Green Remediation

Energy Consumption and Carbon Dioxide Emissions at Superfund Cleanups

Carbon Dioxide Emissions

Energy Use

Energy Cost

Draft

Prepared for
U.S. Environmental Protection Agency
Office of Superfund Remediation and Technology Innovation
Washington, D.C. 20460
EPA Contract EP W-07-037
May 2008

Prepared by
Environmental Management Support, Inc.
www.emsus.com

Energy Consumption and Carbon Dioxide Emissions at Superfund Cleanups

1. Purpose

The cleanup of Superfund and other hazardous waste sites typically consume large quantities of electricity, natural gas, gasoline, and diesel fuel. EPA's Office of Solid Waste and Emergency Response (OSWER) is analyzing the extent of energy use, CO2 emissions, and energy cost of technologies used to treat contaminated materials at National Priorities List (NPL) sites. The analysis will help the Agency to establish benchmarks regarding the energy consumption and carbon emissions of various cleanup approaches; examine operational and management practices typically used to implement these technologies; and identify methods for reducing the energy consumption and optimizing the operations of treatment systems.

This paper describes the methodology used to develop a preliminary estimate of energy use, carbon emissions, and energy cost (also referred to as the remediation carbon footprint) associated with remediation activities at NPL sites. It also includes preliminary results for five frequently used remediation technologies as they have typically been implemented at NPL sites, and discusses some potential refinements and expansions of the analysis. This paper, which includes a detailed description of Version 1.0 of the model, is being released for review and comment on the overall approach, model structure, assumptions, data sources, and specific values used.

OSWER would greatly appreciate comments on this initial version of the analysis, or data that might shed further light on these issues. Comments may be sent to Carlos Pachon, 701-603-9904 or pachon.carlos@epa.gov.

The remainder of this paper includes the following:

- Section 2. Background
- Section 3. Methodology Overview
- Section 4. Model Structure
- Section 5. Preliminary Results
- Section 6. Sensitivity Analysis
- Section 7. References
- Attachment A: Model printouts for each of 5 technologies (A separate file contains the Excel worksheets)

2. Background

An average of $6-8 billion dollars is spent annually on hazardous waste site investigation and cleanup actions in the U.S. These cleanup actions can significantly impact the communities in which they occur and local and regional ecosystems. They also consume significant amounts of electricity and fossil fuels and contribute to air pollutant emissions, including greenhouse gases. In 2007 about 70% of electricity supply was generated by fossil fuel-fired plants. As part of its green remediation initiative, OSWER is examining the extent of energy use and greenhouse gas emissions from cleanup actions.

A part of OSWER's effort, the Technology Innovations and Field Services Division (TIFSD) is developing rough estimates of the annual and long-term energy consumption, energy costs, and carbon dioxide (CO_2) emissions associated with remediation activities at NPL sites through 2030. These estimates will establish a baseline against which to measure any future changes and help identify opportunities for improving the carbon footprint of remediation activities. Depending on evaluation of the results and data availability, the methodology may also be extended to develop a picture of the footprint associated with other programs affected by OSWER initiatives to clean up hazardous waste sites. The footprint estimates, in turn, will help inform OSWER decision-making initiatives and contribute to the development of analytical tools that address energy efficiency and greenhouse gas emissions resulting from cleanup activities.

3. Methodology

The estimates of energy use and emissions are based on a "model facility" analysis. The model facility represents a hypothetical "average" facility or remediation project using a cleanup technology as it is typically implemented in the U.S. Because actual field data on energy use and emissions at remediation projects are sparse, it is impractical to collect remedy system design and performance data that would be representative of all the project applications, site types, and waste site conditions. Some case study data are available for specific sites. Where practical, field data may be used to verify some of the assumptions used in this analysis. It is anticipated that, after the estimates for the NPL applications are completed and reviewed, a similar approach can be used for other remediation technologies, as well as for other cleanup programs, such as RCRA corrective action, underground storage tanks, and state and brownfield programs.

This initial analysis includes five remediation technologies frequently used at NPL sites: pump and treat (P&T), soil vapor extraction (SVE), multi-phase extraction (MPE), air sparging (AS), and thermal desorption (TD). These are the most frequently used active treatment technologies at NPL sites. For each technology examined, this analysis included four steps: (a) characterizing the "typical," or model remediation project, (b) estimating the number of applications of each technology, (c) developing and selecting key inputs and global assumptions, and (d) developing the model structure. Following initial consensus by Office of Site Remediation and Technology Innovation (OSRTI) technical experts, the process components and structure of each model were evaluated by an EPA vetting team comprised of representatives from OSWER headquarters and regional offices. Comments from this process were incorporated into the models.

The first three steps that comprised this analysis are discussed below and the fourth step (model structure) is described in Section 5.

3.1 Establishing the Model Technology Components

For each technology, the key treatment processes and engineering or mechanical components with significant energy demands were enumerated, to establish a "typical" operating scenario. For each process component, this scenario included such elements as equipment size (e.g., horsepower of a pump), number of equipment units in a typical system, hours of operation, and energy demand. The model does not account for system inefficiencies such as faulty equipment parts or redundant design or for site-specific conditions related to the nature of target contaminants, climate, geology, hydrology, or regional infrastructures. In developing this typical, or model, system, the team strived to depict an average of all applications of the technology at NPL sites. While it is understood that conditions vary widely from site to site, this type of simplification allows for reasonable estimates at the policy level.

Process components were identified through online review of diverse and readily available information sources, including:

- Site-specific cost and performance reports compiled by the Federal Remediation Technologies Roundtable,
- Federally issued technical guidance or reports on implementation of specific treatment technologies,
- Technology- and site-specific case studies compiled by EPA and other federal agencies,
- Site-specific cleanup summaries in technical conference proceedings,
- Technical articles and product comparisons in technical journals,
- Engineering specifications issued by vendors of commercial products, and
- Anecdotal information provided by project managers in response to specific questions or as part of other OSRTI projects.

The analytical scope does not include primary data collection, personal interviews, or extensive database (including CERCLIS) searches. It is anticipated that future drafts will reflect feedback from Agency program offices. References are included in Section 8.

3.2 Estimating the Number of Applications of Each Technology

In addition to evaluating data on past and current remediation projects, it was also necessary to forecast the number of future applications of each cleanup technology. The study was guided in this effort by a December 2004 OSRTI study which estimated national cleanup needs over a 30 year period and the 11th and 12th editions of *Treatment Technologies for Site Cleanup: Annual Status Report* (ASR), an OSRTI publication. Although the 2004 study indicates the total level of cleanup work needed in the U.S., assuming current regulations and practices, it only provided specific estimates for a few technologies. Nevertheless, it indicates that the there will be a continued demand for hazardous waste cleanups over the period of this analysis (2008-2030).[1] Based on this projection, it was assumed that the selection and implementation of new applications of the five technologies would follow recent trends, which are derived from data in the ASR. These projections are explicitly shown in the spreadsheets. While such projections are always subject to variation and uncertainty, these appear reasonable given recent trends and the future overall demand for remediation.

3.3 Developing and Selecting Key Inputs and Global Assumptions

Key assumptions and inputs, such as energy and emission conversion factors, and average energy costs, were used in a number of calculations in the analysis. These are shown in Exhibits 1 and 2. A number of these inputs, such as the carbon content of fuel, fuel source for electricity supplied (and therefore carbon emissions per kWh), can vary widely around the country, from site to site, and over time, for a number of reasons. In this initial version, the model uses national averages for a number of these variables. For example, the national average electricity price was $0.0914 per kWh as of December 2007. However, the rate typically varies widely by region, sub-region, time of day, season, pricing categories (commercial, industrial, residential), special arrangements with power suppliers, (interruptible service, volume pricing, or off-grid or private sources), and other factors. The model is structured so that a user can input different factors for these variables. For example, if progress is made toward achieving a renewable portfolio standard (RPS) in a state, the percentage of electricity derived from fossil fuels can be revised when applying the model to that state.

[1] This 23-year period was used to harmonize with the planning efforts of various work groups within EPA.

All costs are in constant 2007 dollars. To get a full picture of costs in nominal dollars, such as would be used for budgeting purposes, these figures would have to be inflated for the outyears and could be substantially higher. Between 1913 and 2006, the annual change in the Consumer Price Index (CPI) averaged 3.41%. The rate for construction costs, which may be more appropriate for predicting some cleanup activities, is somewhat higher.

3.4 Critical Issues that Need Review

OSRTI has developed an analytical structure based on a "model" or "average" remediation project approach. While these models are developed based on a variety of sources, such as surveys, personal field experience, and discussions with professionals within and outside EPA, it is unclear how representative they are of the universe of applications. Some of the key inputs and assumptions that can significantly affect the results of this analysis are listed below:

- Estimate of the number of future applications of each technology
- Estimate of the average duration of operations; for example, this initial analysis uses an average P&T system duration of 30 years
- Average system size and number of components (e.g., pumps, wells)
- Inputs and assumptions regarding energy consumption, conversion factors, and costs
- Percentage of electricity generated from fossil fuels versus non-CO_2 producing sources
- Model structure and calculations

EPA's OSRTI would appreciate any comments or data that might shed further light on these issues. Comments may be sent to Carlos Pachon, 701-603-9904 or pachon.carlos@epa.gov.

EXHIBIT 1: GENERAL ASSUMPTIONS

This table provides the basic global assumptions that are applied in the analysis of all five remediation technologies. Assumptions and inputs that apply to a specific technology are provided in a reference table in the workbook for that technology (Attachment A," Detailed Calculations for Five Technologies at NPL Sites").

1. Assume that all electricity for treatment systems are supplied by public utility.

2. Exclusions from this analysis include:
   - Fossil fuel used for some routine field activities; construction of remedy components; excavation, handling, and transportation of materials, such as soil; and periodic sampling, transportation, and disposal of contaminated media and treatment products,
   - Air emissions from treatment systems (typically containing contaminants at concentrations below regulatory thresholds);
   - Field trials during remediation design; and
   - Installation of treatment systems. In the future, consideration will be given to including construction and installation activities.

3. CO2 emissions are based on the U.S. average: 1.37 lb of CO2 emitted per kWh generated (DOE Energy Information Administration, Electric Power Annual 2005, Table 5.1). This figure may be revised periodically or as needed for a specific region or power source.

4. All costs are in constant 2007 dollars. Actual costs in the future are likely to be higher, and forecasted inflation can be built into these calculations.

5. This analysis assumes fossil sources account for 71% of U.S. electricity demand. Source: U.S. Energy Information Administration, DOE, "Net Generation by Energy Source by Type of Producer," October 22, 2007. http://www.eia.doe.gov/cneaf/electricity/epa/epat1p1.html. DOE publishes averages of this value by region. Specific sites or local areas can have different values. Other values may be used in the model, simply by changing the figure in the "Key Inputs" table.

6. Electricity requirements of equipment are estimated at 0.7456 kW per unit of horsepower (U.S. EPA Climate Change Division, www.epa.gov/climatechange/emissions/ ("Unit Conversions," November 2004).
7. "Major energy-consuming treatment components" of a remediation system are considered those with annual electricity consumption greater than 1,000 kWh/year.

8. At this point, this analysis does not account for operating efficiency of treatment systems, which can be highly variable.

9. This analysis assumes projects described in primary information sources did not undergo remedial system evaluation (RSE) optimization, and does not consider current or future RSE optimization.

10. This analysis does not account for energy-consumption reductions attributed to combined technology applications with shared below-ground components and/or above-ground treatment processes.

11. Energy prices for the model are as of December 2007. Model users can easily update these prices by changing the appropriate figure in the Global Reference Table (also referred to as the "Key Inputs" table).

Exhibit 2. Global Reference Table for Remediation Footprint Analysis

This table provides the basic inputs for all five remediation technologies. Inputs and assumptions that apply to a specific technology are provided in a reference table in the workbook for that technology.

Input Variable	Value	Source
Average duration of operations	Varies with technology	See technology table for each individual technology.
Average period in design and installation	Varies with technology	See technology table for each individual technology.
Future installations of a technology	Varies with technology	See technology table for each individual technology.
CO2 emitted per kWh generated (lbs)	1.37	EIA 2005, Electric Power Annual 2005. Table 5.1
Current electricity cost per kWh ($)	0.0914	EIA, Feb. 2008. Data for Dec. 2007
Pounds per metric ton	2204.62	Standard value
Fossil fuel-derived portion of U.S. electricity (% multiplier)	0.71	*EIA, Annual Energy Outlook 2008. Table A8*
1.5-hp consumption per year (kWh)	9,797	Equipment requirements estimated at 0.7456 kW per unit of horsepower (U.S. EPA Climate Change Division, www.epa.gov/climatechange/emissions, (Nov. 2004).
5-hp consumption per year (kWh)	32,657	0.7456 KW/HP as above
7.5-hp consumption per year (kWh)	48,986	0.7456 KW/HP as above
10-hp consumption per year (kWh)	65,315	0.7456 KW/HP as above
15-hp consumption per year (kWh)	97,972	0.7456 KW/HP as above
20-hp consumption per year (kWh)	130,630	0.7456 KW/HP as above
100-hp consumption per year (kWh)	653,146	0.7456 KW/HP as above
Energy consumption of conventionally-constructed 2,000-sf building (kWh)	16,400	e.g., lighting, air control, computer systems, portable equipment, based on a 2003 estimate of 8.2 kWh per square foot of "service" building (EIA, Table C21, 2006).
CO2 emitted per gallon of gasoline (lbs)	19.56	U.S. DOE, EIA, web site. February 2008. http://www.eia.doe.gov/oiaf/1605/coefficients.html
CO2 emitted per gallon of diesel consumed (lbs)	22.38	U.S. DOE, EIA, web site. February 2008. http://www.eia.doe.gov/oiaf/1605/coefficients.html
Average fuel price for gasoline ($)	3.02	U.S. EIA web site, January 2008. Price as of 12/07. All grades plus taxes. http://www.eia.doe.gov/oil_gas/ petroleum/data_publications/wrgp/mogas_home_page.
Average fuel price for diesel ($)	3.29	U.S. EIA web site, January 2008. http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_home_page.html

4. Model Structure

For each technology, the analysis includes seven related worksheets (Attachment A). These worksheets also draw data from two reference tables: (a) the first table, duplicated in Exhibit 2 above, includes common input variables, such as an energy and emission conversion factors and electricity prices, and (b) a similar table specific to each technology, which is included in the specific worksheet for that technology.

- **Worksheets 1, 2, and 3** together estimate the number of projects that use the technology. The analysis begins with Worksheets 1 and 2, which show past and current projects where the technology has been applied from 1982 through 2007. Worksheet 3 provides projections from 2008 to 2030. In the current draft, these are linear assumptions based on recent trends. If an alternative source for a projection is found, or if there were a reason to increase or decrease them, these changes can be made in these worksheets. Changes in assumptions, such as the amount of time it takes for design and construction, or the duration (lifespan) of the system will also change the number of applications in the outyears.
- **Worksheet 4** calculates electricity consumption for a single "typical" system. It shows the annual average consumption as well as the total for the estimated expected life of the system. Note that the life of the system is not usually equal to the forecast period of this analysis (2008-2030). For example, the average duration of a P&T system is assumed to be 30 years, but the analysis period is 23 years. Summary tables for the reporting of total remediation emissions will be based on the 23-year period. To see the emission or costs over the project duration, a user would need to go to Worksheet 4.[2]
- **Worksheet 5,** also for a single typical system, is similar to Worksheet 4, except that it is for fossil fuels. Currently, it addresses only gasoline and diesel. As further detail is added to the model, or other technologies are included, other fuels, such as natural gas and propane can be added in the same manner.
- **Worksheet 6,** also for a single typical system, totals the CO2 emissions and costs for all the above sources.
- **Worksheet 7** sums all the energy use (kWhs and gallons of fuel), CO2 emissions, and costs for the entire 23-year period for all systems expected to operate during that period. It also shows the average annual values for the total of all systems.
- **Worksheet 8** is a reference table for inputs that are specific to the particular technology. This table can be used to examine the effect of different assumptions, such as the duration of a treatment system.

[2] This 23-year period was used to harmonize with the planning efforts of various work groups within EPA.

5. Preliminary Results Highlights

Exhibit 3 is a summary of the estimated profile of energy use, energy cost, and emissions associated with the five technologies:

- Between 2008 and 2030, 9.3 million metric tons (MMT) of CO2 will be emitted from the use of these five technologies at NPL sites, averaging 404,000 MT annually.
- Between 2008 and 2030, 14.2 billion kWh of electricity will be used in applications of the five technologies at NPL sites, averaging 618 million kWhs annually.
- Between 2008 and 2030, 53 million gallons of gasoline and diesel fuels will be used in the application of these five technologies at NPL sites, averaging 2.3 million gallons annually.
- The cost of this energy, in 2007 dollars, will total $1.4 billion over the period
  - Electricity use accounts for 89% of total energy cost, and fuel accounts for 11%.
  - Electricity use accounts for 95% of total CO_2 emissions, and fuel accounts for 5%.

6. Sensitivity of Results to Key Variables

Exhibit 4 was developed to examine how the estimates vary with moderate changes to a number of key input variables for pump and treat systems. These results indicate that:

- **Emissions** vary from 76% to 98% of baseline (middle) values for the lower estimates and from 102% to 123% of baseline values for the higher estimates for the inputs. The most influential inputs are average number of extraction pumps, and average duration of operations of a P&T system .
- **Best practice energy-efficiency measures** have the potential to reduce electricity consumption by 24% .
- Varying the assumptions by reasonable amount will lower **energy costs by** 1% to 22% for the lower value assumptions (optimistic ones). For the high-value assumption options, energy costs could increase 101% to 120%. The most influential variables are the same as for emissions: average number of extraction pumps, average duration of operations of a P&T system, and intermittent operating schedules.
- The **average number of operating systems** ranges from 79% to 111% of the baseline value. The most influential variables are duration of the average P&T system, average number of new P&T projects selected, and the amount of time it takes to complete predesign, design, and construction.

Exhibit 3. Estimated NPL Sites Energy Consumption, Energy Costs and CO2 Emissions 2008-2030: Per Unit

Per Unit

	kWh Per Unit		Gallons of Fuel Per Unit		CO2 Emissions Per Unit		Energy Cost Per Unit	
	Annual Average (kWh x 1,000)	Total 2008-2030 (kWh x 1,000)	Annual Average (Gallons)	Total 2008-2030 (Gallons)	Annual Average (MT)	Total 2008-2030 (MT)	Annual Average ($ x 1,000)	Total 2008-2030 ($ x 1,000)
Pump and Treat	905	20,816	4,000	92,000	598	13,752	$95	$2,180
Soil Vapor Extraction	232	5,339	2,000	46,000	162	3,726	$27	$627
Multi-Phase Extraction	1,669	38,397	3,952	90,896	1,072	24,667	$165	$3,784
Air Sparging	950	21,847	1,976	45,448	608	13,980	$93	$2,134
Thermal Desorption *	112,969	2,598,298	1,976	45,448	70,219	1,615,043	$10,331	$237,622
Total, five technologies	116,726	2,684,698	13,904	319,792	72,660	1,671,169	$10,711	$246,347

* Thermal desorption project durations average only four months. The figures shown are for 12 months of operations, or three thermal desorption projects.

National Total All Units

	Total National kWh: All Units		Total Gallons of Fuel All Units		Total CO2 Emissions All Units		Total Energy Cost: All Units	
	Annual Average (kWh x 1,000)	Total 2008-2030 (kWh x 1,000)	Annual Average (Gallons)	Total 2008-2030 (Gallons)	Annual Average (MT)	Total 2008-2030 (MT)	Annual Average ($ x 1,000)	Total 2008-2030 ($ x 1,000)
Pump & Treat	489,607	11,260,969	2,163,910	49,769,927	323,456	7,439,480	$51,285	$1,179,558
Soil Vapor Extraction	6,734	154,890	58,018	1,334,406	4,700	108,094	$791	$18,187
Multi-Phase Extraction	18,679	429,625	44,219	1,017,033	12,000	276,004	$1,841	$42,339
Air Sparging	10,156	233,599	21,128	485,943	6,499	149,476	$992	$22,819
Thermal Desorption	92,919	2,137,126	1,625	37,381	57,756	1,328,389	$8,498	$195,446
Total, five technologies	618,096	14,216,209	2,288,900	52,644,690	404,411	9,301,443	$63,406	$1,458,348

Exhibit 4. Sensitivity of Estimates to Critical Inputs

The model allows a user to enter different values for key parameters, in order to examine the impacts on the overall estimates. The following two tables were prepared from the P&T section of the model to demonstrate how the estimates change with variations in the input variables and assumptions. The values were selected based on a number of sources; some are merely placeholder assumptions.

Results of Sensitivity Analysis: CO2 Emissions All Units 2008-2030
Pump and Treat Systems

P&T-Specific Inputs	Middle Value	Low Value	High Value	Middle (Baseline) Value (MT)	Low Value (Ratio to Baseline)	High Value (Ratio to Baseline)
Average annual number of P&T systems installed during 2001-2005	16	12	20	6,199,698	0.95	1.05
Average P&T system operational duration	30	18	42	6,199,698	0.79	1.11
Percentage of projects in predesign, design, or construction that become operational during the year, on average.	0.2	0.1666	0.25	6,199,698	0.98	1.02
Average number of extraction pumps	9	6	12	6,199,698	0.77	1.23
Average no. of above-ground pump/treat houses	1	1	1	6,199,698	1	1
Average no. of aboveground treatment systems	1	1	1	6,199,698	1	1
Average no. of aboveground transfer systems	1	1	1	6,199,698	1	1
Average annual energy consumption of above-ground treatment system	131,400	131,400	144,540	6,199,698	1	1.02
Reduction in electricity consumption achieved by energy-efficient measures (%)	0.00	25	0	6,199,698	0.76	1
Reduction in electricity consumption achieved by intermittent pumping (%)	0.00	25	0	6,199,698	0.76	1
				6,199,698		
Key General Inputs				6,199,698		
% of U.S. electricity from fossil fuels (%)	0.71	60	0.71	6,199,698	0.85	1
Fuel cost/gallon ($)	3	2.25	3.75	6,199,698	1	1
CO2 emitted per gal. of fuel used (lbs)	19.56	16.63	22.50	6,199,698	0.9867	1.0133
Data monitoring/ processing (kWh/yr)	50,000	40000	60000	6,199,698	0.98826	1.01174

Exhibit 4 (Continued)
Results of Sensitivity Analysis: Energy Costs All Units 2008-2030
Pump and Treat Systems (2007 dollars (000))

	Middle	Low	High	Middle (Baseline) Value ($000)	Low Value (Ratio to Baseline	High Value (Ratio to Baseline
P&T-Specific Inputs	Value	Value	Value			
Average annual number of P&T systems installed during 2001-2005	16	12	20	1,346,525	0.95	1.05
Average P&T system operational duration	30	18	42	1,346,525	0.79	1.11
Percentage of projects in predesign, design, or construction that become operational during the year, on average.	0.2	0.1666	0.25	1,346,525	0.98	1.02
Average number of extraction pumps	9	6	12	1,346,525	0.80	1.20
Average number of above-ground pump/treat houses	1	1	1	1,346,525	1	1
Average number of aboveground treatment systems	1	1	1	1,346,525	1	1
Average number of aboveground transfer systems	1	1	1	1,346,525	1	1
Average annual energy consumption of aboveground treatment system	131,400	131,400	144,540	1,346,525	1	1.01
Reduction in electricity consumption achieved by energy-efficient measures (%)	0.00	25	0.00	1,346,525	0.78	1
Reduction in electricity consumption achieved by intermittent pumping (%)	0.00	25	0.00	1,346,525	0.78	1
				1,346,525		
Key General Inputs				1,346,525		
% of U.S. electricity from fossil fuels (%)	0.71	60	0.71	1,346,525	1	1
Fuel cost/gallon ($)	3	2.25	3.75	1,346,525	0.97	1.03
CO2 emitted per gal. of fuel used (lbs)	19.56	16.63	22.50	1,346,525	1,092,043	1,092,043
Data monitoring/processing (kWh/yr)	50,000	40000	60000	1,346,525	0.99	1.01

7. References

Pump and Treat

Federal Remediation Technologies Roundtable. *Remediation Technologies Screening Matrix and Reference Guide (Version 4.0): Ultraviolet (UV) Oxidation* http://www.frtr.gov/matrix2/section4/4_56.html

Federal Remediation Technologies Roundtable. *Remediation Technologies Screening Matrix and Reference Guide (Version 4.0): Air Stripping* http://www.frtr.gov/matrix2/section4/4-46.html

U.S EPA, OSWER, September 1999. *Groundwater Cleanup: Overview of Operating Experience at 28 Sites* EPA 542-R-99-006

U.SEPA, OSWER, December 2001. *Groundwater Pump and Treat Systems: Summary of Selected Cost and Performance Information at Superfund-financed Sites* EPA 542-R-01-021b

U.SEPA, OSWER, December 2002. *Elements for Effective Management of Operating Pump and Treat Systems* EPA 542-R-02-009

U.SEPA, OSWER, April 2005. *Cost-Effective Design of Pump and Treat Systems* EPA 542-R-05-008

U.S. EPA, OSWER, January 2002. *Groundwater Remedies Selected at Superfund Sites* EPA 542-R-01-022

Soil Vapor Extraction

U.S. EPA, OSRTI, March 2006. *Off-Gas Treatment Technologies for Soil Vapor Extraction Systems: State of the Practice* EPA 542-R-05-028

Multi-Phase Extraction

U.S. EPA, OSRTI, March 2006. *Off-Gas Treatment Technologies for Soil Vapor Extraction Systems: State of the Practice* EPA 542-R-05-028

U.S. ACE, June 2002. Engineer Manual: *Engineering and Design – Soil Vapor Extraction and Bioventing* EM 1110-01-4001

Air Sparging

U.S. ACE, June 2002. Engineer Manual: *Engineering and Design – Soil Vapor Extraction and Bioventing* EM 1110-01-4001

Thermal Desorption

Federal Remediation Technologies Roundtable. *Remediation Technologies Screening Matrix and Reference Guide (Version 4.0): Thermal Desorption.* http://www.frtr.gov/matrix2/section4/4-26.html

General Resources

Federal Remediation Technologies Roundtable, (online). *Technology Cost and Performance* profiles on multiple sites http://www.frtr.gov/costperf.htm

U.S. EPA (online). *Personal Emissions Calculator Assumptions and References* http://www.epa.gov/climatechange/emissions/

U.S. DOE Energy Information Administration [online]. http://www.eia.doe.gov/

Various equipment specifications provided online by vendors

Communications

June 18, 2007. OSRTI and EMS, Inc. teleconference on technology-specific footprints of Superfund cleanups based on five common energy-intensive treatment technologies Carlos Pachon invitees: Jean Balent, Kathy Yager, Kelly Madalinski, Dan Powell, Ellen Rubin, Mike Adam, Sid Wolf (EMS, Inc.), Sandra Novotny (EMS, Inc.).

June 19, 2007. Telephone communication with AFCEE (Jim Gonzales [AFCEE] and Sandra Novotny [EMS, Inc.]) confirming AFCEE has not developed a scenario describing components of "typical" treatment systems.

June 10, 2007. Telephone communication with USACE (Dave Becker [USACE] and Sandra Novotny [EMS, Inc.] confirming assumption applicability of: (1) 15-hp blower with no extraction pump for soil vapor extraction and air sparging, and (2) ten 10-hp extraction pumps for dual-line multi-phase extraction processes.

Attachment A. Printout of five technologies

These tables are in a separate Excel file.