRB is capturing all the water that needs to be treated and the excess water treated by the P&T is simply wasted effort. Therefore, the P&T value should be calculated using the same volume of water that is treated by the PRB; i.e., 100,000 gallons per year. This results in the P&T having an O&M cost of $5000/1000 gallons of actual contaminated water, a factor of five more expensive than the PRB.

Comparing unit costs of PRB versus P&T systems by using the annual volume passing through the PRB at a given site is the approach that has been used in this document.

7.2. PRB cost per 1000 gallons of treated water

In order to compare PRB cost with P&T cost we have estimated flow through the PRB systems using data obtained from publications and contacts. To accomplish this we have made a few assumptions regarding the PRB systems:

1. A continuous trench captures water at the natural ground-water velocity over its entire saturated (i.e., below the water table) cross-sectional surface area.
2. An F&G system also captures and passes all the water impinging its entire submerged surface area, including both funnels and gates, passing it through the gates.
3. The PRB systems are properly designed and constructed, hence capturing the entire cross-sectional area of the plume as it migrates.
4. The total volume of water that needs to be treated per unit time is the amount that passes through the PRB per unit time.
5. Radionuclides are not being treated.

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[3] During the lifetime of a P&T system, contaminants are usually readily removed at high concentrations during the early period of operation. As time passes, the concentrations of the removed contaminants decline, their ultimate removal being limited by slow desorption and dissolution phenomena. This means that while some contamination is still being removed, much more uncontaminated water is being drawn into the system and being treated as though contaminated (which it has become during the mixing).

Assumption 1 is reasonable, although the barrier permeability may vary from the aquifer and certain construction procedures might impact the aquifer/PRB interface somewhat (e.g., compaction or clay smearing). Assumption 2 is not exactly accurate since flow modeling and field studies show that water capture is incomplete near the distal ends of the funnel sections. For an F&G system a certain amount of over-engineering is needed to ascertain that the entire plume cross-sectional area is captured and cannot pass over (water mounding) or under the system or around its ends. Because of these concerns, most PRBs installed during the past two years or so have been continuous systems rather than F&G. For purposes of comparison to P&T systems, the differences in our captured volume estimates versus actual capture are probably not very significant, especially for the large F&G systems. Assumption 3 should be valid provided proper site characterization has been accomplished. Implicit in Assumption 4 is that the P&T systems are generally extracting more ground water than is necessary, or even desirable, for treatment of the contaminants. Assumption 5 results because it is likely that PRBs for radioactive contaminants will have to be excavated and the materials disposed. The cost of reactive media removal and disposal while radioactive are not assessed in this document.

Assumption 2 also results in a consideration of how much of the PRB is below the water table, plus the knowledge that not all water impacting the funnel sections of an F&G system is moving through the gate(s). Although water level and capture data were not available for most of the sites, in general, the ratio of capturing to non-capturing surface area seemed to fall in the range of about 2/3. This seemed reasonable so we have assumed a “capture ratio” of 0.666 to evaluate water volume per unit time for these comparisons.

Table 12 provides data relevant to this cost comparison exercise, including the PRB surface areas, ground-water velocities, and annual ground-water volumes passing through the PRBs at two different capture factors. Factor 1 is the 0.666 factor mentioned above and Factor 2 is simply 1, where water capture is equivalent to the amount intercepted by the entire surface area of the PRB. Data for 19 of the 22 sites are presented in this table. A zero value is given for the three sites for which data were not available. Table 13 further sets up this comparison, providing the results of present value (PV) calculations on the annual O&M costs for 10 of the 22 PRB sites at an annual inflation (discount) rate of 4%. These values represent the cost, in terms of dollar values at the time O&M costs were stated (generally 1995 to 2000), over a subsequent 30-year period, including a summary total.

Table 12. Ground-water Flow and Volume Data Relevant to a Unit Cost Evaluation

Site	Total PRB Surface Area, ft^2	GW Flow Velocity, ft/d	PRB Capture Factor 1	Factor 1 GW Volume, gal/yr	PRB Capture Factor 2	Factor 2 GW Volume, gal/yr
USCG Support Center	3648	0.4	6.67E-01	2.66E+06	1	3.98E+06
Intersil Site	800	0.8	6.67E-01	1.16E+06	1	1.75E+06
Watervliet Arsenal	1900	0.15	6.67E-01	5.19E+05	1	7.78E+05
Moffett Federal Airfield	1250	0.35	6.67E-01	7.96E+05	1	1.19E+06
Somersworth Landfill SF Site	32000	1.25	6.67E-01	7.28E+07	1	1.09E+08
Dover AFB, DE	2652	0.18	6.67E-01	8.69E+05	1	1.30E+06
Kansas City Plant, MO	3900	0.59	6.67E-01	4.19E+06	1	6.28E+06
Aircraft Maintenance, OR	18850	0.3	6.67E-01	1.03E+07	1	1.54E+07
Caldwell Trucking, NJ	9000	1.1	6.67E-01	1.80E+07	1	2.70E+07
Former Manufacturing, Fairfield, NJ	3175	0.6	6.67E-01	3.47E+06	1	5.20E+06
Industrial Site, Coffeyville, KS	30600	0.6	6.67E-01	3.34E+07	1	5.01E+07
Industrial Site, NY	6660	0.6	6.67E-01	7.27E+06	1	1.09E+07
Industrial Site, SC	9425	0.14	6.67E-01	2.40E+06	1	3.60E+06
Nickel Rim, Ontario	700	0.13	6.67E-01	1.66E+05	1	2.48E+05
Cape Canaveral, FL	4500	0.05	6.67E-01	4.10E+05	1	6.14E+05
MMR CS-10 Plume, MA	4800	1	6.67E-01	8.74E+06	1	1.31E+07
Pease AFB, NH	4950	0	6.67E-01	0.00E+00	1	0.00E+00
Vancouver, Canada	627	0	6.67E-01	0.00E+00	1	0.00E+00
Warren AFB Spill Site 7, WY	8520	0.9	6.67E-01	1.40E+07	1	2.09E+07
London, Ontario	0	0	6.67E-01	0.00E+00	1	0.00E+00
Moffett, Full-Scale Est.	49500	0.35	6.67E-01	3.15E+07	1	4.73E+07
Dover, AFB Full-Scale Est.	5304	0.18	6.67E-01	1.74E+06	1	2.61E+06

Table 13. Present Value Calculation for Annual PRB Site O&M Costs, Including 30-year Total as Present Value

Year	USCG Support Center	Intersil Site	Moffett Federal Airfield	Aircraft Maintenance, OR	Former Manufacturing, Fairfield, NJ	Nickel Rim, Ontario	Pease AFB, NH	London, Ontario	Moffett, Full-Scale Est.	Dover, AFB Full-Scale Est.
0	$85,000.00	$95,000.00	$90,000.00	$50,000.00	$25,000.00	$30,000.00	$35,000.00	$3,000.00	$72,278.00	$148,000.00
1	$81,730.77	$91,346.15	$86,538.46	$48,076.92	$24,038.46	$28,846.15	$33,653.85	$2,884.62	$69,498.08	$142,307.69
2	$78,587.28	$87,832.84	$83,210.06	$46,227.81	$23,113.91	$27,736.69	$32,359.47	$2,773.67	$66,825.07	$136,834.32
3	$75,564.69	$84,454.65	$80,009.67	$44,449.82	$22,224.91	$26,669.89	$31,114.87	$2,666.99	$64,254.88	$131,571.46
4	$72,658.36	$81,206.40	$76,932.38	$42,740.21	$21,370.10	$25,644.13	$29,918.15	$2,564.41	$61,783.54	$126,511.02
5	$69,863.80	$78,083.08	$73,973.44	$41,096.36	$20,548.18	$24,657.81	$28,767.45	$2,465.78	$59,407.25	$121,645.21
6	$67,176.73	$75,079.88	$71,128.31	$39,515.73	$19,757.86	$23,709.44	$27,661.01	$2,370.94	$57,122.35	$116,966.55
7	$64,593.01	$72,192.19	$68,392.60	$37,995.89	$18,997.95	$22,797.53	$26,597.12	$2,279.75	$54,925.34	$112,467.84
8	$62,108.67	$69,415.57	$65,762.12	$36,534.51	$18,267.26	$21,920.71	$25,574.16	$2,192.07	$52,812.83	$108,142.15
9	$59,719.87	$66,745.74	$63,232.81	$35,129.34	$17,564.67	$21,077.60	$24,590.54	$2,107.76	$50,781.56	$103,982.84
10	$57,422.95	$64,178.60	$60,800.78	$33,778.21	$16,889.10	$20,266.93	$23,644.75	$2,026.69	$48,828.43	$99,983.50
11	$55,214.38	$61,710.19	$58,462.28	$32,479.05	$16,239.52	$19,487.43	$22,735.33	$1,948.74	$46,950.41	$96,137.98
12	$53,090.75	$59,336.72	$56,213.73	$31,229.85	$15,614.93	$18,737.91	$21,860.90	$1,873.79	$45,144.63	$92,440.36
13	$51,048.80	$57,054.54	$54,051.67	$30,028.70	$15,014.35	$18,017.22	$21,020.09	$1,801.72	$43,408.29	$88,884.96
14	$49,085.38	$54,860.13	$51,972.76	$28,873.75	$14,436.88	$17,324.25	$20,211.63	$1,732.43	$41,738.74	$85,466.31
15	$47,197.48	$52,750.13	$49,973.81	$27,763.23	$13,881.61	$16,657.94	$19,434.26	$1,665.79	$40,133.41	$82,179.15
16	$45,382.19	$50,721.28	$48,051.74	$26,695.41	$13,347.70	$16,017.25	$18,686.79	$1,601.72	$38,589.82	$79,018.41
17	$43,636.73	$48,770.46	$46,203.59	$25,668.66	$12,834.33	$15,401.20	$17,968.06	$1,540.12	$37,105.59	$75,979.24
18	$41,958.39	$46,894.67	$44,426.53	$24,681.41	$12,340.70	$14,808.84	$17,276.98	$1,480.88	$35,678.45	$73,056.96
19	$40,344.61	$45,091.03	$42,717.82	$23,732.12	$11,866.06	$14,239.27	$16,612.48	$1,423.93	$34,306.21	$70,247.08
20	$38,792.89	$43,356.76	$41,074.83	$22,819.35	$11,409.67	$13,691.61	$15,973.54	$1,369.16	$32,986.74	$67,545.27
21	$37,300.86	$41,689.19	$39,495.02	$21,941.68	$10,970.84	$13,165.01	$15,359.18	$1,316.50	$31,718.02	$64,947.37
22	$35,866.21	$40,085.76	$37,975.98	$21,097.77	$10,548.88	$12,658.66	$14,768.44	$1,265.87	$30,498.09	$62,449.40
23	$34,486.74	$38,544.00	$36,515.37	$20,286.32	$10,143.16	$12,171.79	$14,200.42	$1,217.18	$29,325.09	$60,047.50
24	$33,160.33	$37,061.54	$35,110.93	$19,506.07	$9,753.04	$11,703.64	$13,654.25	$1,170.36	$28,197.20	$57,737.98
25	$31,884.93	$35,636.10	$33,760.51	$18,755.84	$9,377.92	$11,253.50	$13,129.09	$1,125.35	$27,112.69	$55,517.29
26	$30,658.58	$34,265.48	$32,462.03	$18,034.46	$9,017.23	$10,820.68	$12,624.12	$1,082.07	$26,069.90	$53,382.01
27	$29,479.41	$32,947.57	$31,213.49	$17,340.83	$8,670.41	$10,404.50	$12,138.58	$1,040.45	$25,067.21	$51,328.85
28	$28,345.59	$31,680.36	$30,012.97	$16,673.87	$8,336.94	$10,004.32	$11,671.71	$1,000.43	$24,103.08	$49,354.67
29	$27,255.37	$30,461.88	$28,858.63	$16,032.57	$8,016.29	$9,619.54	$11,222.80	$961.95	$23,176.04	$47,456.41
30	$26,207.09	$29,290.27	$27,748.68	$15,415.93	$7,707.97	$9,249.56	$10,791.15	$924.96	$22,284.66	$45,631.16
Total 30 Yr Annual O&M PV	$1,554,822.83	$1,737,743.16	$1,646,283.00	$914,601.67	$457,300.83	$548,761.00	$640,221.17	$54,876.10	$1,322,111.58	$2,707,220.93

PV costs indicate the amount of money that would have to be set aside today to fully cover the costs of a technology in the present and the future (Gavaskar et al., 2000). The equation used is:

$$PV = \text{Capital Investment} + PV_{\text{annual costs}} \tag{1}$$

The capital cost is incurred in the present, whereas the $PV_{\text{annual costs}}$ occurs both in the present and in the future. The $PV_{\text{annual costs}}$ is calculated as

$$PV_{\text{annual costs}} = \sum_{i=0}^{n} \frac{Y_i}{(1+r)^i} \tag{2}$$

where: i is the year

Y_i is the year i cost

year i = 0 is the construction/startup year (capital investment year)

years i = 1 through n are the operation and maintenance years

n = total years of operation

r = discount rate

Table 13 carries out the year by year calculation of Equation 2 for the O&M costs of the PRB sites assuming an annual inflation rate of 4% included as the discount rate, r.

The total O&M PV costs are carried into Table 14 for the eight PRB sites where we have sufficient data to calculate costs per 1000 gallons of treated water. The upper part of Table 14 provides costs per 1000 gallons of treated ground water in terms of 30-year total O&M cost, construction, and the combined construction plus 30-year O&M. The lower part of the table includes PV for Fe maintenance for the three sites (all used Fe as the reactive media) where estimates were provided. The starting values in the iron maintenance PV calculations were those presented in Table 8 as "Stated Fe Maintenance." It is assumed that iron maintenance occurs twice, at years 10 and 20, during the 30-year life of the PRB. We have not questioned or made assumptions regarding the iron maintenance cost estimates for the sites. The columns in the lower section of Table 14 provide data on (a) the PV cost of iron maintenance for two cycles, (b) iron maintenance PV with O&M PV, (c) both of the previous plus construction costs, and (d) the total PV cost per 1000 gallons for the 30-year period. It is evident that iron maintenance can substantially increase the treatment cost; therefore, it is important that both maintenance techniques and iron longevity receive further study and analysis.

A recent EPA report (U.S. EPA, 1999a) evaluated 28 sites, including cost. Of these 28 sites, three were PRB sites that have also been evaluated in this report. However, their unit costs in that report were not calculated using PV, but presented simply as "average annual operating cost, capital cost per 1,000 gallons treated per year, and average annual operating cost per 1,000 gallons treated per year." Table 15 presents our data for the sites from Table 14 in that context. It includes the values presented in the recent report for the three PRB sites evaluated in the other EPA report: the USCG Support Center, Intersil, and Moffett Federal Airfield sites.

Calculating costs in the manner of Table 15, rather than using lifetime values, biases the costs to extremely high initial values, especially for the construction costs per 1000 gallons. This is because only 1/30th of the total volume of water that is expected to pass through the PRB during its 30-year lifetime is being used as the divisor for the total construction costs. In addition, in terms of setting aside today's money (PV), the O&M costs are also reduced in the 30-year scenario relative to the current, a recent, or average year. In Table 15, capital costs per 1000 gallons for the USCG Support Center and the Intersil site are very close between this document and the U.S. EPA (1999a) report, as are the O&M costs per 1000 gallons for all three sites. This is true even though we used a different approach for the ground-water flow calculations in this report. However, the capital costs per 1000 gallons are significantly different for the Moffett Federal Airfield site. This results from estimation differences for the ground-water volume through the PRB system at Moffett. Ground-water velocity estimates in the A1 surficial sediment unit at Moffett (the zone containing the PRB) range from 0.005 to 2 feet per day (U.S. EPA, 1998b), leaving a large margin for error in calculations[4]. The similarity in Moffett O&M costs per 1000 gallons between the reports was simply fortuitous. The higher O&M cost of this report ($90,000/yr versus $26,000/yr for U.S. EPA, 1999a) was offset by the differences in estimates of annual ground-water volume (796,000 gallons per year versus 200,000 gallons/yr for U.S. EPA, 1999a). The annual volume estimates between the reports were much closer for the other two sites, hence the cost estimates were very comparable.

Table 14. Various Costs per 1000 Gallons of PRB-treated Water, Using O&M PV Calculations and Factor 1 Estimated Annual Flow Through PRBs for a 30-year Period (Including Fe Maintenance Costs for Sites with Estimates)

Site	Total 30 Yr Annual O&M PV	Calc. PRB Construction Cost	30 Yr Total O&M + Construction	Factor 1 (0.67), GW 1000 Gal per 30 Yrs	30 Yr O&M Cost per 1000 Gal	30 Yr Construction Cost per 1000 Gal	30 Yr O&M + Construction Cost per 1000 Gal
USCG Support Center	$1.55E+06	$5.00E+05	$2.05E+06	7.97E+04	$ 19.51	$ 6.27	$ 25.79
Intersil Site	$1.74E+06	$6.56E+05	$2.39E+06	3.49E+04	$ 49.72	$ 18.77	$ 68.49
Moffett Federal Airfield	$1.65E+06	$3.77E+05	$2.02E+06	2.39E+04	$ 68.91	$ 15.80	$ 84.71
Aircraft Maintenance, OR	$9.15E+05	$7.00E+05	$1.61E+06	3.09E+05	$ 2.96	$ 2.27	$ 5.23
Former Manufacturing, Fairfield, NJ	$4.57E+05	$7.25E+05	$1.18E+06	1.04E+05	$ 4.40	$ 6.97	$ 11.37
Nickel Rim, Ontario	$5.49E+05	$3.50E+04	$5.84E+05	4.97E+03	$ 110.43	$ 7.04	$ 117.47
Moffett, Full-Scale Est.	$1.32E+06	$4.62E+06	$5.94E+06	9.46E+05	$ 1.40	$ 4.88	$ 6.28
Dover, AFB Full-Scale Est.	$2.71E+06	$5.82E+05	$3.29E+06	5.21E+04	$ 51.93	$ 11.16	$ 63.09

Sites with Fe Maintenance Estimates	(A) Fe Maint. 30 Yr PV (10 yr cycle)	(B) Fe Maint. 30 Yr PV + 30 Yr O&M PV	(A) + (B) + Calc. PRB Construction Cost	Total PV Cost per 1000 Gal over 30 Years
Intersil Site + Fe Maint.	$4.95E+05	$2.23E+06	$3.38E+06	$ 96.80
Moffett, Full-Scale Est. + Fe Maint.	$5.70E+05	$1.89E+06	$7.08E+06	$ 7.48
Dover, AFB Full-Scale Est. + Fe Maint.	$8.98E+05	$3.60E+06	$5.08E+06	$ 97.52

Table 15. Costs per 1000 Gallons Treated by PRB During a Single or Average Year, Including Data from U.S. EPA, 1999a

Site	Factor 1 (0.67), GW 1000 Gal per Yr	Construction Cost per 1000 Gal	Current Year O&M Cost per 1000 Gal	Capital Cost per 1000 Gal GW Treated Per Year (U.S. EPA, 1999a)	Avg. Annual O&M Cost per 1000 Gal GW Treated per Year (U.S. EPA, 1999a)
USCG Support Center	2.66E+03	$ 188	$ 32	$ 190	$ 33
Intersil Site	1.16E+03	$ 563	$ 82	$ 520	$ 83
Moffett Federal Airfield	7.96E+02	$ 474	$ 113	$ 1,600	$ 110
Aircraft Maintenance, OR	1.03E+04	$ 68	$ 5		
Former Manufacturing, Fairfield, NJ	3.47E+03	$ 209	$ 7		
Nickel Rim, Ontario	1.66E+02	$ 211	$ 181		
Moffett, Full-Scale Est.	3.15E+04	$ 146	$ 2		
Dover, AFB Full-Scale Est.	1.74E+03	$ 335	$ 85		

7.3. *P&T costs per 1000 gallons of treated water*

As per Section 7.1, P&T unit costs (i.e., cost per 1000 gallons) should be based on the volumes treated by the PRBs at the sites, rather than the quantity that could be pumped by the P&T systems. This, as previously stated, assumes that the PRBs are properly constructed and capturing all the contaminated ground water. This is very important, if one is using dollars per 1000 gallons as your unit cost, to avoid automatic bias in favor of higher volume P&T systems. For example, the previously mentioned report (U.S. EPA, 1999a) determines O&M costs per 1000 gallons for both P&T and PRB sites without making this distinction. This results in a chart where the Moffett PRB is the third most expensive among the 28 sites in terms of average annual O&M costs per 1000 gallons and the Intersil PRB site is fifth. Table 16 shows these costs and annual ground-water volume, per the report, for the four most expensive sites. It also recalculates the P&T unit costs based on the annual flow (from the same report) through the PRB at the Moffett site. When this is done, the P&T unit costs are much higher than the PRB unit cost. This recalculation is not meant to be accurate. The Moffett data is for a pilot-scale PRB that was never intended to capture the entire contaminant plume and the recalculated P&T systems are not located at the Moffett site. The calculation is merely demonstrative of the need to carefully choose the means of unit comparisons.

However a data comparison between the P&T system, previously operational at the Intersil site, and the current PRB installation is both demonstrative and indicative of more realistic unit costs. This is shown in Table 17, which again relies on data from the aforementioned report, that also recalculates the Intersil P&T unit cost based on the PRB annual flow at the Intersil site. This is reasonable since it is known that the currently installed PRB is accomplishing the remediation and the P&T system was no longer needed, and was discontinued. Approaching the unit costs in this manner results in the O&M for the P&T system being nearly 50% more expensive than O&M costs for the PRB, $127 versus $86 per 1000 gallons of treated ground water.

7.4. *Comparison of P&T and PRB unit costs at the PRB sites*

As mentioned in Section 6.1 and displayed in Tables 10 and 11, nine of the 22 PRB sites evaluated in this report have either had, or considered, P&T installations. Table 18 displays these data, for both the PRB installations and the P&T in terms of unit costs as cost per 1000 gallons of treated water. This table confirms that construction costs can go in either direction, from PRB being far less expensive to far more expensive than a P&T installation. It also establishes, for the five cases where data are available, that O&M costs for the PRB systems are likely to be much lower than for P&T systems, at least when periodic media maintenance costs are not included. Due to a paucity of data, it is difficult to ascertain whether this O&M cost advantage of PRB systems will persist when periodic media maintenance costs are included.

[4] *Uncertainty in the ground-water velocity at Moffett could also significantly impact the costs presented in Table 14. A higher velocity lowers the unit costs; a lower velocity increases them.*

Table 16. Evaluation of Reported O&M Unit Costs for Four Sites by Modifying the Unit Basis

Site	Type	Avg. Annual O&M Cost (U.S. EPA, 1999a)	1000 Gallons of GW Treated per Yr (U.S. EPA, 1999a)	Annual O&M per 1000 Gal (U.S. EPA, 1999a)	Annual O&M per 1000 Gal at Moffett PRB GW Volume
Libby	P&T	$ 500,000	2900	$ 170	$ 2,500
Old Mill	P&T	$ 210,000	1700	$ 130	$ 1,050
Moffett	PRB	$ 26,000	200	$ 110	$ 130
City Industries	P&T	$ 170,000	50000	$ 97	$ 850

Table 17. Evaluation of Reported P&T Versus PRB Unit Costs at the Intersil Site by Modifying the Unit Basis

Site	Type	Avg. Annual O&M Cost (U.S. EPA, 1999a)	1000 Gallons of GW Treated per Yr (U.S. EPA, 1999a)	Annual O&M per 1000 Gal (U.S. EPA, 1999a)	Annual O&M per 1000 Gal at Intersil PRB GW Volume
Intersil	P&T	$ 140,000	5000	$ 28	$ 127
Intersil	PRB	$ 95,000	1100	$ 83	$ 86

Table 18. Comparison of Costs per 1000 Gallons of Treated Ground Water for Construction and O&M Costs Using PRB and P&T Technologies at the PRB Sites in this Study

Site	Factor 1 GW Volume, 1000 Gal/Yr	A. PRB Construction Cost per 1000 Gal	B. P&T Construction Cost per 1000 Gal	A - B Construction Costs per 1000 Gal	C. Current Year (Annual) PRB O&M Cost per 1000 Gal	D. Current Year (Annual) P&T O&M Cost per 1000 Gal	C-D Current Year (Annual) O&M Costs per 1000 Gal
USCG Support Center	2.66E+03	$ 188	$ 188	$ -	$ 32	$ 75	$ (43)
Intersil Site	1.16E+03	$ 563	$ 279	$ 284	$ 82	$ 122	$ (40)
Watervliet Arsenal	5.19E+02	$ 528	$ 1,608	$ (1,079)	$ -	$ -	NA
Moffett Federal Airfield	7.96E+02	$ 474	$ -	NA	$ 113	$ -	NA
Somersworth Landfill SF Site	7.28E+04	$ 29	$ 357	$ (328)	$ -	$ 47	NA
Dover AFB, DE	8.69E+02	$ 412	$ -	NA	$ -	$ -	NA
Kansas City Plant, MO	4.19E+03	$ 296	$ -	NA	$ -	$ 48	NA
Aircraft Maintenance, OR	1.03E+04	$ 68	$ -	NA	$ 5	$ -	NA
Caldwell Trucking, NJ	1.80E+04	$ -	$ -	NA	$ -	$ -	NA
Former Manufacturing, Fairfield, NJ	3.47E+03	$ 209	$ 101	$ 108	$ 7	$ 28	$ (21)
Industrial Site, Coffeyville, KS	3.34E+04	$ 12	$ -	NA	$ -	$ -	NA
Industrial Site, NY	7.27E+03	$ 137	$ -	NA	$ -	$ 41	NA
Industrial Site, SC	2.40E+03	$ 148	$ -	NA	$ -	$ -	NA
Nickel Rim, Ontario	1.66E+02	$ 211	$ -	NA	$ 181	$ -	NA
Cape Canaveral, FL	4.10E+02	$ 1,781	$ -	NA	$ -	$ -	NA
MMR CS-10 Plume, MA	8.74E+03	$ -	$ -	NA	$ -	$ -	NA
Pease AFB, NH	0.00E+00	NA	NA	NA	NA	NA	NA
Vancouver, Canada	0.00E+00	NA	NA	NA	NA	NA	NA
Warren AFB Spill Site 7, WY	1.40E+04	$ 168	$ -	NA	$ -	$ -	NA
London, Ontario	0.00E+00	NA	NA	NA	NA	NA	NA
Moffett, Full-Scale Est.	3.15E+04	$ 146	$ 44	$ 102	$ 2	$ 22	$ (20)
Dover, AFB Full-Scale Est.	1.74E+03	$ 335	$ 289	$ 46	$ 85	$ 126	$ (41)

8. Summary and Conclusions

Permeable reactive barrier technologies have been incorporated at a large number of sites during the past decade and particularly during the past five years. A record of accomplishment for these PRB sites has begun to develop. In most cases, these systems have been very effective at achieving the site remediation goals. It is now incumbent upon the remediation community to better understand the cost-effectiveness of these systems, as PRB technology is added to the list of standard approaches that can be considered during a remediation feasibility study.

The analyses done for this report indicate several items of major importance that must be addressed before the cost-effectiveness of PRB systems can be fully assessed, some of which are also applicable to other technology assessments:

1. It is critical that all costs be fully tracked and documented during the planning, installation and operation of PRB systems. This should be done for all remedial options and systems, not just PRBs. Guidelines, such as those from the FRTR, have been developed and should be used. Lack of such detailed information weakens comparative analyses and makes them less meaningful.
2. The longevity of the PRB systems and the need, frequency, and extent of media maintenance are critical factors for confirming the initial perception of cost-effectiveness that has accompanied these systems. Additional studies are needed to determine when media maintenance will be necessary and to determine the best and most economical methods for maintenance should it be required.
3. Using traditional unit costs (costs per 1000 gallons) can be misleading when applied to comparing PRB and P&T system cost-effectiveness. This is because PRB systems are fundamentally different in their approach to contaminant remediation from P&T systems and almost never process as much water during a year. It is important to find a relevant basis of unit comparison and both explain and support it when contrasting the feasibility of these two approaches.

This report draws no absolute conclusions regarding the cost-effectiveness of PRB systems relative to P&T systems. This is in large part due to the paucity of available information on installed sites and the lack of knowledge of system longevity that currently exists (numbers 1 and 2, above). The results seem to indicate that PRB systems will generally be cheaper and less troublesome to operate and maintain, especially if periodic reactive media maintenance is not needed. It is likely that cost-effectiveness will depend extensively on the nature of the site and the contaminants. It is also important to consider the less obvious benefits of PRB technologies, relative to P&T, which do not appear in typical cost-comparison exercises. Among these benefits are:

1. In situ technique
    a. minimizes exposure of individuals at the surface to the contaminants
    b. minimizes exposure of individuals at the surface to chemicals used in the P&T treatment trains
    c. minimizes cross-media transfer of the contaminants (e.g., water to atmosphere)
    d. allows the land surface to continue to be used for other purposes (e.g., can be re-paved following PRB installation)
    e. eliminates (in most cases) the need for additional onsite treatment or transport and disposal of contaminated media typically generated by P&T systems; e.g., regeneration of activated carbon and ion exchange resins, disposal of sludge
2. Passive technology
    a. eliminates the need for utility hook-ups, and energy usage following construction
    b. doesn’t pull uncontaminated water to mix with the contaminated plume as P&T systems can
    c. remediation effectiveness not limited by slow contaminant desorption/dissolution processes since the PRB lies in the path of the resultant plume
    d. eliminates the need for full or part-time on-site personnel to maintain the system

Although the costs of PRB systems are not yet absolutely established, it is important to continue installing, documenting, and investigating these systems where appropriate. They remain a powerful addition to a remedial toolkit that has too few effective options for dealing with subsurface contamination.

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Appendix A
Example Contact Questionnaire

Site Name:

Contact:

General Cost and Site Information

Reactive Barrier Information:

Barrier Type (Circle or Select)

| *Funnel & Gate* | *Trench* | *Container* | *Other* |

Reactive Material (e.g., Fe^0)

Reactive Material Mass, Tons

Treated Contaminants (TCE, etc.)

Scale (Full or Pilot)

Contam Conc Maxima in µg/L

Est Total Plume Volume, L

Est. Plume Contam. Mass, Kg

Separate Source Treatment? | *Yes* | *No* |

***TOTAL** PRB Cost>* $

PRB Treatment Unit Cost

(e.g., $/lb TCE treated; $1000/lb TCE)

$

P&T Information:

Onsite P&T System or Cost Estimate? (Circle or Select)

| *Yes* | *No* | *Estimate* |

P&T Total Startup Cost or Estimate $

P&T Unit Cost (e.g., $/lb TCE) $

Annual P&T O&M Cost

Site Info Notes:

Specific PRB Cost and Site Information

Site Characterization

Exploration Well Installation Costs $

Exp Well Sampling Costs $

Exp Well Analytical Costs $

Push Tool Exploration Costs $

Coring Costs $

Core Test Costs $

Geologic/Stratigraphic Costs $

Hydrologic Test Costs $

Site Characteriz. Equipment Costs $

Other Characterization Costs $

Description of Other Char Costs:

***TOTAL** Site Char Costs>* $

Site Characterization Notes:

Design

Lab Tests/Data/Statistical Analysis Costs $

Modeling Costs $

Alternatives Comparison Costs $

Design Plans/Arch. Drawing Costs $

Other Design Costs $

Description of Other Design Costs:

***TOTAL** Design Cost>* $

Design Notes:

Construction

Reactive Media Costs	*$*
Funnel Costs	*$*
Gate Costs	*$*
Trench Costs	*$*
Mobilization Costs	*$*
Equipment Costs	*$*
Health/Safety Costs	*$*
Installation/Labor Costs	*$*
Materials Disposal Costs	*$*
Other Construction Costs	*$*
Describe Other Construction Costs:	
***TOTAL** Construction >*	*$*
Construction Notes:	

Monitoring / O&M

# of Compliance MWs (CMW)	
Avg. Cost of CMW	*$*
# of Performance MWs (PMW)	
Avg. Cost of PMW	*$*
Sampling Events / Year	
Cost / Sampling Event	*$*
Analytical Cost / Event	*$*
Monitoring Equipment Cost	*$*
Annual Monitoring Cost	*$*
Annual Reporting Cost	*$*
Cost of MWs added just for PRB	*$*
Other Initial Monit./Sampling Costs	
Describe Other Monit./Sampl. Costs:	
Monitoring Notes:	

Licensing and Reports

PRB License Fee	*$*
Funnel/Gate License Fee	*$*
Other License Cost	*$*
Design/Construction Report Costs	*$*
Annual License Renewal	*$*
***TOTAL** Initial Lic. & Report Costs >*	*$*
Licenses & Reports Notes:	

Other O&M Costs

Other Annual O&M Costs	*$*
Describe Other O&M Costs:	
Post Installation (PI) PRB Modifications?	*Yes*	*No*		
PI PRB Cost	*$*
Why Were PI PRB Mods Made?	
Additional Plume Treatments Required?	*Yes*	*No*		
Additional Treatment Cost/Year	*$*
Why Were Additional Treatments Needed	
***TOTAL** Annual O&M Costs>*	*$*
O&M Notes:	

Appendix B
Acknowledgments

The U.S. Environmental Protection Agency, Dynamac Corporation and Powell & Associates Science Services wish to thank all who participated in providing valuable information regarding PRB costs at the various sites for this report. Their efforts make this document a useful tool for improving decisions regarding implementation of permeable reactive barriers as an alternative to pump-and-treat. Below is a list of those who contributed information to the development of this report.

Aircraft Maintenance Facility, OR

David Weymann, P.E., PSS
The IT Group
15055 SW Sequoia Parkway, Suite 1400
Portland, OR 97224
Tel: (503) 624-7200 ext 543
Fax: (503) 624-7200
dweymann@theitgroup.com

Cape Canaveral

Jerry Hansen
US Air Force Center For Environmental Excellence
3207 North Road
Brooks AFB, TX 78235-5363
Tel: (210) 536-4353
Fax: (210) 536-4330
jerry.hansen@hqafcee.brooks.af.mil

Fairfield

Stephen Tappert
TRC VECTRE Corporation
333 Route 46 West
Suite 202
Mountain Lakes, NJ 07046
Tel: (973) 402-9900
Fax: (973) 402-4656
STappert@trcsolutions.com

Industrial Site, SC

Steven Schroeder
RMT, Inc.
100 Verdae Blvd.,
PO Box 16778
Greensville, SC 29606-6778
Tel: (864) 281-0030
Fax: (864) 287-0288
steve.schroeder@rmtinc.com

Intersil

Dominique Sorel
Project Hydrogeologist
Geomatrix Consultants
2101 Webster St, 12th floor
Oakland, CA 94612
Tel: (510) 663-4161
Fax: (510) 663-4141
dsorel@geomatrix.com

Kansas City

Paul Dieckmann
Allied Signal PM&T
2000 East 95th Street
PO Box 419159
Kansas City, MO 64141-6159
Tel: (816) 997-2335
Fax: (816) 997-7361
pdieckmann@KCP.com

Moffett AFB

Arun Gavaskar
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201
Tel: (614) 424-3403
Fax: (614) 424-3667
gavaskar@battelle.org

Nickel Rim, Ontario

David Blowes
Waterloo Centre For Groundwater Research
University Of Waterloo
Waterloo, ONTARIO
Tel: (519) 888-4878
Fax: (519) 746-5644
blowes@sciborg.uwaterloo.ca

Pease AFB

Jeffrey Cange
Bechtel Environmental
151 Layfayette Drive
P.O. Box 3500
Oak Ridge, TN 37831-0350
Tel: (423) 220-2255
Fax: (423) 220-2108
jbcange@bechtel.com

Somersworth Landfill

Roger Duwart
U.S. EPA Region 1
1 Congress Street, Suite 1100 (HBO)
Boston, MA 02114-2023
Tel: (617) 918-1259
Fax: (617) 918-1291
duwart.roger@epa.gov

USCG Support Center, Elizabeth City, NC

Robert Puls
U.S. Environmental Protection Agency
R. S. Kerr Environmental Research Center
PO Box 1198
Ada, OK 74821-1198
Tel: 580-436-8543
Fax: 580-436-8703
puls.robert@epamail.epa.gov

Vancouver, Canada

Eric Pringle
Hemmera Envirochem Inc.
Suite 350, 1190 Hornby Street
Vancouver, British Columbia V6Z 2K5, Canada
Tel: (604) 669-0424
Fax: (604) 669-0430
eric.pringle@conorpacific.com

Warren AFB

Michael May
URS Greiner
4582 South Ulster Street
Denver, CO 80237-2637
Tel: (303) 740-3863
michael_may@urscorp.com

Watervliet Arsenal

Russell Marsh
US Army Corps Of Engineers
P.O. Box 1715
Baltimore, MD 21203
Tel: (410) 962-2227
Fax: (410) 962-2318
russell.e.marsh@usace.army.mil

United States
Environmental Protection
Agency

National Risk Management
Research Laboratory
Cincinnati, OH 45268

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