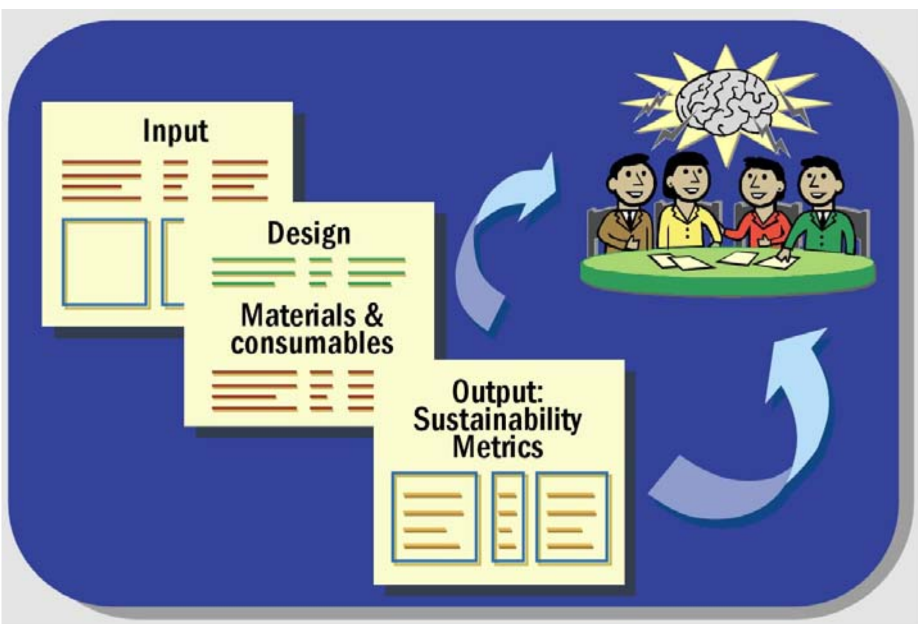
SRT™

SUSTAINABLE REMEDIATION TOOL

Version 2.2

User Guide

September 2011



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U.S. AIR FORCE

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1 MOTIVATION FOR SUSTAINABLE REMEDIATION TOOL

Many responsible parties, including private sector companies and government agencies, are beginning to analyze sustainability factors as part of their decision making processes for new remediation systems as well as for evaluation and optimization of existing systems. Of particular interest to government agencies is a new paradigm for remediation propelled by Executive Orders 13423 and 13514, issued in January 2007 and October 2009 respectively. EO 13423 states that:

> *"…Federal agencies…conduct their environmental…and energy-related activities…in an environmentally, economically, and fiscally sound, integrated, continuously improving, efficient, and sustainable manner."*[1]

> *"…sustainable means to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations of Americans."*[1]

This executive call to operate in a sustainable manner leaves environmental remediation professionals with the need for tools to help develop sustainable remediation practices.

The overarching concepts for sustainability as applied to remediation include a wide range of environmental and human health impacts considered over the short- and long-term. By applying broader and more complete thinking to better inform stakeholders and the public, decisions can be made that minimize the overall environmental burdens and costs of a remediation project. This approach requires a broad system view to integrate all the different and competing environmental factors involved while also requiring a detailed, life-cycle assessment (LCA)-style approach in which the impacts of each step of a process are summed and considered in the overall decision-making process. This method precludes outcomes that may correct one environmental problem but cause or exacerbate another. In this way, both the short- and long-term environmental outcomes, summarized in key metrics, can inform the overall decision.

[1] "Executive Order 13423: Strengthening Federal Environmental, Energy, and Transportation Management," *Federal Register*, Vol. 72, No. 17, pp. 3, 6-7.

At present, remediation designs, technology selections, and remedial process optimization (RPO) focus on risk reduction, compliance with existing laws, implementability, cost, and other metrics. By including sustainability in an environmental restoration program, several new metrics – such as evaluating carbon emissions, energy consumption, worker safety, and resource service for land and/or groundwater – may inform the remediation decision making process. Estimation of these metrics in an easy-to-use tool would provide remediation professionals with a way to consider the sustainability of various remediation technologies while circumventing time-consuming hand calculations of these parameters.

2 WHAT THE SUSTAINABLE REMEDIATION TOOL DOES

The Sustainable Remediation Tool (SRT or Tool) is designed to serve three general purposes: i) planning for the future implementation of remediation technologies at a particular site, ii) comparing remediation approaches on the basis of sustainability metrics, and iii) providing a means to evaluate optimization of remediation technology systems already in place. The Tool allows users to estimate sustainability metrics for specific remedial action technologies. The technologies, selected by the Air Force Center for Engineering and the Environment (AFCEE), are:

Soil Remediation:

- i) Excavation
- ii) Soil Vapor Extraction
- iii) Thermal Treatment

Groundwater Remediation:

- iv) Pump and Treat
- v) Enhanced Bioremediation
- vi) Permeable Reactive Barrier
- vii) In Situ Chemical Oxidation
- viii) Long-term Monitoring / Monitored Natural Attenuation

These eight (8) technologies were made available in SRT Version 2.1 released in May 2010. SRT Version 2.2 simplifies the SRT data entry process for users of the Remedial Action Cost Engineering and Requirements (RACER™) software application. RACER is commonly used for environmental projects to calculate costs for all phases of environmental restoration and remediation. As described in Section 2.5 below, users of RACER version 11.0 (and higher) can export data from RACER and import those data directly into applicable fields in the SRT. The RACER import function is the key change in SRT Version 2.2 (see circled area in Figure 1). Although minor cosmetic changes were also made, SRT calculations and default values remain the same as in Version 2.1.

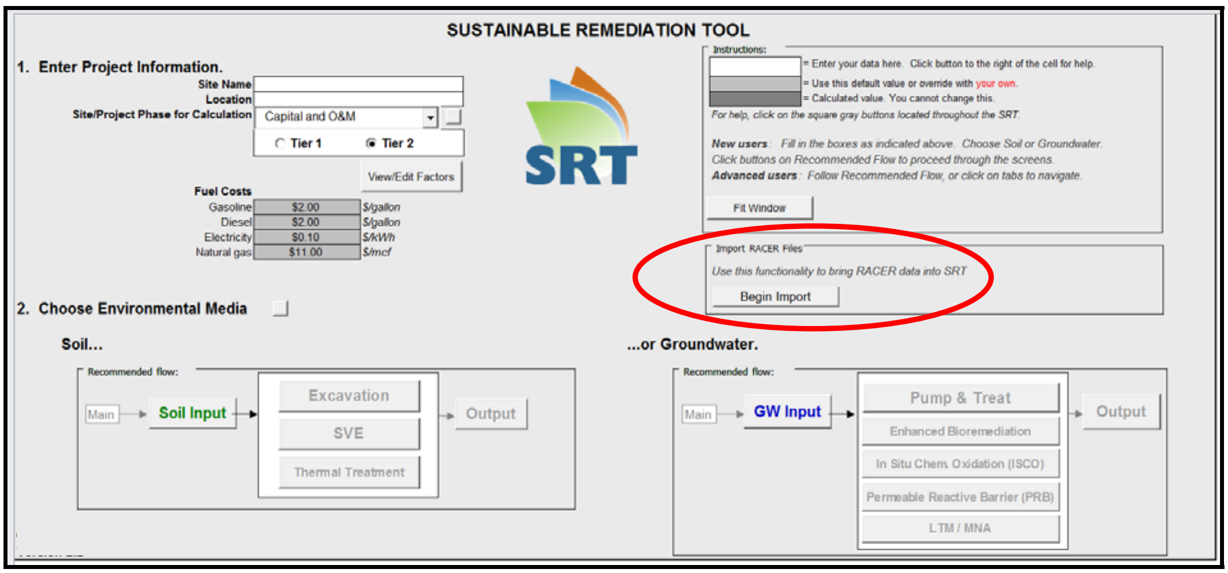


Figure 1: Main Screen for SRT Version 2.2

AFCEE intends to add additional technology modules to the Tool in the future.

The SRT is available free-of-charge to all interested parties. While the Tool's main audience is intended to be US Air Force remediation professionals, anyone who wants to consider sustainability in either the selection of a remedy or in the optimization of an existing remedial system can access the SRT at AFCEE Sustainable Remediation (http://www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sustainableremediation/srt/index.asp).

2.1 Platform

The Tool is built on the Microsoft Excel platform and is structured using analytical "tiers" similar to the tiered structure of the Risk-Based Corrective Action (RBCA) Tool Kit[2]. This tiered structure allows the user to choose the level of effort and detail appropriate for the project at hand. Tier 1 (simplest tier) calculations are based on rules-of-thumb that are widely used in the environmental remediation industry. Tier 2 calculations are more detailed and incorporate more site-specific factors. Tier 2 is recommended for evaluating existing systems and for projects that have advanced to the feasibility study (FS) stage. At the FS stage, conceptual designs should be available, allowing the user to enter more site-specific inputs. This will result in more accurate outputs tailored to the project.

A user might choose Tier 1 rather than Tier 2 if the analysis is required quickly, if detailed or extensive site-specific data currently is not available, if a highly site-specific evaluation is not required, or if for the user desires to make general comparisons between remediation technologies. Conversely, a user might choose to conduct a Tier 2 evaluation if adequate time is available in which to complete the Tier 2 evaluation, if detailed site-specific data currently exist, or if more stand-alone results are required.

2.2 Architecture

The purpose of the SRT is to calculate sustainability metrics for Excavation, Soil Vapor Extraction, Thermal Treatment, Pump and Treat, Enhanced Bioremediation, Permeable Reactive Barrier, In Situ Chemical Oxidation, and Long-term Monitoring / Monitored Natural Attenuation. After choosing whether to evaluate soil or groundwater, the user is directed to three types of screens: Input, Technology, and Output. The **Input screen** for either Soil or Groundwater gathers general information used for all technologies, such as description of the contamination present and general site-specific information (see Figure 2). The Input screen is followed by the **Technology** screens, which require the user to enter various inputs regarding system design and materials and consumables (see Figure 3). Finally, the user is directed to the **Output** screens.

[2] GSI Environmental Inc., "RBCA Tool Kit for Chemical Releases," available at http://www.gsi-net.com/en/software/rbca-for-chemical-releases-v25.html.

Throughout the Tool, there are direct user inputs as well as defaults and calculated values based on rules of thumb or algorithms. Many of the calculated values can be overridden by the user, if more site-specific data are available.

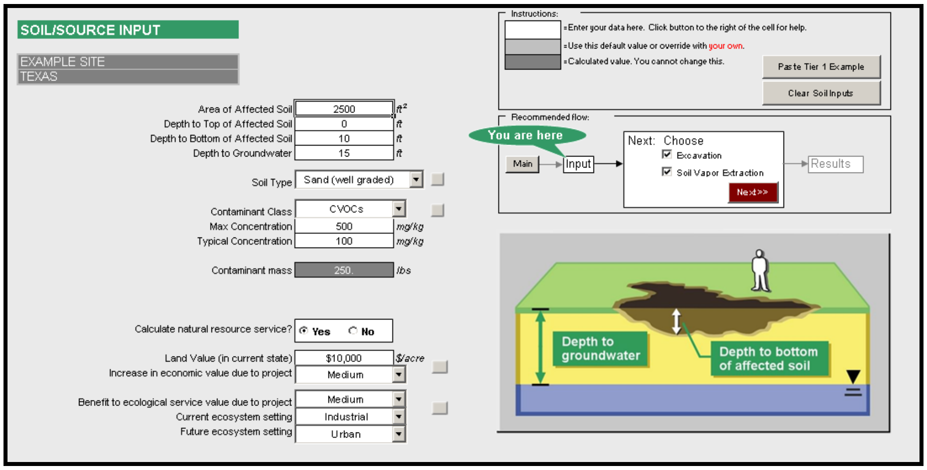


Figure 2: Input screen for soil

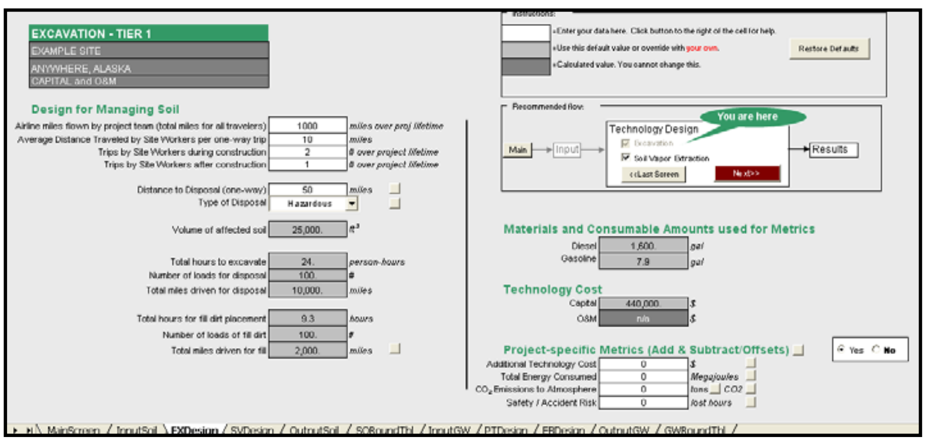


Figure 3: Technology screen for excavation

After entry of basic site data in the Input screen, the **Technology screens contain design and materials and consumables** sections which house algorithms for intermediate calculations, which draw heavily on the LCA approach (Figure 2). These are necessary for the final sustainability metrics calculations. For example, the excavation design section includes an algorithm for calculating the number of truck loads required for disposal of excavated soil. The number of loads is then fed into the algorithm for calculating the gallons of fuel required for transporting that excavated material. This value is then included in the calculation of the number of tons of carbon dioxide released to the atmosphere as a result of the waste transportation activity. For each technology, the SRT calculates design elements and materials and consumables needed for each major component, allowing the user to adjust values, and then feed the totals into the output metrics calculations.

The **Output** screen (see Figure 4) displays the calculated sustainability metrics (e.g., carbon emissions, economic cost, energy consumption, safety / accident risk, and change in resource service from land and/or groundwater). These metrics are organized by environmental media so that soil or groundwater technologies can be compared side-by-side.

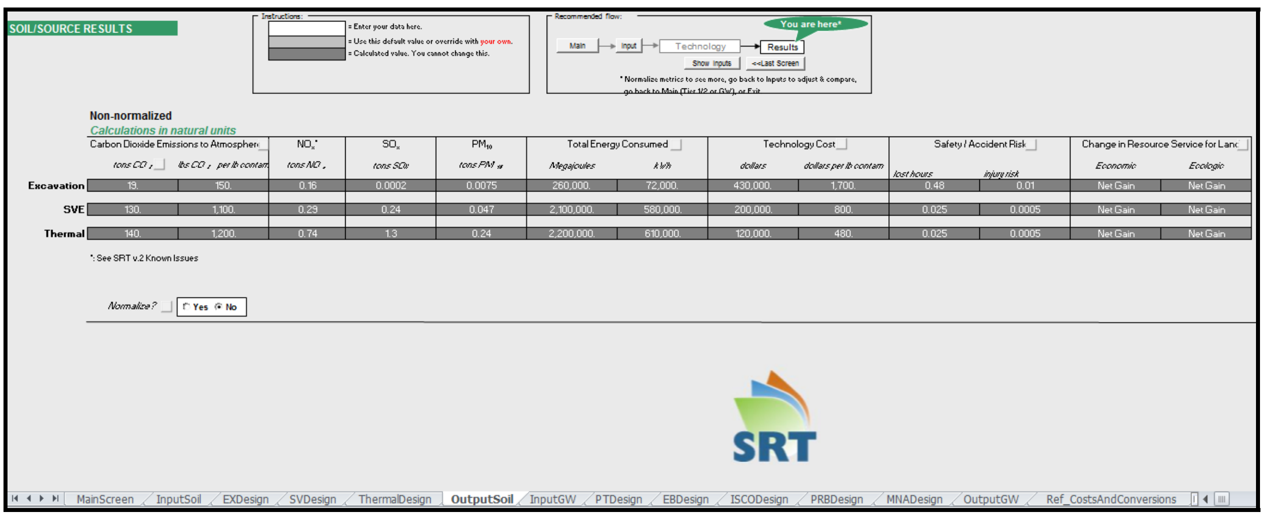


Figure 4: Output Screen for Soil Technologies

Other innovative features of the Tool include the following:

- Conversion of all sustainability metrics to a consistent set of units (for example, converting carbon emissions to life-cycle costs using existing carbon offset costs set by carbon trading markets);
- Use of Scenario Planning, where different futures for carbon offset costs and energy costs are presented to the users (for example, the user can view the results of the sustainability calculations for either a “Business as Usual” scenario, or a “Carbon Constrained World” scenario);
- Use of a consensus-building virtual meeting room, where different decision-makers can weigh the importance of different sustainability metrics (for example, one stakeholder might weigh economic cost as the most important metric, while another stakeholder might weigh carbon emissions as the most important metric.)

2.3 Non-Normalized and Normalized / Cost-Based Measures

The sustainability metrics Output section displays the carbon dioxide emissions, energy use, economic cost, safety / accident risk, and change in resource service for land and groundwater for each technology. The output metrics are presented in both a non-normalized and a normalized cost-based format. The non-normalized metrics are expressed in units of measure specific to each metric (i.e. carbon dioxide emissions are given in tons, and safety / accident risk is reported in number of lost hours due to injuries). The normalized cost-based metrics are expressed in units of U.S. dollars. This means that normalized cost-based carbon dioxide emissions are displayed as the number of US dollars required to offset the carbon dioxide emitted for a particular technology on the Chicago Climate Exchange. In this approach, the sustainability metrics can be summed using a common unit (the US dollar) so the user can easily compare the environmental and economic burdens of various technologies at a particular site.

2.4 Tier 2 System

The Tier 2 portion of the SRT has the same calculation scheme used in Tier 1 but with a significantly increased set of parameters that can be changed by the user. While Tier 1 estimates consumables and allows users to override these default values, it does not allow the user to change the internal default values in order to allow users with limited site-specific information or with limited time to complete a basic evaluation. However, Tier 2 requires the user to directly input quantities of consumables and allows users to input their own specific internal values. For example, in Tier 1 the user has to use an internal default value for the pounds of carbon emitted per pound of PVC used in piping and other equipment. For Tier 2, the user can enter specific values for pounds of carbon emitted per pound of PVC to account for detailed data and assumptions the Tier 2 user would like to make. In terms of input data, the user would have to enter approximately 102 input variables to complete a Tier 1 analysis of all eight technologies (excavation, soil vapor extraction, thermal treatment, pump and treat, enhanced bioremediation, in situ chemical oxidation, permeable reactive barrier, and long-term monitoring / monitored natural attenuation). A Tier 2 user has the option of entering anywhere between 102 and 574 input variables, greatly increasing the power, flexibility, and specificity of the Tool.

2.5 Importing Data from RACER

RACER Version 11.0 and above allows users of that software application to export a data file with values entered into and calculated within RACER. These values include environmental restoration and remediation project information, technologies used, engineering design criteria, and project costs. Many of these input parameters and calculated quantities are also used in the SRT. To simplify the SRT data entry process, the SRT user has the option to import the RACER data file as a starting point for an SRT “Tier 2” evaluation. The import process maps values from RACER into matching fields in the SRT and completes unit conversions as appropriate. Because the data in RACER do not exactly match all the required data in the SRT, the SRT user will need to work though the data entry screens as described in Section 2.2 above after importing the RACER data file, fill in any missing information, and complete the sustainability evaluation.

For Tier 2, the SRT was designed to calculate “from the top down”. That is, values in the top part of input and technology screens are used in subsequent cells occurring lower down on each screen. In a small number of cases, RACER values will replace calculated cells in the SRT (shown in light and dark gray shading). In these situations, the SRT will no longer re-calculate that value if preceding inputs are changed. Instead, it will retain the value from RACER and use that RACER value for subsequent calculations. Certain other quantities from RACER either directly impact the SRT metrics (technology costs) or are imported into read-only SRT cells (number of wells for pump and treat). These cells are outlined in yellow after the RACER import has been completed to highlight that these quantities come from RACER and will not be re-calculated if the user modifies “upstream” SRT input fields.

Key steps to completing the RACER import:

- **From RACER, export an xml file** (See RACER user guide).
- **Open a clean copy of SRT.** Starting the evaluation with an unused copy will help prevent confusion between SRT runs. This will also avoid inadvertent use of an SRT file containing user-modified values instead of the full set of SRT default formulas.
- From the SRT Main Screen, **click on the RACER Import button** on the right side of the window (see Figure 1 above). Follow the instructions in the Import Wizard.
- While still on the Main Screen after the RACER import has been completed, **enter the site location**. Then, select the soil or groundwater input screen and the appropriate technology screens **following the standard SRT data input workflow** (Section 2.2). Add or modify data as needed for the sustainability evaluation.

IMPORTANT: The SRT does not display calculated values until all data entry has been completed. If results are not displayed (i.e., if dashes (“-“) are shown in shaded cells), review the main, input and technology screens to verify that white and shaded data entry cells have been filled in.

APPENDIX A: FREQUENTLY ASKED QUESTIONS

Excel-specific Questions

Why won't the buttons work?

The SRT is built in the Excel 2003 spreadsheet environment and uses macros. The most common reason the buttons will not work is because of the security settings in Excel are set at too high a level.

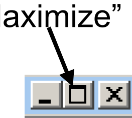
- To correct this problem in **Excel 2003**, navigate to the Tool's menu, Macro, Security, and select Medium security.
- To correct this problem in **Excel 2007**, on the Developer tab, in the Code group, select Macro Security. (If the Developer tab is not displayed, click the Microsoft Office Button in the upper left corner, select Excel Options. Under Popular category and Top options for working with Excel, select Show Developer tab in the Ribbon.) In Macro Security, Macro Settings category, select the option you prefer under Macro Settings.

Also, make sure you are not currently editing a cell. Use the Escape key to leave the current cell without making changes. Tab to leave the current cell, keeping changes.

I can't see the full window or all the tabs. What should I do?

From the Main Screen, click the "Fit Window" button in the Instructions box (located in the upper right of the screen).

Alternately, from any screen, click the "Maximize" button in the Excel window.



Why is #### displayed in a number cell?

The cell is not wide enough to fit the value. To fix this problem, select the cell and the Format menu, Cells. On the Number tab, change the format of the cell until the value is visible. If the values still cannot be read, select the Format menu, Cells, and click on the Font tab. Reduce the font size until the value can be read.

What if I want to get back to the default design values?

If you have overwritten the default design values but want to see them again, you can press the Restore Defaults button on the upper right-hand side of the technology design screen.

IMPORTANT: After importing data from RACER, not all standard SRT features and formatting may be replaced. Instead of re-using an SRT file, we recommend that users start with a clean version of the SRT.

I get "not enough memory" / "not enough system resources to display correctly" errors from Excel. What do I do?

This problem may occur if you have two or three large workbooks open and/or have pages set at different magnifications. Close the error message box, save your work, then re-open your file in its own, separate instance of Excel. Also adjust the screen views to 100%.

Tool-specific Questions

What remediation technologies are included in the Tool?

Eight remediation technologies are available for evaluation in the current version of the Tool. For affected soil, excavation, soil vapor extraction (SVE), and thermal treatment are available. For affected groundwater, pump and treat, enhanced bioremediation, in situ chemical oxidation, permeable reactive barrier, and long-term monitoring / monitored natural attenuation are available. There are plans to add additional soil and groundwater technologies in future versions of the Tool.

What are outputs of the Tool?

The Tool calculates the following sustainability metrics:

- CO_2 emissions to the atmosphere;
- Nitrogen oxides (NO_x);
- Sulfur oxides (SO_x);
- Particulate Matter (PM_{10});
- Total energy consumed;
- Technology cost; Safety / Accident risk; and
- Change in natural resource service.

How does Tier 1 work?

Tier 1 calculations are based on rules-of-thumb for design parameters and crude unit costs or site data-derived cost curves. Tier 1 results are intended to give order of magnitude results. For more detailed calculations, use Tier 2. Additionally, the user is advised that system design parameter and cost calculations appear as estimations in the SRT; users should consult professional system vendors for detailed, site-specific design and cost, as the SRT is a screening level tool, not a design tool.

When should I use Tier 1 vs. Tier 2?

The Tool is structured similar to the tiered structure in the Risk-Based Corrective Action (RBCA) Tool Kit (GSI Environmental Inc., "RBCA Tool Kit for Chemical Releases," available at http://www.gsi-net.com/en/software/rbca-for-chemical-releases-v25.html). This tiered structure allows the user to choose the level of effort and detail appropriate for the project at hand. Tier 1 (simplest tier) calculations are based on Rules-of-Thumb that are widely used in the environmental remediation industry. Tier 2 calculations are more detailed and incorporate site-specific factors. Tier 2 is recommended for evaluating existing systems and for projects that have advanced to the feasibility study (FS) stage. At the FS stage, conceptual designs should be available to fill in more detailed Tier 2 worksheets; Tier 2 outputs will be more site-specific.

Choose **Tier 1** for general comparisons of remediation technologies. Use if:

- quick evaluation is required
- detailed site data is not currently available, or
- an extremely site-specific evaluation is not required.

Choose **Tier 2** if:

- adequate time is available, or
- detailed site data is available (FS stage).

Can I go back-and-forth between Tier 1 and Tier 2?

It is recommended that you not switch back-and-forth between tiers, particularly if user-override values are entered into the technology design tabs. If the same copy of the Tool is used (i.e. you do not save using a different file name), it is recommended that the user select "Restore Defaults" on the particular technology(ies) of interest prior to further data entry. This action will clear the Tool and replace default values, minimizing potential confusion between user-entered values and Tool default values.

What should I do if Tier 1 output metrics look unusually high or low?

Using Tier 2 will allow you greater flexibility in the detailed factors that go into the calculations. Tier 2 allows you to customize the evaluation to reflect detailed site data.

What is the difference between non-normalized and normalized metrics?

Non-normalized metrics are reported in "natural" units, or non-standardized units. Normalized metrics are reported in 2008 US dollars. The developers are aware that normalizing metrics is controversial and that users may not want to convert all metrics to one unit. However, some users find this capability useful for comparisons of metrics. You may choose whether to view normalized metrics on the output screens.

Do I have to calculate natural resource service?

No, you do not have to calculate natural resource service. Assigning values to natural resource services can be beyond the needs or scope of many projects. However, some users find this capability useful for assigning importance to ecosystem factors. If you choose to do this, select Yes on the Input screens when asked if you would like to calculate natural resource service. A few additional questions will be displayed, and the resulting metric will be displayed on the output screen.

If I choose to calculate it, how does the Tool assign monetary values to natural resource service?

The Tool assigns monetary values to two components of natural resource service: economic and ecologic. For the economic component, the Tool uses land values such as real estate costs chosen by the user. For the ecologic component, the Tool uses updates values for biome types based on work by Robert Costanza et al. See Appendices for detailed calculations and referenced values.

What should I do if the default values do not appear in the light gray cells?

If the default design calculations do not appear in the light gray cells, one or more required inputs (white cells) are missing. Check that all white cells contain input values or selections. It may be possible that you have not entered the "Site Name" and/or other parameters on the Main screen or that you are missing required input on either the Soil or Groundwater Input screens. Note that the function that checks for required inputs prior to moving onto the Output screen (and that displays red "X"s if inputs are not present) does not require values for parameters unnecessary for default design calculations. This means that the number of airline miles traveled for a project appears as a required white input cell. However, the metric outputs will still be calculated properly (assuming no airline miles), and the input check window will display a green checkmark.

What does it mean if Tool outputs display as #N/A?

If one or more of the Tool's output calculations display as #N/A, it means that the value is not available because there are missing inputs. In this case, carefully check that all of the white cells (required inputs) are filled in or selected correctly. Also, a Tool-generated error message will notify you of which tabs/screens are missing required input. Be sure to check that you have entered “Site Name” and “Location” on the Main Screen.

APPENDIX B: REFERENCED VALUES

SOIL & GROUNDWATER INPUTS AND ASSOCIATED VALUES		
Value Name	**Value**	**Reference**
Soil Type: Sandy Gravel, Soil Bulk Density	102 lbs / ft^3	Sand with gravel, dry, SI Metrics, 2007, http://www.simetric.co.uk/si_materials.htm
Soil Type: Sandy Gravel, Porosity	0.35	Based on Meinzer (1923a); Davis (1969); Cohen (1965); and MacCary and Lambert (1962) as Quoted by C.W. Fetter http://www.co.portage.wi.us/groundwater/undrstnd/soil.htm. See also, Connor et al., 1997, "Soil Attenuation Model for Derivation of Risk-Based Soil Remediation Standards", User Guide for RBCA Tool Kit for Chemical Releases, 2007, and http://www.simetric.co.uk/si_materials.htm
Soil Type: Sandy Gravel, Hydraulic Conductivity	0.1 cm / s	Based on Meinzer (1923a); Davis (1969); Cohen (1965); and MacCary and Lambert (1962) as Quoted by C.W. Fetter http://www.co.portage.wi.us/groundwater/undrstnd/soil.htm. See also, Connor et al., 1997, "Soil Attenuation Model for Derivation of Risk-Based Soil Remediation Standards", User Guide for RBCA Tool Kit for Chemical Releases, 2007, and http://www.simetric.co.uk/si_materials.htm and Bear (1988). *Dynamics of Fluids in Porous Media*, Table 5.5.1, p. 136.
Soil Type: Sand (well graded), Soil Bulk Density	100 lbs / ft^3	Median sample density for excavated earth is 100 lbs / ft3, SI Metrics, 2007, http://www.simetric.co.uk/si_materials.htm
Soil Type: Sand (well graded), Porosity	0.25	Based on Meinzer (1923a); Davis (1969); Cohen (1965); and MacCary and Lambert (1962) as Quoted by C.W. Fetter http://www.co.portage.wi.us/groundwater/undrstnd/soil.htm. See also, Connor et al., 1997, "Soil Attenuation Model for Derivation of Risk-Based Soil Remediation Standards", User Guide for RBCA Tool Kit for Chemical Releases, 2007, and http://www.simetric.co.uk/si_materials.htm

SOIL & GROUNDWATER INPUTS AND ASSOCIATED VALUES		
Soil Type: Sand (well graded), Hydraulic Conductivity	0.01 cm / s	Connor et al, 1997, Table 2; SW and Bear (1988). *Dynamics of Fluids in Porous Media*, Table 5.5.1, p. 136.
Soil Type: Sand (poorly graded), Soil Bulk Density	100 lbs / ft^3	Median sample density for excavated earth is 100 lbs / ft3, SI Metrics, 2007, http://www.simetric.co.uk/si_materials.htm
Soil Type: Sand (poorly graded), Porosity	0.35	Based on Meinzer (1923a); Davis (1969); Cohen (1965); and MacCary and Lambert (1962) as Quoted by C.W. Fetter http://www.co.portage.wi.us/groundwater/undrstnd/soil.htm. See also, Connor et al., 1997, "Soil Attenuation Model for Derivation of Risk-Based Soil Remediation Standards", User Guide for RBCA Tool Kit for Chemical Releases, 2007, and http://www.simetric.co.uk/si_materials.htm
Soil Type: Sand (poorly graded), Hydraulic Conductivity	0.01 cm/s	Connor et al, 1997, Table 2; SP and Bear (1988). *Dynamics of Fluids in Porous Media*, Table 5.5.1, p. 136.
Soil Type: Silt, Soil Bulk Density	95 lbs / ft^3	Connor et al., 1997, "Soil Attenuation Model for Derivation of Risk-Based Soil Remediation Standards", User Guide for RBCA Tool Kit for Chemical Releases, 2007, and http://www.simetric.co.uk/si_materials.htm
Soil Type: Silt, Porosity	0.4	Based on Meinzer (1923a); Davis (1969); Cohen (1965); and MacCary and Lambert (1962) as Quoted by C.W. Fetter http://www.co.portage.wi.us/groundwater/undrstnd/soil.htm. See also, Connor et al., 1997, "Soil Attenuation Model for Derivation of Risk-Based Soil Remediation Standards", User Guide for RBCA Tool Kit for Chemical Releases, 2007, and http://www.simetric.co.uk/si_materials.htm
Soil Type: Silt, Hydraulic Conductivity	0.0001 cm / s	Connor et al, 1997, Soil Attenuation Model, Table 2; ML and Bear (1988). *Dynamics of Fluids in Porous Media*, Table 5.5.1, p. 136.
Soil Type: Clay, Soil Bulk Density	90 lbs / ft^3	Average densities of clays from SI Metrics, http://www.simetric.co.uk/si_materials.htm (Accessed 9/6/08)
Soil Type: Clay, Porosity	0.45	Based on Meinzer (1923a); Davis (1969); Cohen (1965); and MacCary

SOIL & GROUNDWATER INPUTS AND ASSOCIATED VALUES		
		and Lambert (1962) as Quoted by C.W. Fetter http://www.co.portage.wi.us/groundwater/undrstnd/soil.htm. See also, Connor et al., 1997, "Soil Attenuation Model for Derivation of Risk-Based Soil Remediation Standards", User Guide for RBCA Tool Kit for Chemical Releases, 2007, and http://www.simetric.co.uk/si_materials.htm
Soil Type: Clay, Hydraulic Conductivity	0.0000001 cm / s	Connor et al, 1997, Soil Attenuation Model, Table 2; Clay, Silty and Bear (1988). *Dynamics of Fluids in Porous Media*, Table 5.5.1, p. 136.

EXCAVATION		
Value Name	**Value**	**Reference**
Distance from site to fill source (one way)	10 miles	Design Team
Dump Truck Volume	12 $yards^3$	Median volume of dump truck from Means, 2005
Fluff Factor	Gravel, 15%; Sands, 15%; Silt, 30%; Clay, 30%	RACER™
Fuel Consumption Rate, Diesel, Mid-sized Dump Truck	8 miles / gal	Mid-sized dump truck fuel consumption, G.E.O. Carbon Calculator, 2008
Fuel Consumption Rate, Excavator	3 miles / gal	Design Team
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Mileage, Vehicle for Transportation	15 miles / gal	Design Team (BW)
Rate, Excavation	48 metric tons / hr (with value converted to tons/hr for use in tool)	Performance data from FRTR website http://www.frtr.gov/matrix2/section4/4-29.html gives 18,200 metric tones excavated in 2 months as a typical value. Assuming workers excavate 9-hours per day for 21 days per month, the rate of excavation is 48 metric tons excavated per hour.
Rate, Fill Spread	448.5 yd^3 / hr	Rate to spread unclassified fill, Means,

EXCAVATION		
		2005
Rate, Spread / Compaction	654 yd^3 / hr	Rate to spread / compact with sheepsfoot roller, 8" lift, Means, 2005
Rate, Water Compaction	174.3 yd^3 / hr	Rate of water compaction, Means, 2005

SOIL VAPOR EXTRACTION		
Value Name	**Value**	**Reference**
Activated Carbon, Conversion Factor	10 lbs GAC / lb contaminant	The default assumption is 10 pound of granular activated carbon for each pound of contaminant; based on Nyer 1993 ROT, p. 127
Activated Carbon, Miles Traveled for Disposal (roundtrip)	400 miles / trip	Design Team
Fuel Consumption Rate, Drilling	32 gal / day	Design Team (BW). Assumes drilling completed with smaller rig (4 gal/hr) for 8 hrs / day.
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Fuel Consumption Rate, Trenching	6.25 gal / hr	Design Team
Mileage, Vehicle for Activated Carbon Disposal	3 miles / gal	Design Team
Mileage, Vehicle for Transportation	15 miles / gal	Design Team (BW)
Natural Gas Supplemental Fuel, CVOCs, Henry's Law Constant	9.1 atm/M	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Trichloroethylene as representative
Natural Gas Supplemental Fuel, CVOCS, log Kow	2.38	Kuo, 1999, Practical Design Calculations for Groundwater and Soil

SOIL VAPOR EXTRACTION		
		Remediation, Table II.3.C, Assume Trichloroethylene as representative
Natural Gas Supplemental Fuel, CVOCS, MW	131.4 g / mol	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Trichloroethylene as representative
Natural Gas Supplemental Fuel, Total BTEX, Henry's Law Constant	5.55 atm/M	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Benzene as representative
Natural Gas Supplemental Fuel, Total BTEX, log Kow	2.13	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Benzene as representative
Natural Gas Supplemental Fuel, Total BTEX, MW	78.1 g / mol	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Benzene as representative
Natural Gas Supplemental Fuel, CVOCs (TCE), co_Cp	0.269 Btu / lb-°F	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_mw_c	18	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_mw_h	0.001	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_mw_o	0	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_mw_s	0	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_Tc	2000	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_Cp	0.266 Btu / lb-°F	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental	92	Kuo, 1999, Practical Design

SOIL VAPOR EXTRACTION		
Fuel, Total BTEX (Benzene) co_mw_c		Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_mw_h	8	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_mw_o	0	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_mw_s	0	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_Tc	1800	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Rate, Drilling	100 ft / day	Driller Correspondence
Rate, Trenching	300 ft / hr	Design Team
Soil Type: Sand (poorly graded), SVE Duration	1 yr	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given diameter
Soil Type: Sand (poorly graded), SVE ROI	17.5 ft	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given diameter
Soil Type: Sand (well graded), SVE Duration	1 yr	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf
Soil Type: Sand (well graded), SVE ROI	17.5 ft	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given diameter
Soil Type: Sandy Gravel, SVE Duration	0.5 yr	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf
Soil Type: Sandy Gravel, SVE ROI	17.5 ft	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given diameter
Soil Type: Silt, SVE Duration	2 yrs	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf
Soil Type: Silt, SVE ROI	11 ft	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given diameter

SOIL VAPOR EXTRACTION		
System Operating Time	8,320 hrs / yr	Assumed that annual system operating time is 95% of a given year, Design Team
System Pump Power Requirements	5 hp	Design Team

THERMAL TREATMENT		
Value Name	**Value**	**Reference**
Activated Carbon, Conversion Factor	10 lbs GAC / lb contaminant	The default assumption is 10 pound of granular activated carbon for each pound of contaminant; based on Nyer 1993 ROT, p. 127
Activated Carbon, Miles Traveled for Disposal (roundtrip)	400 miles / trip	Design Team
Fuel Consumption Rate, Drilling	32 gal / day	Design Team (BW). Assumes drilling completed with smaller rig (4 gal/hr) for 8 hrs / day.
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Fuel Consumption Rate, Trenching	6.25 gal / hr	Design Team
Mileage, Vehicle for Activated Carbon Disposal	3 miles / gal	Design Team
Mileage, Vehicle for Transportation	15 miles / gal	Design Team (BW)
Natural Gas Supplemental Fuel, CVOCs, Henry's Law Constant	9.1 atm/M	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Trichloroethylene as representative

THERMAL TREATMENT		
Natural Gas Supplemental Fuel, CVOCS, log Kow	2.38	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Trichloroethylene as representative
Natural Gas Supplemental Fuel, CVOCS, MW	131.4 g / mol	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Trichloroethylene as representative
Natural Gas Supplemental Fuel, Total BTEX, Henry's Law Constant	5.55 atm/M	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Benzene as representative
Natural Gas Supplemental Fuel, Total BTEX, log Kow	2.13	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Benzene as representative
Natural Gas Supplemental Fuel, Total BTEX, MW	78.1 g / mol	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation, Table II.3.C, Assume Benzene as representative
Natural Gas Supplemental Fuel, CVOCs (TCE), co_Cp	0.269 Btu / lb-°F	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_mw_c	18	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_mw_h	0.001	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_mw_o	0	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_mw_s	0	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, CVOCs (TCE), co_Tc	2000	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene)	0.266 Btu / lb-°F	Kuo, 1999, Practical Design Calculations for Groundwater and Soil

THERMAL TREATMENT		
co_Cp		Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_mw_c	92	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_mw_h	8	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_mw_o	0	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_mw_s	0	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Natural Gas Supplemental Fuel, Total BTEX (Benzene) co_Tc	1800	Kuo, 1999, Practical Design Calculations for Groundwater and Soil Remediation
Rate, Drilling	100 ft / day	Driller Correspondence
Rate, Trenching	300 ft / hr	Design Team

ENHANCED BIOREMEDIATION		
Value Name	**Value**	**Reference**
Donor, Conversion Factor	2.8 lb CO_2 / lb substrate + 0.7 lb CO_2 / lb CVOCs	Consider both anaerobic and aerobic degradation: 1) Anaerobic CVOC treatment: - Assume i) complete oxidation to CO_2 without carbonate system sink ii) emulsified vegetable oil-type donor ($C_{56}H_{100}O_6$) $C_{56}H_{100}O_6 + 78O_2 \rightarrow 56CO_2 + 50\ H_2O$ Multiplying by molecular weights yields 2.8 lb CO_2 / lb substrate. 2) Aerobic CVOC treatment: - Assume i) complete oxidation to CO2 without carbonate system sink ii) no co-substrate supplied (e.g. methane, propane, butane, etc.) iii) use TCE (C_2Cl_3H) as representative CVOC

ENHANCED BIOREMEDIATION		
		$C_2Cl_3H + 3/2O_2 + H_2O \rightarrow 2CO_2 + 3H^+ + 3Cl^-$ Multiplying by molecular weights yields 0.67 lb CO_2 / lb TCE. Total CO_2 released for anaerobic CVOC treatment includes 1) CO_2 released by substrate and 2) potential CO_2 released by CVOC itself: 2.8 lb CO_2 / lb substrate + 0.7 lb CO_2 / lb CVOCs (Design Team)
Donor, Percent of Pore Space	1%	From two sources: 1) Rule-of-Thumb proposed for emulsified vegetable oil addition during the development of the Sustainable Remediation Forum (SuRF) 6 Sample Problems Site Scenario (email dated 1/3/08); 2) Evaluation of the final "SuRF6_Case_Study_Dechor.xls" file (derived from the AFCEE *Principles and Practices* document), where the calculated substrate addition amount (74,500 pounds of vegetable oil, or about 9,720 gallons) is about 0.75% of 1.3 million gallons of pore space. This was rounded up to 1%.
Oxygen additive, Conversion Factor	3.3 lb CO_2 / lb BTEX + 0 lb CO_2 / lb oxygen additive	Consider both anaerobic and aerobic degradation: 1) Aerobic BTEX treatment: - Assume i) complete oxidation to CO_2 without carbonate system sink ii) BTEX serves as sole source of carbon and energy (no co-substrate) iii) calculated CO_2 values for individual BTEX components (e.g. Benzene, Toluene, etc.) were averaged and rounded to two significant digits. Below are equations for Benzene as example: $C_6H_6 + 15/2O_2 \rightarrow 6CO_2 + 3\ H_2O$ Multiplying by molecular weights and averaging yields 3.3 lb CO_2 / lb BTEX. 2) Anaerobic BTEX treatment: - Assume anaerobic degradation pathway the same as aerobic pathway.

ENHANCED BIOREMEDIATION		
		(Design Team)
Fuel Consumption Rate, Drilling	32 gal / day	Design Team (BW). Assumes drilling completed with smaller rig (4 gal/hr) for 8 hrs / day.
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Injection Well Spacing	20 ft	Injection well spacing is assumed to be 20 feet; Parsons Principles and Practices for Enhanced Bioremediation
Rate, Drilling	100 ft / day	Fugro correspondence

PUMP & TREAT		
Value Name	**Value**	**Reference**
Activated Carbon, Freundlich parameter, CVOCs, 1 / n	0.62	US Army Corps of Engineers, 2001, Adsorption Design Guide, http://www.usace.army.mil/publications/design-guides/dg1110-1-2/chap2.pdf, Table 2-2), Table 2-2 after Dobbs and Cohen, 1980 K and 1 / n for TCE and Benzene are used as defaults for Tier 1.
Activated Carbon, Freundlich parameter, CVOCs, K Parameter	28	US Army Corps of Engineers, 2001, Adsorption Design Guide, http://www.usace.army.mil/publications/design-guides/dg1110-1-2/chap2.pdf, Table 2-2), Table 2-2 after Dobbs and Cohen, 1980
Activated Carbon, Freundlich parameter, Total BTEX, 1 / n	1.6	US Army Corps of Engineers, 2001, Adsorption Design Guide, http://www.usace.army.mil/publications/design-guides/dg1110-1-2/chap2.pdf, Table 2-2), Table 2-2 after Dobbs and Cohen, 1980 K and 1 / n for TCE and Benzene are used as defaults for

PUMP & TREAT		
		Tier 1.
Activated Carbon, Freundlich parameter, Total BTEX, K Parameter	1	US Army Corps of Engineers, 2001, Adsorption Design Guide, http://www.usace.army.mil/publications/design-guides/dg1110-1-2/chap2.pdf, Table 2-2), Table 2-2 after Dobbs and Cohen, 1980
Activated Carbon, Miles Traveled for Disposal (roundtrip)	400 miles / trip	Design Team
Activated Carbon, System Pump Power	10 hp	Design Team
Fuel Consumption Rate, Drilling	32 gal / day	Design Team (BW). Assumes drilling completed with smaller rig (4 gal/hr) for 8 hrs / day.
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Fuel Consumption Rate, Trenching	6.25 gal / hr	Design Team
Mileage, Vehicle for Activated Carbon Disposal	3 miles / gal	Design Team
Mileage, Vehicle for Transportation	15 miles / gal	Design Team (BW)
Natural Gas supplemental fuel flow rate	2.21 scfm	Kuo, 1999, p. 246, Example VII.2.5
Rate, Drilling	100 ft / day	Driller (Fugro) Correspondence
Rate, Trenching	300 ft / hr	Design Team
Steel, Length Pipe Per Well	10 ft / well	Design Team
Steel, Non-pipe Steel Per Well	50 lbs / well	Design Team

PUMP & TREAT		
Steel, Treatment System, Activated Carbon	400 lbs	Design Team
Steel, Treatment System, Air Stripper	950 lbs	Design Team
System Operating Time	8,320 hrs / yr	Design Team

IN SITU CHEMICAL OXIDATION		
Value Name	**Value**	**Reference**
Distance to Oxidant supplier	50 miles one-way	Design Team
Fuel Consumption Rate, Drilling	10 gal / day	Design Team
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Fuel Consumption Rate, Oxidant delivery	17.6 mpg	Design Team
Fuel Consumption Rate, Travel	15 mpg	Design Team
Oxidant load delivery capacity	10,000 lbs per truckload	Design Team
Rate, Drilling	100 ft / day	Fugro correspondence
Rate, Safety factor for injuries per hour due to oxidant risk	0.0000165 injuries / hr	Design Team, US Bureau of Labor Statistics for chemical handlers
Rate, Trenching	200 ft / day	Design Team

PERMEABLE REACTIVE BARRIER		
Value Name	**Value**	**Reference**
Distance to Gravel/Sand/Mulch source	20 miles one-way	Design Team
Distance to Iron source	1,000 miles one-way	Design Team
Distance to disposal (spoils)	20 miles one-way	Design Team
Iron, Conversion Factor	4 lb CO_2 / lb Zero-valent iron	Design Team
Fuel Consumption Rate, Delivery and disposal of materials	8 mpg	Design Team
Fuel Consumption Rate, Drilling	32 gal / day	Design Team (BW). Assumes drilling completed with smaller rig (4 gal/hr) for 8 hrs / day.
Fuel Consumption Rate, Loading	10 gal / hr	Design Team
Fuel Consumption Rate, Trenching	6.25 gal / hr	Design Team
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Rate, Drilling	100 ft / day	Fugro correspondence
Rate, Trenching	200 ft / day	Design Team

LONG-TERM MONITORING / MONITORED NATURAL ATTENUATION		
Value Name	**Value**	**Reference**
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.

CONVERSION FACTORS AND OUTPUTS		
Value Name	**Value**	**Reference**
Conversions, Default Activated Carbon, CO_2	2.7 lb CO_2 / lb	Derived from Vignes, 2001 and EIA Electricity
Conversions, Default PVC Pipe	2.03 lbs / ft	Driscoll, Groundwater and Wells, Appendix 13D (Schedule 40, 4")
Conversions, Default PVC Pipe, CO_2	1.824 lb CO_2 / lb	NREL CO2 outputs to nature from PVC cradle to resin
Conversions, Default PVC Pipe, Energy	5.4 kWh / lb	NREL PVC cradle to resin natural gas input, btu converted to kWh
Conversions, Default PVC Pipe, NOx	0.00318 lb / lb	NREL NOx outputs to nature from PVC cradle to resin
Conversions, Default PVC Pipe, SOx	0.0105 lb / lb	NREL SOx outputs to nature from PVC cradle to resin
Conversions, Default PVC Pipe, PM10	0.00018 lb / lb	NREL PM10 outputs to nature from PVC cradle to resin
Conversions, Default Steel Pipe	10.79 lbs / ft	Driscoll, Groundwater and Wells, Appendix 13B-6 (4")
Conversions, Default Steel Pipe, CO_2	2.948 lbs CO_2 / lb	Derived from Energy Information Administration
Conversions, Default Steel Pipe, Energy	2.2 kWh / lb	Upper end of range from Energy Information Administration (metal casting)
Conversions, Default Steel Pipe, NOx	0.002227 lb / lb	US Life Cycle Index Database (www.nrel.gov/lci)

CONVERSION FACTORS AND OUTPUTS		
Conversions, Default Steel Pipe, SOx	0.003153 lb / lb	US Life Cycle Index Database (www.nrel.gov/lci)
Conversions, Default Steel Pipe, PM10	0.00005843 lb / lb	US Life Cycle Index Database (www.nrel.gov/lci)
Conversions, Diesel, CO_2	25.8 lb CO_2 / gal	National Renewable Energy Laboratory, www.nrel.gov
Conversions, Diesel, Cost	$2.00 / gal	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Conversions, Diesel, Energy	170 MJ / gal	National Renewable Energy Laboratory, www.nrel.gov, converted to MJ / gal
Conversions, Diesel, NOx	0.20923 lb / gal	Heavy duty diesel truck (33,001 – 60,000 lbs), EMFAC 2007 (version 2.3): 0.04184591 lb/mile multiplied by 5 mpg (default mpg for diesel trucks)
Conversions, Diesel, SOx	0.00020065 lb / gal	Heavy duty diesel truck (33,001 – 60,000 lbs), EMFAC 2007 (version 2.3): 0.00004013 lb/mile multiplied by 5 mpg (default mpg for diesel trucks)
Conversions, Diesel, PM10	0.0099786 lb / gal	Heavy duty diesel truck (33,001 – 60,000 lbs), EMFAC 2007 (version 2.3) : 0.00199572 lb/mile multiplied by 5 mpg (default mpg for diesel trucks)
Conversions, Electricity, CO_2	1.34 lb CO_2 / kWh	US Average from Energy Information Administration, 2002; Updated State-level Greenhouse Gas Emission Coefficients for Electricity Generation 1998-2000 http://tonto.eia.doe.gov/ftproot/environment/e-supdoc-u.pdf
Conversions, Electricity, Cost	$0.10 / kWh	EPA, 2005, Cost-effective Design of Pump and Treat Systems, http://www.frtr.gov//pdf/optimization/gw_mon_cost-effective-design_030805.pdf
Conversions, Electricity, Energy	11 MJ / kWh	Electricity generation is 32% efficient, National Renewable Energy Laboratory, www.nrel.gov, converted to MJ / kWh

CONVERSION FACTORS AND OUTPUTS		
Conversions, Electricity, NOx	0.008069 lb/kWh	Design Team; 3.66 x 10^3 g/MWh is life-cycle emissions from coal conventional power plant from Kaplan, Decarolis, and Thorneloe, 2009. Converted to lb/kWh by x (1 MWh / 1000 kWh) x (1 lb / 453.6 g)
Conversions, Electricity, SOx	0.01589594 lb/kWh	Design Team; 6.89 x 10^3 g/MWh is life-cycle emissions from coal conventional power plant from Kaplan, Decarolis, and Thorneloe, 2009. Converted to lb/kWh by x (1 MWh / 1000 kWh) x (1 lb / 453.6 g)
Conversions, Electricity, PM10	0.002843915 lb/kWh	Design Team; 1.29 x 10^3 g/MWh is life-cycle emissions from coal conventional power plant from Kaplan, Decarolis, and Thorneloe, 2009. Converted to lb/kWh by x (1 MWh / 1000 kWh) x (1 lb / 453.6 g)
Conversions, Gasoline, CO_2	20.17 lb CO_2 / gal	National Renewable Energy Laboratory, www.nrel.gov
Conversions, Gasoline, Cost	$2.00 / gal	Average regular grade price, http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Conversions, Gasoline, Energy	150 MJ / gal	National Renewable Energy Laboratory, www.nrel.gov, converted to MJ / gal
Conversions, Gasoline, NOx	0.015078 lb / gal	Design Team
Conversions, Gasoline, SOx	0.0001599 lb / gal	Design Team
Conversions, Gasoline, PM10	0.00129015 lb / gal	Design Team
Conversions, Natural Gas, CO_2	122 lb CO_2 / mcf	Natural Gas Combustion in Industrial Equipment, National Renewable Energy Laboratory, www.nrel.gov/lci
Conversions, Natural Gas, Cost	$11.00 / mcf	Average industrial natural gas price, January 2009 (http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm); website accessed 4/23/09.
Conversions, Natural Gas, Energy	1,000 MJ / mcf	http://hypertextbook.com/facts/2002/JanyTran.shtml, average natural gas content is 37 MJ / 1 m3, converted to

CONVERSION FACTORS AND OUTPUTS		
		MJ/mcf: (37 MJ/1 m3) x (1 m3/35.3 ft3) x (1000 ft3/1 mcf) = 1,048 MJ/mcf; round to 1,000 MJ/mcf
Conversions, Natural Gas, NOx	0.189594 lb/mcf	NREL/SR-580-24089 Appendix A, Table 142: 0.086 g/MJ, converted to lb/mcf by x (1,000 MJ/1 mcf) x (1 lb/453.6 g)
Conversions, Natural Gas, SOx	0.00063933 lb/mcf	NREL/SR-580-24089 Appendix A, Table 142: 0.00029 g/MJ, converted to lb/mcf by x (1,000 MJ/1 mcf) x (1 lb/453.6 g)
Conversions, Natural Gas, PM10	0.00308642 lb/mcf	NREL/SR-580-24089 Appendix A, Table 142: 0.0014 g/MJ, converted to lb/mcf by x (1,000 MJ/1 mcf) x (1 lb/453.6 g)
Conversions, Oxygen Additive	4.24 lbs / gal	Density of oxygen additive (assumed commercial product such as Oxygen Release Compound Advanced™) from Regenesis ORC Advanced™ MSDS, 2007
Conversions, Oxygen Additive, CO_2	3.3 lb CO_2 / lb BTEX + 0 lb CO_2 / lb oxygen additive	See previous table, Enhanced Bioremediation conversion factor for “Oxygen Additive, Conversion Factor”
Conversions, Substrate	7.89 lbs / gal	Density of substrate (assumed emulsified vegetable oil similar to soybean oil) from ESTCP 2006, Figure 3.1, p. 27.
Conversions, Substrate, CO_2	2.8 lb CO_2 / lb substrate + 0.7 lb CO_2 / lb CVOCs	See previous table, Enhanced Bioremediation conversion factor for “Donor, Conversion Factor”
Conversions, Oxidant	4 lb CO_2 / lb	Design Team
Conversions, ZVI (Iron)	1.21 lb CO_2 / lb	Design Team
Ecosystem Service, Cropland	$1,100 / ac	Adjusted Costanza, 1997 value ((Value converted to acres * 1.45 (conversion from 1994 to 2008 dollars) * 20 (NPV from 3% discount rate, over 30 years))
Ecosystem Service, Forest (Temperate/ Boreal)	$3,500 / ac	Adjusted Costanza, 1997 value ((Value converted to acres * 1.45 (conversion from 1994 to 2008 dollars) * 20 (NPV from 3% discount rate, over 30 years))

CONVERSION FACTORS AND OUTPUTS		
Ecosystem Service, Grassland	\$2,700 / ac	Adjusted Costanza, 1997 value ((Value converted to acres * 1.45 (conversion from 1994 to 2008 dollars) * 20 (NPV from 3% discount rate, over 30 years))
Ecosystem Service, Industrial	\$0.01 / ac	Assumed value is small, non-zero number. (Design Team)
Ecosystem Service, Lake/River	\$99,000 / ac	Adjusted Costanza, 1997 value ((Value converted to acres * 1.45 (conversion from 1994 to 2008 dollars) * 20 (NPV from 3% discount rate, over 30 years))
Ecosystem Service, Stream	\$49,000 / ac	Adjusted Costanza, 1997 value ((Half of Lake/River value converted to acres * 1.45 (conversion from 1994 to 2008 dollars) * 20 (NPV from 3% discount rate, over 30 years))
Ecosystem Service, Swamp/ Wetland	\$230,000 / ac	Adjusted Costanza, 1997 value ((Value converted to acres * 1.45 (conversion from 1994 to 2008 dollars) * 20 (NPV from 3% discount rate, over 30 years))
Ecosystem Service, Urban	\$930 / ac	Adjusted Costanza, 1997 value ((10% of Terrestrial value converted to acres * 1.45 (conversion from 1994 to 2008 dollars) * 20 (NPV from 3% discount rate, over 30 years))
Ecosystem Service, Wetlands	\$170,000 / ac	Adjusted Costanza, 1997 value ((Value converted to acres * 1.45 (conversion from 1994 to 2008 dollars) * 20 (NPV from 3% discount rate, over 30 years))
Safety / Accident Risk, hours worked	2.74×10^{-9} injuries and / or illnesses / hr / yr	Derived from Bureau of Labor Statistics, 2007): 5.3 recordable cases for “Heavy and civil engineering construction” / 966.3 employees) x (100 employees / 200,000 hrs worked / yr)
Safety / Accident Risk, hours worked (oxidant handling)	1.65×10^{-5} injuries	Derived from 2007 Bureau of Labor statistics (3.3 injuries per 200,000 hours worked for chemical manufacturing workers).
Safety / Accident Risk, lost hours per injury	48 lost hrs / injury	Design Team, derived from above
Safety / Accident Risk, miles traveled	91 injuries / 100,000,000 vehicle miles traveled	NHTSA, 2005

CONVERSION FACTORS AND OUTPUTS		
Safety / Accident Risk, vehicle speed	40 mph	Design Team, derived from above
Scenario, Capitalization Rate	0.03	Design Team
Scenario, CO_2, Bank of America (high cost)	\$40 / ton CO_2	Bank of America notice, Spring 2008
Scenario, CO_2, Business-as-Usual Scenario	\$2 / ton CO_2	Chicago Climate Exchange, May 2009
Scenario, CO_2, Carbon Constrained World Scenario, increase per year	15%	Design Team
Scenario, Energy, Available but Expensive, increase per year	5% annual cost increase after Year 1	Design Team
Scenario, Energy, Business-as-Usual	\$0.10 / kWh	EPA, 2005, Cost-effective Design of Pump and Treat Systems, http://www.frtr.gov//pdf/optimization/gw_mon_cost-effective-design_030805.pdf
Scenario, Energy, Increasing Energy Cost, increase per year	10% annual cost increase after Year 1	Design Team

HELP BUTTONS REFERENCED VALUES		
Value Name	**Value (including units)**	**Reference**
CO_2 Sequestration Rate, Industrial, Range	0 metric tons / ac / yr	National Carbon Offset Coalition, Inc. (NCOC) http://www.ncoc.us/
CO_2 Sequestration Rate, Industrial, Arithmetic Mean	0 metric tons / ac / yr	Trulio, Lynne, et al 2007. White paper on Carbon Sequestration and Tidal Marsh Restoration. http://www.southbayrestoration.org/pdf_files/Carbon%20Sequestration%20Dec%2020%2007.pdf
CO_2 Sequestration Rate, Urban, Range	0 metric tons / ac / yr	National Carbon Offset Coalition, Inc. (NCOC) http://www.ncoc.us/
CO_2 Sequestration Rate, Urban, Arithmetic Mean:	0 metric tons / ac / yr	Trulio, Lynne, et al 2007. White paper on Carbon Sequestration and Tidal Marsh Restoration.

HELP BUTTONS REFERENCED VALUES		
		http://www.southbayrestoration.org/pdf_files/Carbon%20Sequestration%20Dec%2020%2007.pdf
CO_2 Sequestration Rate, Cropland, Range	0.2 – 0.6 metric tons / ac / yr	National Carbon Offset Coalition, Inc. (NCOC) http://www.ncoc.us/
CO_2 Sequestration Rate, Cropland, Arithmetic Mean	0.42 metric tons / ac / yr	Trulio, Lynne, et al 2007. White paper on Carbon Sequestration and Tidal Marsh Restoration. http://www.southbayrestoration.org/pdf_files/Carbon%20Sequestration%20Dec%2020%2007.pdf
CO_2 Sequestration Rate, Forest, Range	0.05 – 3.9 metric tons / ac / yr	National Carbon Offset Coalition, Inc. (NCOC) http://www.ncoc.us/
CO_2 Sequestration Rate, Forest, Arithmetic Mean	0.99 metric tons / ac / yr	Trulio, Lynne, et al 2007. White paper on Carbon Sequestration and Tidal Marsh Restoration. http://www.southbayrestoration.org/pdf_files/Carbon%20Sequestration%20Dec%2020%2007.pdf
CO_2 Sequestration Rate, Grassland / Rangeland, Range	0.12 – 1.0 metric tons / ac / yr	National Carbon Offset Coalition, Inc. (NCOC) http://www.ncoc.us/
CO_2 Sequestration Rate, Grassland / Rangeland, Arithmetic Mean	0.46 metric tons / ac / yr	Trulio, Lynne, et al 2007. White paper on Carbon Sequestration and Tidal Marsh Restoration. http://www.southbayrestoration.org/pdf_files/Carbon%20Sequestration%20Dec%2020%2007.pdf
CO_2 Sequestration Rate, Swamp / Floodplains / Wetland, Range	2.23 – 3.71 metric tons / ac / yr	National Carbon Offset Coalition, Inc. (NCOC) http://www.ncoc.us/
CO_2 Sequestration Rate, Swamp / Floodplains / Wetland, Arithmetic Mean	2.97 metric tons / ac / yr	Trulio, Lynne, et al 2007. White paper on Carbon Sequestration and Tidal Marsh Restoration. http://www.southbayrestoration.org/pdf_files/Carbon%20Sequestration%20Dec%2020%2007.pdf
Number of Trips Required	-	http://www.frtr.gov/matrix2/section3/table3_2.pdf EPA Remediation Technology Cost compendium, 2000, pg. 6-2 EPA's P&T Design Guidelines, 1997, pg. 21

HELP BUTTONS REFERENCED VALUES		
SVE, Vapor Treatment Method	-	EPA Guidance (EPA-542-R-05-028), March 2006, Off-Gas Treatment Technologies for Soil Vapor Extraction Systems: State of the Practice http://www.clu-in.org/download/remed/EPA542R05028.pdf
CO_2 Emissions Associated with Driving Small Car (40 mpg)	1,500 miles / mo	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Driving SUV (15 mpg)	1,500 miles / mo	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Air Travel (per person)	1,500 miles / mo	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Train Travel (per person)	1,500 miles / mo	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Electricity Usage	5,000 kWh / mo	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Natural Gas Usage	10,000 feet^3 / mo	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Fuel Oil Heating	100 gallons / mo	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Driving Small Car (40 mpg)	5.31 tons / yr	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Driving SUV (15 mpg)	14.13 tons / yr	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Air Travel (per person)	8.73 tons / yr	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Train Travel (per person)	4.05 tons / yr	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Electricity Usage	45.00 tons / yr	http://www.carbonify.com/carbon-calculator.htm

HELP BUTTONS REFERENCED VALUES		
CO_2 Emissions Associated with Natural Gas Usage	2.00 tons / yr	http://www.carbonify.com/carbon-calculator.htm
CO_2 Emissions Associated with Fuel Oil Heating	13.37 tons / yr	http://www.carbonify.com/carbon-calculator.htm
Quality of GW	-	EPA, 1986, Guidelines for Groundwater Classification under EPA Groundwater Protection Strategy, Final Draft

APPENDIX C: LIST OF ACRONYMS AND ABBREVIATIONS

AFCEE	Air Force Center for Engineering and the Environment
ac	acre
BTEX	Benzene, Toluene, Ethylbenzene and Xylenes
Btu	British thermal unit
Cp	Mean heat capacity of air (SVE Supplemental Fuel calculation)
CO_2	Carbon dioxide
COC	Chemical of Concern
Co_Tc	Temperature of combustion for COC (Tier 2 Costs and Conversions)
Co_mw_c	Molecular weight percent carbon (Tier 2 Costs and Conversions)
Co_mw_o	Molecular weight percent oxygen (Tier 2 Costs and Conversions)
Co_mw_s	Molecular weight percent sulfur (Tier 2 Costs and Conversions)
co_Cp	Heat capacity of contaminant (Tier 2 Costs and Conversions)
Co_1overN	Freundlich parameter for Pump and Treat activated carbon calculation (Tier 2 Costs and Conversions)
Conc	Concentration
CRF	Concentration Reduction Factor
cuyd	cubic yard, also CY or yd^3
CVOCs	Chlorinated Volatile Organic Compounds
DZBF	Dual Zone Balancing Factor (Thermal, saturated zone)
Dsf	Density of supplemental fuel (Tier 2 Costs and Conversions)
EB	Enhanced Bioremediation
EPA	Environmental Protection Agency
EXDesign	Excavation Design screen
FS	Feasibility Study
GAC	Granular Activated Carbon
gpd	Gallons per day
GW	Groundwater
GWRoundTbl	Groundwater Roundtable screen
HR	Heat recovery (SVE Supplemental Fuel calculation)

Hsf	Heating value supplemental fuel (SVE Supplemental Fuel calculation)
ICEs	Internal Combustion Engines
ISCODesign	In Situ Chemical Oxidation (ISCO) Design Screen
Koc	Partitioning coefficient
Kp	Partitioning coefficient
LCA	Life Cycle Assessment
Max	Maximum
Mcf	Thousand cubic feet (unit for natural gas)
MNADesign	Long-term Monitoring Design / Monitored Natural Attenuation Screen
MSDS	Material Safety Data Sheet
MW	Molecular weight
NCOC	National Carbon Offset Coalition
NO_x	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NPV	Net Present Value
NRV	Natural Resource Value
O&M	Operations and Maintenance
PCE	Tetrachloroethylene, also perchloroethylene
PM_{10}	Particulate Matter (PM_{10}: inhalable coarse particles which are smaller than 10 micrometers)
ppm	Parts per million
ppmV	Parts per million by volume
PRBDesign	Permeable Reactive Barrier (PRB) Design Screen
Proj	Project
PTDesign	Pump and Treat Design screen
P&T	Pump and Treat
PVC	Polyvinyl Chloride
PWS	Public Water Supply
Qsf	Supplemental fuel flow rate (SVE supplemental fuel calculation)
Qw	Off-gas stream flow rate (SVE Supplemental Fuel calculation)
RBCA	Risk Based Corrective Action

Ref	Reference
ROI	Radius of Influence
ROT	Rule of Thumb
RPO	Remedial Process Optimization
Scfm	Standard cubic feet per minute
Sch	Schedule (e.g. Schedule 40 PVC pipe)
SO_x	Sulfur Oxides
SORoundTbl	Soil Roundtable screen
SUV	Sport Utility Vehicle
SVDesign	SVE Design screen
SVE	Soil Vapor Extraction
Tc	Combustion temperature (SVE Supplemental Fuel calculation)
TCE	Trichloroethylene
TDS	Total Dissolved Solids
The	Temperature after heat exchanger (SVE supplemental fuel calculation)
ThermalDesign	Thermal Treatment Design screen
Therm Ox	Thermal Oxidation
Tw	Temperature of waste air from venting well (SVE supplemental fuel calculation)
USCS	Unified Soil Classification System
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound
WQP	Water Quality Protection

APPENDIX D: TIER 1 EXCAVATION COSTS AND OTHER DETAILED CALCULATIONS

D.1 BACKGROUND

This section describes the Tier 1 costs and other calculations used in the Excavation module of the Sustainable Remediation Tool (SRT). For the purpose of this tool, we refer to Excavation to mean physical removal and off-site transportation and disposal of contaminated soil followed by placement and compaction of clean soil into the excavated area.

Section 2.0 below addresses technology and energy cost calculations for the Excavation module. The technology cost is calculated from unit costs available from published sources. Unit costs include factors such as labor, materials, and energy. Because one of the objectives of the SRT is to track energy usage and associated costs separately, while avoiding double-counting, part of the total cost is apportioned to energy while the remaining cost is treated as "Technology Cost." The energy cost component is then calculated separately, based on the amount of key fuels used and associated prices. The technology and energy costs may be further divided, depending upon user selection of project phase (Capital or O&M cost calculations). However, the Excavation module calculations consider all costs to be in the Capital phase, as the treatment duration (excavation activity) is assumed to be one year.

Section 3.0 below contains tables of non-cost calculations and the relevant assumptions / rules-of-thumb for those calculations.

D.2 COST CALCULATIONS

D.2.1 Technology Cost

Technology costs for Excavation are based on unit costs for remediation of the volume of affected media input by the user.

Basic Tier 1 Derivation of Technology Cost[1]

Technology	Volume	x Unit Cost	Cost Reported in SRT, based on Project Phase
Excavation	soil volume (cu yd)	$400/cu yd (haz) -or- (88.59 x volume x fluff factor) + 4007 (non-hazardous)	Assumes all costs in Capital Phase

Notes:

[1] Choose Tier 2 to view or modify these factors.

<u>Technology Cost Calculations for Excavation</u>

A basic assumption for excavation is that activities are conducted within one year. Therefore, the costs are not divided between Capital and O&M phases. The Tier 1 formula for excavation cost follows:

- For hazardous disposal, technology cost = [Volume of excavated soil in cu yd * Fluff factor * Cost per cu yd for disposal], where the cost for disposal is $400/cu yd.
- For non-hazardous disposal, technology cost = (88.59 x (Volume of affected soil x fluff factor) + 4007

Unit cost of $400/cu yd is derived from Federal Remediation Technologies Roundtable costs, which range from $270 / ton to $460 / ton (http://www.frtr.gov/matrix2/section4/4-29.html). These values are converted to $ / cu yd using a bulk density rate of 90 lbs / ft^3 and by then taking the geometric mean of the converted values ($328/cu yd and $559/cu yd), which is rounded to $400/cu yd for hazardous disposal. For non-hazardous disposal, cost estimates from RACER™ were used to develop the algorithm.

D.2.2 User-Supplied Additional Costs

The costs described above are displayed in the summary section of the individual technology screens. Below the cost summary on these screens, the SRT allows the user to enter additional project costs and other metrics. These additional, project-specific costs are added to the pre-calculated totals, and are displayed on the "output" screens.

D.2.3 Cost Factors for Energy Costs

The SRT includes calculations, with user overrides allowed, for the amount of fuel and energy used for each technology. For the Excavation module, calculations are done for gasoline and diesel. The cost-converted energy metric is displayed in the "normalized" section of the SRT's output screen. The cost conversion is the sum of the amount of energy type multiplied by cost, for each type of fuel/energy used.

Energy Type	Cost	Cost Reference
Gasoline	$2.00 / gallon	Average regular grade price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Diesel	$2.00 / gallon	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.

D.2.4 User-Supplied Additional Energy

The SRT allows the user to enter additional, project-specific metrics, including energy in megajoules. To complete the normalized/cost-based calculation for energy, the conversion from megajoules to dollars uses factors for gasoline. The converted value is added to the energy costs above, and is displayed on the "output" screens, if the user chooses to view the normalized values.

D.3 NON-COST CALCULATIONS

The following assumptions apply to non-cost calculations in the Excavation module:

- All excavation activity is assumed to take place in the first year, so all costs are considered capital costs.

- The number of trips during construction is assumed to be a minimum of 3 trips for the first 1,000 cubic feet of contaminated soil and 1 additional trip for each additional 300 cubic feet (Design Team).
- The number of trips post-construction is assumed to be 2 trips (Design Team).

EXCAVATION VARIABLES & CALCULATIONS		
Value Name	**Units**	**Calculations & Assumptions**
User-required Input		
Area of Affected Soil	$Feet^2$	--
Depth to Top of Affected Soil	Feet	--
Depth to Bottom of Affected Soil	Feet	--
Airline miles flown by project team (total miles for all travelers)	Miles over project lifetime	--
Average Distance Traveled by Site Workers per one-way trip	Miles	--
Trips by Site Workers during construction	# over project lifetime	--
Trips by Site Workers after construction	# over project lifetime	--
Distance to Disposal (one-way)	Miles	--
Type of Disposal	Choose: Hazardous or Non-hazardous	--
Additional Technology Cost	Dollars ($)	--
Additional Energy Consumed	Megajoules	--
Additional CO_2 Emissions	tons	--
Additional Safety / Accident Risk	Lost hours due to injuries / illnesses	--
Tool-calculated Value or User Override		

EXCAVATION VARIABLES & CALCULATIONS		
Volume of affected soil	Cubic feet	= Total Thickness of Affected Soil x Area of Affected Soil, where Total Thickness of Affected Soil = Depth to Bottom of Affected Soil – Depth to Top of Affected Soil
Total hours to excavate	Hours	= Volume of Affected Soil in cubic feet x Soil density x (1 ton/2000 lbs) / Excavation rate, where Soil density = 100 lbs/ft^3 (Median sample density for excavated earth: 100 lbs / ft^3, SI Metrics, 2007, http://www.simetric.co.uk/si_materials.htm) Excavation rate = 53 tons/hr, converted from 48 metric tons / hr. Performance data from FRTR website http://www.frtr.gov/matrix2/section4/4-29.html gives 18,200 metric tones excavated in 2 months as a typical value. Assuming workers excavate 9-hours per day for 21 days per month, the rate of excavation is 48 metric tons excavated per hour.
Number of loads for disposal	# loads	= Volume of Affected Soil in cubic feet x Fluff factor / Dump truck volume x (1 cu yd / 27 ft^3), where Fluff factor = 1.15 for Gravel, 1.15 for Sands, 1.3 for Silt, and 1.3 for Clay (RACER™) Dump truck volume = 12 cu yd (Median volume of dump truck from Means, 2005)
Total miles driven for disposal	Miles	= Number of loads for disposal x 2 x Distance to disposal
Total hours for fill dirt placement	Hours	=[Area of Affected Soil x (1 yd^2 / 9 ft^2) / Fill spread rate in cu yd/hr] + [Number of loads of fill dirt x Dump truck volume / Rate of water compaction in cu yd/hr] + [Total volume of fill dirt / Spread & compaction rate in cu yd/hr], where Fill spread rate = 448.5 cu yd/hr (Rate to spread unclassified fill, Means, 2005) Dump truck volume = 12 cu yd (Median volume of dump truck from Means, 2005)

EXCAVATION VARIABLES & CALCULATIONS		
		Rate of water compaction = 174.3 cu yd/hr (Means, 2005) Spread & compaction rate = 654 cu yd/hr (Rate to spread / compact with sheepsfoot roller, 8” lift, Means, 2005)
Number of loads of fill dirt	# loads	= Volume of Affected Soil in cubic feet x Fluff factor / Dump truck volume x (1 cu yd / 27 ft^3), where Fluff factor = 1.15 for Gravel, 1.15 for Sands, 1.3 for Silt, and 1.3 for Clay (RACER™) Dump truck volume = 12 cu yd (Median volume of dump truck from Means, 2005)
Total miles driven for fill	Miles	Number of loads of fill dirt x 2 x Distance from site to fill source, where Distance from site to fill source = 10 miles one-way (Design Team)
Diesel	Gallons	= (Total hours to excavate + Total hours for fill dirt placement) x Excavator fuel consumption rate + (Total miles driven for disposal / Dump truck fuel consumption rate), where Excavator fuel consumption rate = 3 gal/hr (Design Team) Dump truck fuel consumption rate = 8 mpg (Mid-sized dump truck fuel consumption, G.E.O. Carbon Calculator, 2008)
Gasoline	Gallons	= Miles traveled / Vehicle mileage (travel), where Miles traveled = Distance to site x 2 x (Number of trips during construction + Number of trips post-construction) Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW)

EXCAVATION VARIABLES & CALCULATIONS		
Jet Fuel	Gallons	= Jet fuel use rate per passenger x Weight of passenger + luggage x Airline miles flown by project team, where Jet fuel use rate per passenger = 0.037 gal / 3800 mile (see Excavation Rules-of-Thumb) Weight of passenger + luggage assumed to = 200 lbs (Jet fuel is lumped into gasoline volume)
Cost (Capital)	Dollars ($)	= Volume of Affected Soil in cubic yards x Fluff factor x $360/cu yd if Hazardous, or = (88.59 x Volume of affected soil x fluff factor) + 4007 if non-Hazardous, where Fluff factor = 1.15 for Gravel, 1.15 for Sands, 1.3 for Silt, and 1.3 for Clay (RACER™) Unit cost including energy = $400/cu yd for hazardous; ($400/cu yd x 90% = $360/cu yd, Design Team; see Section 2.1) Non-hazardous algorithm developed from RACER™ cost estimates assuming unit price of $25.00 / CY for landfill disposal (Jet fuel is lumped into gasoline volume)
Tool-calculated Value		
Volume of affected soil	Cubic yards	= Volume of affected soil in cubic feet / (27 ft^3/cu yd)
Tool-calculated Metrics		
CO_2 Emissions	tons CO_2	= (Diesel x 25.8 lb/gal / 2000) + (Gasoline x 20.17 lb/gal / 2000) + User-defined additional CO_2 CO_2 conversions from nrel.gov; (Jet fuel is lumped into gasoline volume)
NOx	tons NOx	= (Diesel x 0.20922955 lb/gal / 2000) + (Gasoline x 0.015078 lb/gal / 2000)

EXCAVATION VARIABLES & CALCULATIONS		
SOx	tons SOx	= (Diesel x 0.00020065 lb/gal / 2000) + (Gasoline x 0.0001599 lb/gal / 2000)
PM10	tons PM10	= (Diesel x 0.0099786 lb/gal / 2000) + (Gasoline x 0.00129015 lb/gal / 2000)
Total Energy Consumed	Megajoules	= (Diesel x 170 MJ/gal) + (Gasoline x 150 MJ/gal) + User-defined additional Energy (Jet fuel is lumped into gasoline volume)
Technology Cost	Dollars ($)	See Section 2.0
Change in Resource Service: Ecologic, Economic	Net gain or net loss	<u>Ecologic Change in Resource Service</u> = Final ecologic resource service value – Initial ecologic resource service value If Change = Positive, Net gain If Change = Negative, Net loss, where Initial ecologic resource service value = Area of affected soil x Adjusted biome-specific value x Modifying factor, where Adjusted biome-specific value = $0/ac for Industrial, $930/ac for Urban, $1,100/ac for Cropland, $2,700/ac for Grassland/Rangeland, $3,500/ac for Forest, or $230,000/ac for Wetlands (Design Team modification of Costanza et al., 1997) Modifying factor = If Benefit to ecological service value is High, 0.5 If Benefit to ecological service value is Medium, 0.2 If Benefit to ecological service value is Low, 0.05 (Design Team) Final ecologic resource service value = Affected area x Adjusted biome-specific value for future setting

EXCAVATION VARIABLES & CALCULATIONS		
		Economic Change in Resource Service = Area of affected soil x Economic land value in contaminated state x Modifying factor for increased value due to cleanup, where Modifying factor for increased value due to cleanup = If Level of contamination is High, 0.5 If Level of contamination is Medium, 0.2 If Level of contamination is Low, 0.05 (Design Team)
Safety/Accident Risk	Lost hours	= Total hours worked x Injuries per hour + Total vehicle miles traveled x Injuries per mile, where Total hours worked = Hours worked + Hours for travel (post-construction/site visit) Hours worked = 50% x Capital Cost / $80/hr labor rate (Design Team) Hours for travel = 10 + Distance to site x 2 / 40 mph (Design Team) Injuries per hour = 2.7×10^{-9} (derived from US Bureau of Labor Statistics, 2007) Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of post-construction trips Injuries per mile = 9.1×10^{-7} (NHTSA, 2005)

D.3.1 Key Factors / Rules-of-Thumb

In Tier 1, the tool uses several "Rules-of-Thumb" (RoT) in order to calculate sustainability metrics while limiting user inputs. These RoT are derived from a combination of published values and equations and project team experience. The following table provides the key RoT used in the Excavation technology module of Tier 1.

EXCAVATION RULES-OF-THUMB		
Value Name	**Value**	**Reference**
Distance from site to fill source (one way)	10 miles	Design Team
Dump Truck Volume	12 cu yd	Median volume of dump truck from Means, 2005
Fluff Factor	Gravel, 15%; Sands, 15%; Silt, 30%; Clay, 30%	RACER™
Fuel Consumption Rate, Diesel, Mid-sized Dump Truck	8 miles / gal	Mid-sized dump truck fuel consumption, G.E.O. Carbon Calculator, 2008
Fuel Consumption Rate, Excavator	3 miles / gal	Design Team
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Mileage, Vehicle for Transportation	10 miles / gal	Design Team
Rate, Excavation	48 metric tons / hr (with value converted to tons/hr for use in tool)	Performance data from FRTR website http://www.frtr.gov/matrix2/section4/4-29.html gives 18,200 metric tones excavated in 2 months as a typical value. Assuming workers excavate 9-hours per day for 21 days per month, the rate of excavation is 48 metric tons excavated per hour.
Rate, Fill Spread	448.5 yd^2 / hr	Rate to spread unclassified fill, Means, 2005
Rate, Spread / Compaction	654 cu yd / hr	Rate to spread / compact with sheepsfoot roller, 8" lift, Means, 2005
Rate, Water Compaction	174.3 cu yd / hr	Rate of water compaction, Means, 2005

D.4 REFERENCES

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APPENDIX E: TIER 1 SOIL VAPOR EXTRACTION (SVE) COSTS AND OTHER DETAILED CALCULATIONS

E.1 BACKGROUND

This section describes the Tier 1 costs and other calculations used in the Soil Vapor Extraction (SVE) module of the Sustainable Remediation Tool (SRT), Beta version. For the purpose of this tool, we refer to Soil Vapor Extraction to mean in situ removal of soil contaminants by creation of a vacuum in the soil to extract volatile and/or semi-volatile compounds. The SRT considers either the case of adsorption of compounds onto activated carbon for off-site disposal or the case of destruction through the use of thermal oxidation.

Section 2.0 below addresses technology and energy cost calculations for the SVE module.

Section 3.0 below contains tables of non-cost calculations and the relevant assumptions / rules-of-thumb for those calculations.

E.2 COST CALCULATIONS

E.2.1 Technology Costs

Technology cost for SVE is calculated using a formula derived from RACER™ cost estimates.

Technology Cost Calculations for SVE

The Tier 1 calculation for SVE costs, developed from RACER, follows. The amount reported in the SRT summary depends upon the user's selection of Capital, O&M, or both.

- Technology Cost (Capital), Activated carbon = 532.13 x Linear feet drilled + 38793
- Technology Cost (O&M), Activated carbon = 130.07 x Linear feet drilled + 15553, with maximum of $400,000

- Technology Cost (Capital), Therm. Ox. = 481.75 x Linear feet drilled + 164070
- Technology Cost (O&M), Therm. Ox. = 175.78 x Linear feet drilled + 17419, with maximum of $400,000.

where

Linear feet drilled = Number of wells x Depth to bottom of affected soil

E.2.2 User-Supplied Additional Costs

The costs described above are displayed in the summary section of the individual technology screens. Below the cost summary on these screens, the SRT allows the user to enter additional project costs and other metrics. These additional, project-specific costs are added to the pre-calculated totals, and are displayed on the "output" screens.

E.2.3 Cost Factors for Energy Costs

The SRT includes calculations, with user overrides allowed, for the amount of fuel and energy used for each technology. Calculations are done for gasoline, diesel, electricity, and natural gas. The cost-converted energy metric is displayed in the "normalized" section of the SRT's output screens. The cost conversion is the sum of the amount of energy type multiplied by cost, for each type of fuel/energy used. The Tier 1 costs for each energy type are:

Energy Type	Cost	Cost Reference
Gasoline	$2.00 / gallon	Average regular grade price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Diesel	$2.00 / gallon	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Electricity	$0.10 kWh	Electricity Cost from EPA 2005, Cost-effective Design of Pump and Treat Systems (http://www.frtr.gov//pdf/optimization/gw_mon_cost-effective_design_030805.pdf)
Natural Gas	$11.00 / mcf	Average industrial natural gas price, January 2009 (http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm); Website accessed 4/23/09.

E.2.4 User-Supplied Additional Energy

The SRT allows the user to enter additional, project-specific metrics, including energy in megajoules. To complete the normalized/cost-based calculation for energy, the conversion from megajoules to dollars uses factors for gasoline. The converted value is added to the energy costs above, and is displayed on the "output" screens, if the user chooses to view the normalized values.

E.3 NON-COST CALCULATIONS

The following assumptions apply to non-cost calculations in the Soil Vapor Extraction module:

- The number of trips during construction is assumed to be a minimum of 5 trips for the first 1,000 cubic feet of contaminated soil and 1 additional trip for each additional 2,000 cubic feet (Design Team).
- The number of trips post-construction is assumed to be 12 trips per year multiplied by the project duration (Design Team).
- Annual operating time is assumed to be 95% (8,320 hrs/yr), as 100% operating time is unrealistic (Design Team). This factor is also used in the Pump and Treat module.
- An overall 95% efficiency factor is applied to account for the fact that 100% of contaminant cannot be removed (Design Team).

SOIL VAPOR EXTRACTION VARIABLES & CALCULATIONS		
Value Name	**Units**	**Calculations & Assumptions**
User-required Input		
Area of Affected Soil	$Feet^2$	--
Depth to Top of Affected Soil	Feet	--
Depth to Bottom of Affected Soil	Feet	--
Depth to Groundwater	Feet	--
Soil Type	Choose: Sandy gravel; Sand (well graded); Sand (poorly graded); Silt; Clay	--
Contaminant Class	Choose: CVOCs; Total BTEX	--

SOIL VAPOR EXTRACTION VARIABLES & CALCULATIONS		
Max. Concentration	mg/kg	--
Typical Concentration	mg/kg	--
Airline miles flown by project team (total miles for all travelers)	Miles over project lifetime	--
Average Distance Traveled by Site Workers per one-way trip	Miles	--
Trips by Site Workers during construction	# over project lifetime	--
Trips by Site Workers after construction	# over project lifetime	--
Additional Technology Cost	Dollars ($)	--
Additional Energy Consumed	Megajoules	--
Additional CO_2 Emissions	tons	--
Additional Safety / Accident Risk	Lost hours due to injuries / illnesses	--
Tool-calculated Value or User Override		
Duration	Years	= 0.5 if Sandy gravel; 1 if Sand (well graded); 1 if Sand (poorly graded); 2 if Silt; Not feasible if Clay (Typical SVE duration from FRTR is 2 years; http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf)
Number of wells	#	= Area of Affected Soil / (Pi x (Radius of influence x ROI overlap) ^2), where Radius of influence (ROI) = 17.5 ft if Sandy gravel; 17.5 ft if Sand (well graded); 17.5 ft if Sand (poorly graded); 11 ft if Silt; Not feasible if Clay ROI overlap = 0.9 (Design Team; Included to ensure adequate well coverage for the affected area.) ROIs derived from FRTR information: 35 ft diameter

SOIL VAPOR EXTRACTION VARIABLES & CALCULATIONS		
		for gravels and sands; 22 ft diameter for silts and clays (FRTR, http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf)
Length of manifold	Feet	= ROI x 2 x Number of wells, where Radius of influence (ROI) = 17.5 ft if Sandy gravel; 17.5 ft if Sand (well graded); 17.5 ft if Sand (poorly graded); 11 ft if Silt; Not feasible if Clay
Vapor treatment method	Choose: Activated Carbon; Thermal Oxidizer	= Activated carbon if Max. concentration <100 mg/kg; otherwise, thermal oxidizer
PVC	Pounds	= [(Number of wells x Depth of Affected Soil) + Length of manifold] x 2.03 lbs/ft PVC Value calculated for Capital or both Capital and O&M phases. 2.03 lbs/ft PVC from Driscoll, Groundwater and Wells, Appendix 13D
Activated carbon	Pounds	= 10 lbs activated carbon x Contaminant Mass, where Contaminant Mass = Typical Concentration / 1,000,000 x Area of Affected Soil x (Depth to Bottom of Affected Soil – Depth to Top of Affected Soil) x Soil density Soil density = 102 lb/ft^3 if Sandy gravel; 100 lb/ft^3 if Sand (well graded); 100 lb/ft^3 if Sand (poorly graded); 95 lb/ft^3 if Silt; 90 lb/ft^3 if Clay (SI Metrics) 10 lbs activated carbon / lb contaminant mass based on Nyer, 1993, p. 127
Electricity	kWh	= Pump power requirements x 0.7457 kWh/hp x Operating time per year x Duration, where Pump power requirements = 5 hp Operating time per year = 24 hrs/day x 365 days/yr

SOIL VAPOR EXTRACTION VARIABLES & CALCULATIONS		
		x 95% = 8,320 hrs/yr Note: Project duration multiplied by 95% to account for assumption of annual system operating time is 95% (system does not operate 100% of the time) (Design Team).
Diesel (Capital)	Gallons	= Diesel for trenching + Diesel for drilling, where Diesel for trenching = Linear feet for trenching / Trenching rate x Trenching fuel consumption rate, where Linear feet for trenching = Length of manifold Trenching rate = 300 ft/hr Trenching fuel consumption rate = 6.25 gal/hr Diesel for drilling = Linear feet for drilling / Drilling rate x Drilling fuel consumption rate, where Linear feet for drilling = Number of wells x Depth to Bottom of Affected Soil Drilling rate = 100 ft/day Drilling fuel consumption = 32 gal/day
Diesel (O&M)	Gallons	= Miles traveled for activated carbon disposal / Vehicle mileage for transportation of activated carbon disposal, where Miles traveled for activated carbon disposal = Activated carbon / 20,000 x 400 miles (Vignes, assume 20,000 lbs activated carbon / truck; 400 miles assumed by Design Team for 1 roundtrip activated carbon disposal) Vehicle mileage for transportation of activated carbon disposal = 5 mpg (Design Team)
Gasoline (Capital)	Gallons	= Miles traveled / Vehicle mileage (travel), where Miles traveled = Distance to site x 2 x Number of trips during construction

SOIL VAPOR EXTRACTION VARIABLES & CALCULATIONS		
		Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW) (Jet fuel is lumped into gasoline volume)
Gasoline (O&M)	Gallons	= (Miles traveled / Vehicle mileage), where Miles traveled = Distance to site x 2 x Number of trips post-construction Vehicle mileage assumed to = 15 mpg (Design Team, BW) (Jet fuel is lumped into gasoline volume)
Natural gas	mcf	See Appendix A for Thermal Oxidizer natural gas calculations. If activated carbon is chosen, the amount of natural gas used in regeneration is calculated in the following way: Natural gas for activated carbon regeneration = Activated carbon x 7,000 btu/1,000 lb carbon x 1 mcf/1,000 btu (Vignes)
Jet Fuel	Gallons	= Jet fuel use rate per passenger x Weight of passenger + luggage x Airline miles flown by project team, where Jet fuel use rate per passenger = 0.037 gal / 3800 mile Weight of passenger + luggage assumed to = 200 lbs (Design Team) (Jet fuel is lumped into gasoline volume)
Cost (Capital)	Dollars ($)	See Section 2.0
Cost (O&M, annual)	Dollars ($)	See Section 2.0
Tool-calculated Value		

SOIL VAPOR EXTRACTION VARIABLES & CALCULATIONS		
Contaminant Mass	Pounds	= Typical Concentration / 1,000,000 x Area of Affected Soil x (Depth to Bottom of Affected Soil – Depth to Top of Affected Soil) x Soil density Soil density = 102 lb/ft^3 if Sandy gravel; 100 lb/ft^3 if Sand (well graded); 100 lb/ft^3 if Sand (poorly graded); 95 lb/ft^3 if Silt; 90 lb/ft^3 if Clay (SI Metrics)
Tool-calculated Metrics		
CO_2 Emissions	tons CO_2	= (PVC x 1.824 lb/lb / 2,000) + (Activated carbon x 2.7 lb/lb / 2,000) + (Electricity x 1.34 lb/kWh / 2,000) + (Diesel x 25.8 lb/gal / 2,000) + (Gasoline x 20.17 lb/gal / 2,000) + (Natural gas x 122 lb/mcf / 2,000) + User-defined additional CO_2 CO_2 conversions from nrel.gov; (Jet fuel is lumped into gasoline volume)
NOx	tons NOx	= (PVC x 0.00318 / 2000) + (Electricity x 3.66 / 2000) + (Diesel x 0.20922955 / 2000) + (Gasoline x 0.015078 / 2000) + (Natural gas x 86 / 2000)
SOx	tons SOx	= (PVC x 0.0105 / 2000) + (Electricity x 6.89 / 2000) + (Diesel x 0.00020065 / 2000) + (Gasoline x 0.0001599 / 2000) + (Natural gas x 0.29 / 2000)
PM10	tons PM10	= (PVC x 0.00018 / 2000) + (Electricity x conversion factors) + (Diesel x 0.0099786 / 2000) + (Gasoline x 0.00129015 / 2000) + (Natural gas x conversion factors)
Total Energy Consumed	Megajoules	= (Electricity x 11 MJ/kWh) + (Diesel x 170 MJ/gal) + (Gasoline x 150 MJ/gal) + (Natural gas x 1 MJ/mcf) + User-defined additional Energy Energy conversions from nrel.gov (Jet fuel is lumped into gasoline volume)
Technology Cost	Dollars ($)	See Section 2.0
Change in Resource Service: Ecologic, Economic	Net gain or net loss	<u>Ecologic Change in Resource Service</u> = Final ecologic resource service value – Initial ecologic resource service value

SOIL VAPOR EXTRACTION VARIABLES & CALCULATIONS		
		If Change = Positive, Net gain If Change = Negative, Net loss, where Initial ecologic resource service value = Area of affected soil x Adjusted biome-specific value x Modifying factor, where Adjusted biome-specific value = $0/ac for Industrial, $930/ac for Urban, $1,100/ac for Cropland, $2,700/ac for Grassland/Rangeland, $3,500/ac for Forest, or $230,000/ac for Wetlands (Design Team modification of Costanza et al., 1997) Modifying factor = If Benefit to ecological service value is High, 0.5 If Benefit to ecological service value is Medium, 0.2 If Benefit to ecological service value is Low, 0.05 (Design Team) Final ecologic resource service value = Affected area x Adjusted biome-specific value for future setting Economic Change in Resource Service = Area of affected soil x Economic land value in contaminated state x Modifying factor for increased value due to cleanup, where Modifying factor for increased value due to cleanup = If Level of contamination is High, 0.5 If Level of contamination is Medium, 0.2 If Level of contamination is Low, 0.05 (Design Team)
Safety/Accident Risk	Lost hours	= Total hours worked x Injuries per hour + Total vehicle miles traveled x Injuries per mile, where

SOIL VAPOR EXTRACTION VARIABLES & CALCULATIONS		
		Total hours worked = Hours worked + Hours for travel (post-construction/site visit) Hours worked = 50% x Capital Cost / $80/hr labor rate (Design Team) Hours for travel = 10 + Distance to site x 2 / 40 mph (Design Team) Injuries per hour = 2.7 x 10^{-9} (derived from US Bureau of Labor Statistics, 2007) Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of post-construction trips Injuries per mile = 9.1 x 10^{-7} (NHTSA, 2005)

E.3.1 Key Factors / Rules-of-Thumb

In Tier 1, the tool uses several “Rules-of-Thumb” (RoT) in order to calculate sustainability metrics while limiting user inputs. These RoT are derived from a combination of published values and equations and project team experience. The following table provides the key RoT used in the SVE technology module of Tier 1.

SOIL VAPOR EXTRACTION RULES-OF-THUMB		
Value Name	**Value**	**Reference**
Activated Carbon, Conversion Factor	10 lbs GAC / lb contaminant	The default assumption is 10 pound of granular activated carbon for each pound of contaminant; based on Nyer 1993 ROT, p. 127
Activated Carbon, Miles Traveled for Disposal	400 miles / trip	Design Team
Fuel Consumption Rate, Drilling	10 gal / day	Driller Correspondence

SOIL VAPOR EXTRACTION RULES-OF-THUMB		
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Fuel Consumption Rate, Trenching	6.25 gal / hr	Design Team
Mileage, Vehicle for Activated Carbon Disposal	3 miles / gal	Design Team
Mileage, Vehicle for Transportation	10 miles / gal	Design Team
Rate, Drilling	100 ft / day	Driller Correspondence
Rate, Trenching	390 ft / hr	Design Team
Soil Type: Sand (poorly graded), SVE Duration	1 yr	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf
Soil Type: Sand (poorly graded), SVE Radius of Influence (ROI)	17.5 ft	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given diameter
Soil Type: Sand (well graded), SVE Duration	1 yr	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf
Soil Type: Sand (well graded), SVE ROI	17.5 ft	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given diameter
Soil Type: Sandy Gravel, SVE Duration	0.5 yr	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf
Soil Type: Sandy Gravel, SVE ROI	17.5 ft	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given diameter
Soil Type: Silt, SVE Duration	2 yrs	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf
Soil Type: Silt, SVE ROI	11 ft	http://www.frtr.gov/matrix2/section4/Soil_Vapor_Extraction.pdf, half of given

SOIL VAPOR EXTRACTION RULES-OF-THUMB		
		diameter
System Operating Time	8,320 hrs / yr	Hours in one year = (8,760 hrs / yr) x 95% (Design Team; assume 95% operating time)
System Pump Power Requirements	5 hp	Design Team

E.4 REFERENCES

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APPENDIX F: TIER 1 THERMAL TREATMENT COSTS AND OTHER DETAILED CALCULATIONS

F.1 BACKGROUND

This section describes the Tier 1 costs and other calculations used in the Thermal module of the Sustainable Remediation Tool (SRT). For the purpose of this tool, we refer to Thermal treatment to mean in situ heating of soil contaminants to extract volatile and/or semi-volatile compounds. The user is advised that system design parameter and cost calculations appear as estimations in the SRT; users should consult professional Thermal treatment vendors for detailed, site-specific design and cost, as the SRT is a screening level tool, not a design tool.

The SRT considers Thermal Conductive Heating, Electrical Resistivity Heating, and Steam Injection. While it appears in the Soil technologies section of the SRT, the Thermal module does take into account the possibility of treating both unsaturated and saturated soil remediation zones. To account for the overall influence of saturated soils on Thermal treatment, the user can choose to use the default or to modify the “Dual Zone Balancing Factor,” which estimates the relative proportions of saturated and unsaturated zones. This DZBF factor applies to remediation duration estimates.

Section 2.0 below addresses technology and energy cost calculations for the SVE module.

Section 3.0 below contains tables of non-cost calculations and the relevant assumptions / rules-of-thumb for those calculations.

F.2 COST CALCULATIONS

F.2.1 Technology Costs

The SRT calculates costs for thermal treatment based on design team and RACER-derived unit costs for remediation of the volume of affected media input by the user.

Basic Tier 1 Derivation of Technology Cost

Technology	Volume	x Unit Cost	Cost Reported in SRT, based on Project Phase
Thermal	Contaminated soil volume (cu yd)	$126 \times e^{(-6E-6 \times volume)}$	Assumes all costs in Capital Phase

F.2.2 User-Supplied Additional Costs

The costs described above are displayed in the summary section of the individual technology screens. Below the cost summary on these screens, the SRT allows the user to enter additional project costs and other metrics. These additional, project-specific costs are added to the pre-calculated totals, and are displayed on the "output" screens.

F.2.3 Cost Factors for Energy Costs

The SRT includes calculations, with user overrides allowed, for the amount of fuel and energy used for each technology. Calculations are done for gasoline, diesel, electricity, and natural gas. The cost-converted energy metric is displayed in the "normalized" section of the SRT's output screens. The cost conversion is the sum of the amount of energy type multiplied by cost, for each type of fuel/energy used. The Tier 1 costs for each energy type are:

Energy Type	Cost	Cost Reference
Gasoline	$2.00 / gallon	Average regular grade price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Diesel	$2.00 / gallon	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Electricity	$0.10 kWh	Electricity Cost from EPA 2005, Cost-effective Design

		of Pump and Treat Systems (http://www.frtr.gov//pdf/optimization/gw_mon_cost-effective_design_030805.pdf)
Natural Gas	$11.00 / mcf	Average industrial natural gas price, January 2009 (http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm); Website accessed 4/23/09.

F.2.4 User-Supplied Additional Energy

The SRT allows the user to enter additional, project-specific metrics, including energy in megajoules. To complete the normalized/cost-based calculation for energy, the conversion from megajoules to dollars uses factors for gasoline. The converted value is added to the energy costs above, and is displayed on the “output” screens, if the user chooses to view the normalized values.

F.3 NON-COST CALCULATIONS

The following assumptions apply to non-cost calculations in the Thermal Treatment module:

- The materials and consumables (as well as cost) are lumped into the Capital Phase, as Thermal projects tend to have short durations (Design Team).
- Annual operating time is assumed to be 100% (Design Team).
- To account for the overall influence of saturated soils on Thermal treatment, the user can choose to use the default or to modify the “Dual Zone Balancing Factor,” which estimates the relative proportions of saturated and unsaturated zones. This DZBF applies to remediation duration estimates.
- For Thermal Conductive Heating, the DZBF = (-0.276 x percentage of contaminated soil above the water table) + 1.3034 (Design Team).
- For Electrical Resistivity Heating, the DZBF = (-1.12 x percentage of contaminated soil above the water table) + 2.2336 (Design Team).
- For Steam Injection, the DZBF = 1, which means only unsaturated zone behavior is considered.

THERMAL TREATMENT VARIABLES & CALCULATIONS		
Value Name	**Units**	**Calculations & Assumptions**
User-required Input		
Area of Affected Soil	ft^2	--

THERMAL TREATMENT VARIABLES & CALCULATIONS		
Depth to Top of Affected Soil	ft	--
Depth to Bottom of Affected Soil	ft	--
Depth to Groundwater	ft	--
Soil Type	Choose: Sandy gravel; Sand (well graded); Sand (poorly graded); Silt; Clay	--
Contaminant Class	Choose: CVOCs; Total BTEX	--
Max. Concentration	mg/kg	--
Typical Concentration	mg/kg	--
Airline miles flown by project team (total miles for all travelers)	Miles over project lifetime	--
Average Distance Traveled by Site Workers per one-way trip	Miles	--
Trips by Site Workers during construction	# over project lifetime	--
Trips by Site Workers after construction	# over project lifetime	--
Type of Treatment	-	Choose: Thermal Conductive Heating, Electrical Resistivity Heating, or Steam Injection
Additional Technology Cost	Dollars ($)	--
Additional Energy Consumed	Megajoules	--
Additional CO_2 Emissions	tons	--
Additional Safety / Accident Risk	Lost hours due to injuries / illnesses	--

THERMAL TREATMENT VARIABLES & CALCULATIONS		
Tool-calculated Value or User Override		
Thermal Conductive Heating		
Type of vapor treatment	-	= If Maximum concentration < 100 mg/kg, Activated Carbon. Otherwise, Thermal Oxidizer.
Contaminant mass	lb	= Typical concentration x Area of affected soil x (Depth to bottom of affected soil - Depth to top of affected soil x soil density x 10^{-6}), where Soil Density = 102 lb/ft3 if Sandy gravel, = 100 lb/ft3 if Sand (well graded), = 100 if Sand (poorly graded), = 95 if Silt, = 90 if Clay
Upper bound temperature achieved (Tu)	° Celsius	= 500
Well diameter	in	= 4 or 6
Manifold diameter	in	= 6 or 8
Well spacing	ft	= 7 or 15
Condenser capacity	lb/h	= 500
Soil particle density	lb/ft3	= Soil density / (1 – Porosity), where Soil density = 102 lb/ft3 if Sandy gravel, = 100 lb/ft3 if Sand (well graded), = 100 if Sand (poorly graded), = 95 if Silt, = 90 if Clay. Porosity = 0.35 if Sandy gravel, = 0.25 if Sand (well graded), = 0.35 if Sand (poorly graded), = 0.4 if Silt, = 0.45 if Clay.
Fraction of heat lost by soil	-	= 0.1
Area heated by each well	ft^2	=(Well spacing)^2 x sin(60°), where Well Spacing = 7

THERMAL TREATMENT VARIABLES & CALCULATIONS		
		feet or 15 feet
Number of heater only wells	-	=Area of affected soil / Area heated by each well
Number of producer wells (heater vacuum wells)	-	= Heater only well / 3
Well depth	ft	= Depth to bottom of affected soil + 2
Latent heat of vaporization of water at atmospheric pressure	kW day/lb	= 1.83×10^{-2}
Average power input per unit length of thermal conduction well	kW/ft	= 0.295
Air density	lb/ft3	= 0.0745
Soil density	lb/ft3	= 102 lb/ft3 if Sandy gravel, = 100 lb/ft3 if Sand (well graded), = 100 if Sand (poorly graded), = 95 if Silt, = 90 if Clay
Heat capacity of soil	kW day/lb/°C	=0.0000055
Porosity	-	= 0.35 if Sandy gravel, = 0.25 if Sand (well graded), = 0.35 if Sand (poorly graded), = 0.4 if Silt, = 0.45 if Clay
Density of water	lb/ft3	= 62.42
Heat capacity of water	kW day/lb/°C	= 0.000022
Typical water saturation	-	= 0.6
Boiling point of water at atmospheric pressure	° Celsius	= 100
Typical initial temperature for near-surface soil	° Celsius	= 13
Stainless steel weight per length of well	lb/ft	= 4.76 if Well diameter = 4 in; 7.28 if Well diameter = 6
Stainless steel weight per length of manifold	lb/ft	= 7.28 if Manifold diameter = 6 in; 9.81 if Manifold diameter = 8
Length of manifold	ft	=Number of heater only wells x Well spacing

THERMAL TREATMENT VARIABLES & CALCULATIONS		
Condenser quantity	-	= Peak vapor generation / Condenser capacity
Stainless steel weight Total	lb	= [(Number of heater well + Number of producer wells) x Length of wells] x Stainless steel weight per length of well + Length of manifold x Stainless steel weight per length of manifold + (200 x Condenser quantity)
Additional linear feet of PVC	ft	= 0
PVC weight	lb/ft	= 2.03
PVC weight Total	lb	= Additional linear feet of PVC x PVC weight
Activated carbon	lb	= 10 lbs activated carbon x Contaminant mass
Linear feet for trenching	ft	= Length of manifold
Trenching rate	ft/hr	= 300
Trenching fuel consumption rate	gal/hr	= 6.25
Fuel for trenching	gal	= Linear feet for trenching / Trenching rate x Trenching fuel consumption rate
Linear feet for drilling	ft	= (Number of heater only wells + Number of producer wells) x Length of wells
Drilling rate	ft/day	= 100
Drilling fuel consumption rate	gal/day	= 32
Fuel (diesel) for drilling	gal	= Linear feet for drilling / Drilling rate x Drilling fuel consumption rate
Total Distance for AC disposal	mi	= Activated carbon weight / Truck capacity for Activated Carbon x Distance for Activated Carbon disposal
Vehicle mileage for AC disposal	miles per gal	= 5
Diesel for AC disposal	gal	= Total distance for AC disposal / Vehicle mileage for AC disposal
Diesel consumption Total	gal	= Diesel for Drilling + Diesel for Trenching + Diesel for AC disposal
Natural Gas for AC Regeneration	mcf	See Appendix F-1
Natural Gas for Therm Ox	mcf	See Appendix F-1
Peak vapor power generation	ft^3	= [Air Density x (1- Typical Water Saturation) + (Density of water x Typical Water Saturation)] x Porosity x Area of affected soil x (Depth to bottom of affected soil - depth to top of affected soil)} / remediation duration, where Air Density = 0.0745 lb/ft^3 Density of water = 62.42 lb/ft^3

THERMAL TREATMENT VARIABLES & CALCULATIONS		
		Typical Water Saturation = 0.6
Vacuum Pump power requirements	kW	= 5 if peak of pump power generation is< 90 lb/h
	kW	= 10 if peak of pump power generation is >90 lb/h
Electricity for Vacuum pump	kWh	= Vacuum pump power requirements x Remediation duration x 24
Electricity for TCH	kWh	= (Number of heater only well + Number of producer well) x Average power input per unit length of thermal conduction well x Length of heater and producer well x Remediation Duration x 24, where Average power input per unit length of thermal conduction well = 0.295 kW/ft
Total Electricity	kWh	= Electricity for TCH + Electricity for vacuum pump
Jet fuel use rate per passenger	gal/mile	= 0.0000097
Weight of passenger + luggage	lb	= 200
Total jet fuel	gal	= Jet fuel use rate per passenger x Weight of passenger + luggage x Air miles traveled
Miles traveled (gasoline)	miles	= Distance to Site x 2 x (Number of construction trips + Number of post-construction trips)
Vehicle mileage	miles per gal	= 15
Total gasoline	gal	= Miles traveled / Vehicle mileage
Total gasoline (gasoline + jet fuel)	gal	= Total gasoline + Total jet fuel
Electrical Resistivity Heating		
Type of vapor treatment	-	= If Maximum concentration < 100 mg/kg, Activated Carbon. Otherwise, Thermal Oxidizer.
Contaminant mass	lb	= Typical concentration x Area of affected soil x (Depth to bottom of affected soil - Depth to top of affected soil x soil density x 10^{-6}), where Soil Density = 102 lb/ft3 if Sandy gravel, = 100 lb/ft3 if Sand (well graded), = 100 if Sand (poorly graded), = 95 if Silt, = 90 if Clay
Upper bound temperature achieved (Tu)	° Celsius	= 100

THERMAL TREATMENT VARIABLES & CALCULATIONS		
Electrode diameter	in	= 4
Manifold diameter	in	= 6 or 8
Electrode spacing	ft	= 8.5 or 20
Condenser capacity	lb/h	= 500
Soil particle density	lb/ft3	= Soil density / (1 – Porosity), where Soil density = 102 lb/ft3 if Sandy gravel, = 100 lb/ft3 if Sand (well graded), = 100 if Sand (poorly graded), = 95 if Silt, = 90 if Clay. Porosity = 0.35 if Sandy gravel, = 0.25 if Sand (well graded), = 0.35 if Sand (poorly graded), = 0.4 if Silt, = 0.45 if Clay.
Fraction of heat lost by soil	-	= 0.1
Area heated by each electrode	ft^2	=(Electrode spacing)^2 x sin(60°), where Electrode Spacing = 8.5 feet or 20 feet
Number of electrodes	-	=Area of affected soil / Area heated by each electrode
Number of vapor recovery wells	-	= Number of electrodes
Length of electrodes	ft	= Depth to bottom of affected soil
Length of vapor recovery wells	ft	= Depth to bottom of affected soil
Latent heat of vaporization of water at atmospheric pressure	kW day/lb	= 1.83×10^{-2}
Average power input per unit length of electrode	kW/ft	= 0.295
Air density	lb/ft3	= 0.0745
Soil density	lb/ft3	= 102 lb/ft3 if Sandy gravel,

THERMAL TREATMENT VARIABLES & CALCULATIONS		
		= 100 lb/ft3 if Sand (well graded), = 100 if Sand (poorly graded), = 95 if Silt, = 90 if Clay
Heat capacity of soil	kW day/lb/°C	=0.0000055
Porosity	-	= 0.35 if Sandy gravel, = 0.25 if Sand (well graded), = 0.35 if Sand (poorly graded), = 0.4 if Silt, = 0.45 if Clay
Density of water	lb/ft3	= 62.42
Heat capacity of water	kW day/lb/°C	= 0.000022
Typical water saturation	-	= 0.6
Boiling point of water at atmospheric pressure	° Celsius	= 100
Typical initial temperature for near-surface soil	° Celsius	= 13
Stainless steel weight per length of well	lb/ft	= 4.76 if Well diameter = 4 in; 7.28 if Well diameter = 6
Stainless steel weight per length of electrode	lb/ft	= 5.4
Stainless steel weight Total	lb	= (Number of electrodes x Length of electrodes x Stainless steel weight per length of electrode) + (Number of vapor recovery wells x Length of wells x Stainless steel weight per length of well)
Additional linear feet of PVC	ft	= 0
PVC weight	lb/ft	= 2.03
Length of manifold	ft	=Number of electrodes x Electrode spacing + 200
Condenser quantity	-	= Peak vapor generation / Condenser capacity
PVC weight Total	lb	= [(Condenser quantity x 200) + Additional linear feet of PVC + Length of manifold] x PVC weight
Activated carbon	lb	= 10 lbs activated carbon x Contaminant mass
Linear feet for trenching	ft	= Length of manifold
Trenching rate	ft/hr	= 300
Trenching fuel consumption	gal/hr	= 6.25

THERMAL TREATMENT VARIABLES & CALCULATIONS		
rate		
Fuel for trenching	gal	= Linear feet for trenching / Trenching rate x Trenching fuel consumption rate
Linear feet for drilling	ft	= Number of electrodes x Length of electrodes
Drilling rate	ft/day	= 100
Drilling fuel consumption rate	gal/day	= 32
Fuel (diesel) for drilling	gal	= Linear feet for drilling / Drilling rate x Drilling fuel consumption rate
Total Distance for AC disposal	mi	= Activated carbon weight / Truck capacity for Activated Carbon x Distance for Activated Carbon disposal
Vehicle mileage for AC disposal	miles per gal	= 5
Diesel for AC disposal	gal	= Total distance for AC disposal / Vehicle mileage for AC disposal
Diesel consumption Total	gal	= Diesel for Drilling + Diesel for Trenching + Diesel for AC disposal
Natural Gas for AC Regeneration	mcf	See Appendix F-1
Natural Gas for Therm Ox	mcf	See Appendix F-1
Peak vapor power generation	ft^3	= [Air Density x (1- Typical Water Saturation) + (Density of water x Typical Water Saturation)] x Porosity x Area of affected soil x (Depth to bottom of affected soil - depth to top of affected soil)} / remediation duration, where Air Density = 0.0745 lb/ft^3 Density of water = 62.42 lb/ft^3 Typical Water Saturation = 0.6
Vacuum Pump power requirements	kW	= 5 if peak of pump power generation is< 90 lb/h
	kW	= 10 if peak of pump power generation is >90 lb/h
Electricity for Vacuum pump	kWh	= Vacuum pump power requirements x Remediation duration x 24
Electricity for ERH	kWh	= Number of electrodes x Average power input per unit length of electrode x Length of electrode x Remediation Duration x 24, where Average power input per unit length of electrode = 0.295 kW/ft
Total Electricity	kWh	= Electricity for ERH + Electricity for vacuum pump
Jet fuel use rate per passenger	gal/mile	= 0.0000097

THERMAL TREATMENT VARIABLES & CALCULATIONS		
Weight of passenger + luggage	lb	= 200
Total jet fuel	gal	= Jet fuel use rate per passenger x Weight of passenger + luggage x Air miles traveled
Miles traveled (gasoline)	miles	= Distance to Site x 2 x (Number of construction trips + Number of post-construction trips)
Vehicle mileage	miles per gal	= 15
Total gasoline	gal	= Miles traveled / Vehicle mileage
Total gasoline (gasoline + jet fuel)	gal	= Total gasoline + Total jet fuel
Steam Injection		
Soil density	lb/ft3	= 102 lb/ft3 if Sandy gravel, = 100 lb/ft3 if Sand (well graded), = 100 if Sand (poorly graded), = 95 if Silt, = 90 if Clay
Heat capacity of soil	kW day/lb/°C	=0.0000055
Porosity	-	= 0.35 if Sandy gravel, = 0.25 if Sand (well graded), = 0.35 if Sand (poorly graded), = 0.4 if Silt, = 0.45 if Clay
Density of water	lb/ft3	= 62.42
Heat capacity of water	kW day/lb/°C	= 0.000022
Typical water saturation	-	= 0.6
Upper bound temperature achieved	°F	= 340
Initial average temperature value for soil	°F	= 55
Well diameter	in	= 4 or 6
Remediation duration	days	= 180
Boiler fuel supply	-	= Natural gas or Diesel

THERMAL TREATMENT VARIABLES & CALCULATIONS		
Injection well configuration	-	= Single set or Double set; Single set if (Depth to bottom of affected soil - Depth to top of affected soil) < 30 ft; Double set if (Depth to bottom of affected soil - Depth to top of affected soil) > 30 ft
Number of injection wells	-	Single set = Area of affected soil / PI / (Radius of Influence x Radius of Influence overlap)^2, where Radius of Influence = 13 ft if area of Affected Soil < 20,000 ft2, = 15 ft if area of Affected Soil > 20,000 ft2; Radius of Influence overlap = 0.9 Double set = 2 x Area of affected soil / PI / (Radius of Influence x Radius of Influence overlap)^2, where Radius of Influence= 13 ft if area of Affected Soil < 20000 ft2, =15 ft if area of Affected Soil > 20000 ft2; Radius of Influence overlap=0.9
Number of extraction points	#	Single set, Area of affected soil < 4,000 ft^2 = Number of injection wells / 5 Double set, Area of affected soil < 4,000 ft^2 = Number of injection wells / 10 Single set, Area of Affected soil > 4,000 ft^2 = Number of injection wells / 3 Double set, Area of Affected soil > 4,000 ft^2 = Number of injection wells / 6
Length of well	ft	= Depth to bottom of affected soil
Radius of Influence (ROI)	ft	= 13, if Area of affected soil < 20,000 ft^2
	ft	= 15, if Area of affected soil > 20,000 ft^2
ROI overlap	ft	= 0.9
Condenser capacity	lb/h (pph)	= 500
Increase in temperature	°F	= Upper bound temperature achieved - Initial average temperature for soil
Steam energy (80% dry steam)	BTU/lb	= 743
Stainless steel weight per length of well	lb/ft	= 4.76 if Well diameter = 4 in; 7.28 if Well diameter = 6
Additional feet of steel	ft	= 0

THERMAL TREATMENT VARIABLES & CALCULATIONS		
Stainless steel weight Total	Lb	= ((Number of wells x Length of well) + Additional feet of steel) x Stainless steel weight per length of well
Additional linear feet of PVC	ft	= 0
PVC weight	lb/ft	= 2.03
Length of manifold	ft	=Number of injection wells x ROI x 2
Condenser quantity	-	= Total steam injection rate / Condenser capacity
PVC weight Total	lb	= [(Condenser quantity x 200) + Additional linear feet of PVC + Length of manifold] x PVC weight
Activated carbon	lb	= 10 lbs activated carbon x Contaminant mass
Linear feet for trenching	ft	= Length of manifold
Trenching rate	ft/hr	= 300
Trenching fuel consumption rate	gal/hr	= 6.25
Fuel for trenching	gal	= Linear feet for trenching / Trenching rate x Trenching fuel consumption rate
Linear feet for drilling	ft	= Number of injection wells x Depth to bottom of affected soil
Drilling rate	ft/day	= 100
Drilling fuel consumption rate	gal/day	= 32
Fuel (diesel) for drilling	gal	= Linear feet for drilling / Drilling rate x Drilling fuel consumption rate
Total Distance for AC disposal	mi	= Activated carbon weight / Truck capacity for Activated Carbon x Distance for Activated Carbon disposal
Vehicle mileage for AC disposal	miles per gal	= 5
Diesel for AC disposal	gal	= Total distance for AC disposal / Vehicle mileage for AC disposal
Steam breakthrough time	days	= [(Heat Capacity of Soil x (1- Porosity) x Area of affected soil x (depth to bottom of affected soil - depth to top of affected soil) x Soil density + (Density of water x Heat Capacity of Water x Porosity x Typical Water Saturation)] x (Upper bound temperature achieved - Typical initial temperature value for near - surface soil) / Total steam injection rate / Steam energy / 24
Steam boiler size	lb/h (pph)	= 500 if Steam Injection rate < 500, = 1,500 if 500 < Steam Injection rate < 1,500 = 2,500 if 1,500 < Steam Injection rate < 2,500 = 6,000 if 2,500 < Steam Injection rate < 6,000

THERMAL TREATMENT VARIABLES & CALCULATIONS		
		= 10,000 if Steam Injection rate > 6,000
Steam boiler quantity	#	= Total steam Injection rate / Steam boiler size
Diesel for boiler	gal	= [(Steam Boiler Size / 34.5 / 13.5 x 2544.43) / 179137 x 24 x [(Steam Breakthrough time) +(Remediation duration - Steam Breakthrough time) /7)]
Diesel consumption Total	gal	= Diesel for Drilling + Diesel for Trenching + Diesel for AC disposal + Diesel for boiler
Natural Gas for boiler	mcf	=[(Steam Boiler Size / 34.5 / 13.5 x 2544.43) / 1000 x 24 x [Steam Breakthrough time + (((Remediation duration) - Steam Breakthrough time) /7)] x 0.001
Natural Gas for AC Regeneration	mcf	See Appendix F-1
Natural Gas for Therm Ox	mcf	See Appendix F-1
Total natural gas	mcf	= Natural gas for boiler + Natural gas for AC regeneration or + Natural gas for Therm Ox
Steam injection pressure per well	psi	= 23.52 + [(Depth to top of affected soil -10) x 0.88]
Specific volume of steam	ft3/lb	= 15 if Steam Injection Pressure per Well < 30 psi = 9 if Steam Injection Pressure per Well < 50 psi = 5 if Steam Injection Pressure per Well < 100 psi
Permeability	darcy	= 12 if Soil Type is Sandy gravel = 5 if Sand (well graded) or Sand (poorly graded) = 1 if Clay =0.1 if Silt
Hydraulic conductivity	ft/hr	= (Permeability x 3 x 10^{-4}) x Steam density x (Gravity x 12.96 x 10^{6}) / Steam viscosity
Total steam injection rate	lb/h (pph)	= Number of injection well x Steam injection pressure per well x (Well diameter)^2 x PI x Permeability
Total air flow	ft3/min	= Total steam injection rate x Specific volume of steam / 60
Vacuum pump power requirements	hp	= 5 if Total air flow < 90 ft^3/min = 7.5 if Total air flow < 140 $ft^{3/}$min = 10 if Total air flow < 190 ft3/min = 15 if Total air flow < 290 ft^3/min = 30 if Total air flow > 290 ft^3/min
Number of vacuum pumps	-	= Total air flow / 580
Electricity for vacuum pump	kWh	= Vapor power requirements x Number of vacuum

THERMAL TREATMENT VARIABLES & CALCULATIONS		
		pump x 0.7457 x Remediation duration x 24
Total electricity	kWh	= Electricity for vacuum pump
Jet fuel use rate per passenger	gal/mile	= 0.0000097
Weight of passenger + luggage	lb	= 200
Total jet fuel	gal	= Jet fuel use rate per passenger x Weight of passenger + luggage x Air miles traveled
Miles traveled (gasoline)	miles	= Distance to Site x 2 x (Number of construction trips + Number of post-construction trips)
Vehicle mileage	miles per gal	= 15
Total gasoline	gal	= Miles traveled / Vehicle mileage
Total gasoline (gasoline + jet fuel)	gal	= Total gasoline + Total jet fuel
Tool-calculated Values		
Thermal Conductive Heating		
Remediation Duration	day	= (Area heated by each well x { [Soil particle density x Heat Capacity of Soil x (1- Porosity) x (Upper bound temperature achieved - Typical initial temperature value for near-surface soil)] + [Density of water x Heat capacity of water x Porosity x Typical water saturation] x (Boiling point of water at atmospheric pressure – Typical initial temperature value for near-surface soil) + Density of water x Latent heat of vaporization of water at atmospheric pressure x Porosity x Typical water saturation } / Average power input per unit length of thermal conduction well) / (1 – Fraction of heat provided lost by soil)
Electrical Resistivity Heating		
Remediation Duration	day	= (Area heated by each electrode x { [Soil particle density x Heat Capacity of Soil x (1- Porosity) + Density of water x Heat capacity of water x Porosity x Typical water saturation] x (Upper bound temperature achieved - Typical initial temperature value for near-surface soil) + Density of water x Latent heat of vaporization of water at atmospheric pressure x Porosity x Typical water saturation } / Average power input per unit length of thermal conduction well) / (1 – Fraction of heat provided lost by soil)
Tool-calculated Metrics		

THERMAL TREATMENT VARIABLES & CALCULATIONS		
CO_2 Emissions		= (PVC x 1.824 lb/lb / 2000) + (Steel x 2.948 lb/lb / 2000) + (Diesel x 25.8 lb/gal / 2000) + (Gasoline x 20.17 lb/gal / 2000) + (Activated carbon x 2.7 lb/lb / 2000) + (Natural gas x 122 lb/mcf / 2,000) + User-defined additional CO_2 CO_2 conversions from nrel.gov; Activated carbon conversion derived from Vignes, 2001 and Energy Information Administration (Jet fuel is lumped into gasoline volume)
NOx	tons NOx	= (PVC x 0.00318 / 2000) + (Steel x 0.002227 / 2000) + (Electricity x 3.66 / 2000) + (Diesel x 0.20922955 / 2000) + (Gasoline x 0.015078 / 2000) + (Natural gas x 86 / 2000)
SOx	tons SOx	= (PVC x 0.0105 / 2000) + (Steel x 0.003153 / 2000) + (Electricity x 6.89 / 2000) + (Diesel x 0.00020065 / 2000) + (Gasoline x 0.0001599 / 2000) + (Natural gas x 0.29 / 2000)
PM10	tons PM10	= (PVC x 0.00018 / 2000) + (Steel x 0.00005843 / 2000) + (Electricity x conversion factors) + (Diesel x 0.0099786 / 2000) + (Gasoline x 0.00129015 / 2000) + (Natural gas x conversion factors)
Total Energy Consumed	Megajoules	= (Electricity x 11 MJ/kWh) + (Diesel x 170 MJ/gal) + (Gasoline x 150 MJ/gal) + (Natural gas x 1 MJ/mcf) + User-defined additional Energy (Jet fuel is lumped into gasoline volume)
Technology Cost	Dollars ($)	See Section 2.0
Change in Resource Service: Ecologic, Economic	Net gain or net loss	<u>Ecologic Change in Resource Service</u> = Final ecologic resource service value – Initial ecologic resource service value If Change = Positive, Net gain If Change = Negative, Net loss, where Initial ecologic resource service value = Area of affected soil x Adjusted biome-specific value x Modifying factor, where Adjusted biome-specific value = $0/ac for Industrial, $930/ac for Urban,

THERMAL TREATMENT VARIABLES & CALCULATIONS		
		$1,100/ac for Cropland, $2,700/ac for Grassland/Rangeland, $3,500/ac for Forest, or $230,000/ac for Wetlands (Design Team modification of Costanza et al., 1997) Modifying factor = If Benefit to ecological service value is High, 0.5 If Benefit to ecological service value is Medium, 0.2 If Benefit to ecological service value is Low, 0.05 (Design Team) Final ecologic resource service value = Affected area x Adjusted biome-specific value for future setting Economic Change in Resource Service = Area of affected soil x Economic land value in contaminated state x Modifying factor for increased value due to cleanup, where Modifying factor for increased value due to cleanup = If Level of contamination is High, 0.5 If Level of contamination is Medium, 0.2 If Level of contamination is Low, 0.05 (Design Team)
Safety/Accident Risk	Lost hours	= Total hours worked x Injuries per hour + Total vehicle miles traveled x Injuries per mile, where Total hours worked = Hours worked + Hours for travel (post-construction/site visit) Hours worked = 50% x Cost / $80/hr labor rate (Design Team) Hours for travel = 10 + Distance to site x 2 / 40 mph (Design Team)

THERMAL TREATMENT VARIABLES & CALCULATIONS		
		Injuries per hour = 2.7 x 10^{-9} (derived from US Bureau of Labor Statistics, 2007) Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of post-construction trips Injuries per mile = 9.1 x 10^{-7} (NHTSA, 2005)

F.3.1 Key Factors / Rules-of-Thumb

In Tier 1, the tool uses several "Rules-of-Thumb" (RoT) in order to calculate sustainability metrics while limiting user inputs. These RoT are derived from a combination of published values and equations and project team experience. The following table provides the key RoT used in the Thermal technology module of Tier 1.

THERMAL TREATMENT RULES-OF-THUMB		
Value Name	**Value**	**Reference**
Activated Carbon, Conversion Factor	10 lbs GAC / lb contaminant	The default assumption is 10 pound of granular activated carbon for each pound of contaminant; based on Nyer 1993 ROT, p. 127
Activated Carbon, Miles Traveled for Disposal	400 miles / trip	Design Team
Fuel Consumption Rate, Drilling	10 gal / day	Driller Correspondence
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.

THERMAL TREATMENT RULES-OF-THUMB		
Fuel Consumption Rate, Trenching	6.25 gal / hr	Design Team
Mileage, Vehicle for Activated Carbon Disposal	3 miles / gal	Design Team
Mileage, Vehicle for Transportation	10 miles / gal	Design Team
Rate, Drilling	100 ft / day	Driller Correspondence
Rate, Trenching	390 ft / hr	Design Team

F.4 REFERENCES

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APPENDIX F-1: SVE and Thermal Natural Gas Calculations

	Variable name	Value	Units	Explanation
Step 1	Qw		scfm	If Vapor Treatment Method is Thermal Oxidizer, then calculate the supplemental fuel (natural gas) requirements. Assumptions from Kuo, 1999, Example VII.2.5 (p. 246): Off-gas stream flow rate (Qw) = 200 scfm; Combustion temperature (Tc) = 1800 degrees F (2000 degrees F, if halogenated compounds (Table VII.2.B)) Temperature selection is based user input of contaminant type; Heat recovery (HR) = 70%; Temperature of waste air from venting well (Tw) = 65 degrees F; Using these assumptions and user inputs, calculate the temperature after the heat exchanger (The). The = HR/100 * Tc + (1-HR/100)*Tw
	Tc		F	
	HR		--	
	Tw		F	
	The		F	
Step 2	COC Heating value			Calculate heating value of the COC in the air stream (Kuo, 1999, p. 240-241), and convert to Btu/lb. The COC is selected from the input screen. First, calculate heating value from Dulong's formula (Eq. VII.2.3; p. 241): Heating value (Btu/lb) = 145.4C + 620(H - O/8) + 41S, where the numbers in the formula are constants, and C, H, O, and S are the molecular weight % of each element. Then, calculate the heat content of the air containing the contaminant, and convert to Btu/lb. Heating value (Btu/lb) = Heating value from above formula * COC concentration in air expressed in ppmV * (0.27e-6) / Density of air stream. To calculate the COC concentration in air (ppmV), follow formulas and Ex V.1.2D from Kuo, 1999 (p. 146). Assumptions from Kuo, 1999, p. 246 & 240: Average specific heat (Cp) = 0.266 Btu/lb-degree F (if Tc = 1800) or 0.269 (if Tc = 2000) (Figure VII.2.A). Density of air stream (Dw) = 0.0739 lb/scf. Other assumptions: Porosity based on soil type; Organic content = 0.03; Water saturation = 45%. Bulk density of soil (g/cm^3) will be based on soil type input by user. Physical properties (molecular weight, Henry's Law constant, vapor pressure, Log Kow) will be based on a representative
	Porosity			
	Organic content			
	Water saturation			
	Soil bulk density		g/cm^3	
	Subsurface temperature		C	
	Henry's dimensionless			
	Koc			
	Kp		L/kg	
	Soil Concentra		mg/L	

	tion			compound for the selected contaminant class: Trichloroethylene for CVOCs and Benzene for BTEX.
	Soil Vapor Concentration		mg/m3	
	Conversion factor			
	Concentration in ppmV		ppmV	
	Density of air stream		lb/scf	
	Waste gas heating value		Btu/lb	
Step 3	Dsf		lb/scf	Calculate flow rate of supplemental fuel in standard cubic feet per minute (Kuo, 1999, Eq. VII.2.8, p. 245). Qsf = Dw * Qw *(Cp (1.1Tc - The - 0.1Tr) - Hw) / Dsf (Hsf - 1.1Cp(Tc-Tr)) More assumptions (p. 245): Density of supplemental fuel (Dsf) = 0.0408 lb/scf for methane; Reference temperature (Tr) = 77 degrees F; Heating value of supplemental fuel (Hsf) = 21,600 Btu/lb for methane. NOTE: If calculated Qsf is negative due to high contaminant concentration, set Qsf = 0.
	Tr		F	
	Hsf		Btu/lb	
	Cp		Btu/lb-degreeF	
	Qsf		scfm	
Step 4	Operation time		hrs/year	Convert flow rate to supplemental fuel usage over the course of the project: Fuel usage (mcf) = (Qsf / 1000) * 60 * 24 * 365 * project duration * 95% (user input, in years) Note: Project duration multiplied by 95% to account for assumption of annual system operating time is 95% (system does not operate 100% of the time) (Design Team).
	Natural Gas for Therm Ox		mcf	
Natural gas requirements for SVE/Activated Carbon Regeneration	Conversion factor		btu/lb act. carbon	If activated carbon is the vapor treatment method, calculate the amount of natural gas for activated carbon regeneration by using a conversion factor.
	Natural gas for		mcf	

	activated carbon			
	Natural gas used for metrics (Therm Ox or Activated Carbon)		mcf	Natural gas is calculated for O&M or both Capital and O&M projects.

APPENDIX G: TIER 1 ENHANCED BIOREMEDIATION COSTS AND OTHER CALCULATIONS

G.1 BACKGROUND

This section describes the Tier 1 costs and other calculations used in the Enhanced Bioremediation module of the Sustainable Remediation Tool (SRT). For the purpose of this tool, Enhanced Bioremediation refers to treatment of groundwater contamination through the injection of an electron donor (e.g. lactate, vegetable oil, etc.) or oxygen additive to promote microbial degradation of contaminants. SRT calculations consider a single application of donor and no subsequent monitoring of groundwater quality. (No monitoring is considered here because future plans for the tool include adding a Long-term Monitoring module.)

Section 2.0 below addresses technology and energy cost calculations for the Enhanced Bioremediation module. The Enhanced Bioremediation module calculations consider all costs to be in the Capital phase, as the treatment duration is assumed to be one year.

Section 3.0 below contains tables of non-cost calculations and the relevant assumptions / rules-of-thumb for those calculations.

G.2 COST CALCULATIONS

G.2.1 Technology Cost

Technology cost for Enhanced Bioremediation is calculated using formulas derived from site data for cost per volume treated. The formulas were developed using the Enhanced Bioremediation module of RACER™.

<u>Technology Cost Calculations for Enhanced Bioremediation</u>

The Tier 1 calculation for Enhanced Bioremediation costs follows.

- Technology Cost, Aerobic conditions (treat BTEX) = 35.366 x (Volume treated) + 33,071
- Technology Cost, Anaerobic conditions (treat VOCs) = 31.728 x (Volume treated) + 15,744

G.2.2 User-Supplied Additional Costs

The costs described above are displayed in the summary section of the individual technology screens. Below the cost summary on these screens, the SRT allows the user to enter additional project costs and other metrics. These additional, project-specific costs are added to the pre-calculated totals, and are displayed on the "output" screens.

G.2.3 Cost Factors for Energy Costs

The SRT includes calculations, with user overrides allowed, for the amount of fuel and energy used for each technology. For the Enhanced Bioremediation module, calculations are done for gasoline and diesel. The cost-converted energy metric is displayed in the "normalized" section of the SRT's output screen. The cost conversion is the sum of the amount of energy type multiplied by cost, for each type of fuel/energy used. The Tier 1 costs for each energy type are:

Energy Type	Cost	Cost Reference
Gasoline	$2.00 / gallon	Average regular grade price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Diesel	$2.00 / gallon	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.

G.2.4 User-Supplied Additional Energy

The SRT allows the user to enter additional, project-specific metrics, including energy in megajoules. To complete the normalized/cost-based calculation for energy, the conversion from megajoules to dollars uses factors for gasoline. The converted value is added to the energy costs above, and is displayed on the "output" screens, if the user chooses to view the normalized values.

G.3 NON-COST CALCULATIONS

The following assumptions apply to non-cost calculations in the Enhanced Bioremediation module:

- All treatment occurs in the first year, so all costs are considered capital costs.
- Treatment with a liquid donor if CVOCs or slurry donor if BTEX is assumed for all applicable calculations.
- Number of trips during construction = Minimum of 5 trips to the site for the 1st 1,000 ft^2 of contaminated plume. Add 1 trip for each additional 2,000 ft^2 of plume. (Design Team)
- Number of trips post-construction = 12. (Design Team)
- Selecting "Treat Source Only" vs. "Treat Source + Plume":
  - Choosing "Treat Source + Plume" assumes a reduction in concentration throughout the entire contaminated zone. All groundwater zones input by the user are considered.
  - Choosing "Treat Source Only" assumes reduced source concentrations, a delayed plume response based on groundwater travel time. Only Zone 1 of the groundwater information input by the user is considered.
- An overall 95% efficiency factor is applied to account for the fact that 100% of contaminant cannot be removed (Design Team).

ENHANCED BIOREMEDIATION VARIABLES & CALCULATIONS		
Value Name	**Units**	**Calculations & Assumptions**
User-required Input		
Airline miles flown by project team (total miles for all travelers)	Miles over project lifetime	--
Average Distance Traveled by Site Workers per one-way trip	Miles	--
Trips by Site Workers during construction	# over project lifetime	--
Trips by Site Workers after construction	# over project lifetime	--
How efficient is the Bioremediation project?	Choose: High (95%), Medium (90%), or Low (50%); default is Medium	--
Treat Source Only or Source plus Plume?	Choose: Source Only or Source + Plume	--
Length of piping per well	Feet	--

ENHANCED BIOREMEDIATION VARIABLES & CALCULATIONS		
See plume response in how many years from present?	Years	--
Additional Technology Cost	Dollars ($)	--
Additional Energy Consumed	Megajoules	--
Additional CO_2 Emissions	tons	--
Additional Safety / Accident Risk	Lost hours due to injuries / illnesses	--
Tool-calculated Value or User Override		
Number of wells	#	= Area treated / (π x $(20\ ft)^2$), where Area treated = If "Source + Plume" is selected, Area of all GW Plumes summed; If "Source Only" is selected, Area of Zone (source) only Well spacing assumed to be radius = 20 ft (AFCEE *Principles and Practices for Enhanced Bioremediation*)
Volume of donor / substrate or oxygen additive	Gallons if substrate, Pounds if oxygen additive	= Volume for treatment x Percent pore space for donor x 7.481 conversion factor, where Volume for treatment = Sum of pore volume of each treated zone (Area x thickness x porosity) For CVOCs, volume for treatment is multiplied by percent pore space for donor (1%) and is converted to gallons. For BTEX, the oxygen additive is calculated as dissolved mass x 10 kg hydrocarbon/kg BTEX x 2.8 kg oxygen/kg hydrocarbon x 1 kg additive / 0.17 kg oxygen, divided by 0.45 to convert to pounds (Design Team).
PVC	Pounds	= Length of pipe per well x Number of wells x 2.03 lbs/ft conversion factor
Diesel	Gallons	= Length of pipe per well x Number of wells / Drilling rate x Drilling fuel consumption rate, where Drilling rate assumed to = 100 ft/day (Fugro

ENHANCED BIOREMEDIATION VARIABLES & CALCULATIONS		
		correspondence) Drilling fuel consumption rate assumed to = 32 gal/day (Design Team, BW; Assumes drilling completed with smaller rig (4 gal/hr) for 8 hrs/day.)
Gasoline	Gallons	= Vehicle mileage (travel) x Miles traveled, where Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW) Miles traveled = Distance to site x 2 x (Number of trips during construction + Number of trips post-construction)
Jet Fuel	Gallons	= Jet fuel use rate per passenger x Weight of passenger + luggage x Total air miles for all passengers, where Jet fuel use rate per passenger = 0.037 gal / 3800 mile Weight of passenger + luggage assumed to = 200 lbs
Cost (Capital)	Dollars ($)	If Aerobic conditions, Cost = 35.366 x (Volume treated) + 33,071 If Anaerobic conditions, Cost = 31.728 x (Volume treated) + 15,744 (RACER™) All costs assumed to be in the capital phase (Design team).
Tool-calculated Value		
Original Plume: Area	Acres	= Maximum plume length from Zones 1-4 x Maximum plume width from Zones 1-4 x 0.000023 acres/ft^2 conversion factor
Original Plume: Length	Feet	= Maximum plume length from Zones 1-4
Original Plume: Volume	Million gallons	= Total pore volume x 7.28 conversion factor / 1,000,000, where

ENHANCED BIOREMEDIATION VARIABLES & CALCULATIONS		
		Total pore volume = Sum of pore volume of each treated zone (Area x thickness x porosity)
Original Plume: Dissolved Mass	Kilograms	= Sum of GW zone "doughnut" areas x Aquifer thickness x Porosity x Representative concentration x conversion factors
Plume After Project: Area	Acres	Plume After Project factors: New concentration (after project) = Original concentration in zone, based on user inputs x Remediation Factor, where Original concentration (source) = User input Zone 1 high concentration Original concentration (Zone 1) = User input Zone 1 Low, etc, for each Zone entered Remediation factor = 95%, 90%, or 50%, for user input design efficiencies of High, Medium, and Low, respectively (Design Team) Plume after project area = the sum of new plume length x new plume width for each zone. New plume length is discussed below. New plume widths are proportional (i.e. New W = Original W x (New Length / Original Length)
Plume After Project: Length	Feet	The lengths of each plume zone are calculated based on the slope and intercept of the line formed by natural log of concentration pairs (Source to Zone 1, Zone 1 to Zone 2, etc.) vs. distance in feet. The maximum new length is the value displayed in the design screen of the SRT. After calculating the formula of the line which fits the new concentrations, the new length is calculated for each original concentration value (i.e. so user can see original length at, say 1 mg/L, and the new length at 1 mg/L). The maximum of the new lengths is the value displayed on the SRT design tab.
Plume After Project: Volume	Million gallons	= Length x Width x Aquifer thickness x Aquifer porosity, for each zone, subtracting the volume of smaller zones contained within that zone. The total plume volume is the sum of the above x

ENHANCED BIOREMEDIATION VARIABLES & CALCULATIONS		
		7.48 gal/ft^3 divided by 1,000,000.
Plume After Project: Dissolved Mass	Kilograms	= Volume of each zone ("doughnut") x 28.3 unit conversion x geometric mean of the high and low of each zone. The total dissolved mass is the sum of the mass values for each zone. For the Source Treatment Only option, the Remediation Factor is as above. Time to Evaluate Plume = User input Seepage Velocity = Value in ft/year, calculated from user inputs (Conductivity x Gradient / Porosity x conversion factors) Breakthrough distance = Seepage velocity x Time to Evaluate Plume divided by 3 For Source Treatment Only, the basic calculations are as above for treating the entire plume. However, if new lengths are larger than the breakthrough distance, the new length is not considered (the length used instead is the original length of that zone).
Tool-calculated Metrics		
CO_2 Emissions	Tons	= (PVC x 1.824 lb/lb / 2000) + [(Volume of substrate x density of substrate) x If CVOCs, 2.8 lb CO_2/lb substrate/2000 + (Contaminant mass CVOCs x 0.7 lb CO_2/lb CVOCs)/2000] or [If BTEX, Contaminant mass x 3.3 lb CO_2 / lb BTEX/2000 + (oxygen additive x 0 lb CO_2 / lb oxygen additive) + (Diesel x 25.8 lb/gal / 2000) + (Gasoline x 20.17 lb/gal / 2000) + User-defined additional CO_2 CO_2 conversions from nrel.gov; Substrate and oxygen additive conversions from Design Team (see Enhanced Bioremediation rules-of-thumb for details); Density of substrate is 7.89 lb/gal for vegetable oil from ESTCP 2006, Figure 3.1 (p. 27); Density of oxygen additive is 4.24 lb/gal for ORC Advance™, from MSDS. (Jet fuel is lumped into gasoline volume)
NOx	tons NOx	= (PVC x 0.00318 / 2000) + (Diesel x

ENHANCED BIOREMEDIATION VARIABLES & CALCULATIONS		
		0.20922955 / 2000) + (Gasoline x 0.015078 / 2000)
SOx	tons SOx	= (PVC x 0.0105 / 2000) + (Diesel x 0.00020065 / 2000) + (Gasoline x 0.0001599 / 2000)
PM10	tons PM10	= (PVC x 0.00018 / 2000) + (Diesel x 0.0099786 / 2000) + (Gasoline x 0.00129015 / 2000)
Total Energy Consumed	Megajoules	= (Diesel x 170 MJ/gal) + (Gasoline x 150 MJ/gal) + User-defined additional Energy (Jet fuel is lumped into gasoline volume)
Technology Cost	Dollars ($)	See Section 2.0
Change in Resource Service (plume reduction)	Million gallons	= Plume volume after project – Original plume volume
Safety/Accident Risk	Lost hours	= Total hours worked x Injuries per hour + Total vehicle miles traveled x Injuries per mile, where Total hours worked = Hours worked + Hours for travel (post-construction/site visit) Hours worked = 50% x Capital Cost / $80/hr labor rate (Design Team) Hours for travel = 10 + Distance to site x 2 / 40 mph (Design Team) Injuries per hour = 2.7×10^{-9} (derived from US Bureau of Labor Statistics, 2007) Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of post-construction trips Injuries per mile = 9.1×10^{-7} (NHTSA, 2005)

G.3.1 Key Factors / Rules-of-Thumb

In Tier 1, the tool uses several "Rules-of-Thumb" (RoT) in order to calculate sustainability metrics while limiting user inputs. These RoT are derived from a combination of published values and equations and project team experience. The following table provides the key RoT used in each technology module of Tier 1.

ENHANCED BIOREMEDIATION KEY FACTORS / RULES-OF-THUMB		
Value Name	**Value**	**Reference**
Donor, Conversion Factor	2.8 lb CO_2 / lb substrate + 0.7 lb CO_2 / lb CVOCs	Consider both anaerobic and aerobic degradation: 1) Anaerobic CVOC treatment: - Assume i) complete oxidation to CO_2 without carbonate system sink ii) emulsified vegetable oil-type donor ($C_{56}H_{100}O_6$) $C_{56}H_{100}O_6 + 78O_2 \rightarrow 56CO_2 + 50\ H_2O$ Multiplying by molecular weights yields 2.8 lb CO_2 / lb substrate. 2) Aerobic CVOC treatment: - Assume i) complete oxidation to CO2 without carbonate system sink ii) no co-substrate supplied (e.g. methane, propane, butane, etc.) iii) use TCE (C_2Cl_3H) as representative CVOC $C_2Cl_3H + 3/2O_2 + H_2O \rightarrow 2CO_2 + 3H^+ + 3Cl^-$ Multiplying by molecular weights yields 0.67 lb CO_2 / lb TCE. Total CO_2 released for anaerobic CVOC treatment includes 1) CO_2 released by substrate and 2) potential CO_2 released by CVOC itself: 2.8 lb CO_2 / lb substrate + 0.7 lb CO_2 / lb CVOCs (Design Team)

ENHANCED BIOREMEDIATION KEY FACTORS / RULES-OF-THUMB		
Donor, Percent of Pore Space	1%	From two sources: 1) Rule-of-Thumb proposed for emulsified vegetable oil addition during the development of the Sustainable Remediation Forum (SuRF) 6 Sample Problems Site Scenario (email dated 1/3/08); 2) Evaluation of the final “SuRF6_Case_Study_Dechor.xls” file (derived from the AFCEE *Principles and Practices* document), where the calculated substrate addition amount (74,500 pounds of vegetable oil, or about 9,720 gallons) is about 0.75% of 1.3 million gallons of pore space. This was rounded up to 1%.
Oxygen additive, Conversion Factor	3.3 lb CO_2 / lb BTEX + 0 lb CO_2 / lb oxygen additive	Consider both anaerobic and aerobic degradation: 1) Aerobic BTEX treatment: - Assume i) complete oxidation to CO_2 without carbonate system sink ii) BTEX serves as sole source of carbon and energy (no co-substrate) iii) calculated CO_2 values for individual BTEX components (e.g. Benzene, Toluene, etc.) were averaged and rounded to two significant digits. Below are equations for Benzene as example: $C_6H_6 + 15/2O_2 \rightarrow 6CO_2 + 3\ H_2O$ Multiplying by molecular weights and averaging yields 3.3 lb CO_2 / lb BTEX. 2) Anaerobic BTEX treatment: - Assume anaerobic degradation pathway the same as aerobic pathway. (Design Team)
Fuel Consumption Rate, Drilling	32 gallons / day	Design Team, BW; Assumes drilling completed with smaller rig (4 gal/hr) for 8 hrs/day.
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08,

ENHANCED BIOREMEDIATION KEY FACTORS / RULES-OF-THUMB		
		http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team
Injection Well Spacing	20 ft	Injection well spacing is assumed to be 20 feet; AFCEE *Principles and Practices for Enhanced Bioremediation*
Rate, Drilling	100 ft / day	Fugro correspondence

G.4 REFERENCES

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APPENDIX H: TIER 1 PUMP AND TREAT COSTS AND OTHER CALCULATIONS

H.1 BACKGROUND

This section describes the Tier 1 costs and other calculations used in the Pump and Treat module of the Sustainable Remediation Tool (SRT). For the purpose of this tool, Pump and Treat refers to treatment of groundwater contamination through the pumping of water to activated carbon adsorption canisters or air stripper.

Section 2.0 below addresses technology and energy cost calculations for the Pump and Treat module.

Section 3.0 below contains tables of non-cost calculations and the relevant assumptions / rules-of-thumb for those calculations.

H.2 COST CALCULATIONS

H.2.1 Technology Cost

Technology cost for Pump and Treat is calculated using formulas derived from site data for cost per volume treated. These site data are from USEPA, 2001, Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat Systems and Permeable Reactive Barriers.

<u>Technology Cost Calculations for Pump and Treat</u>

The Tier 1 calculation for Pump and Treat costs follows.

- Technology Cost (Capital) = (277,189 x Volume treated$^{-0.781}$) x Volume treated
- Technology Cost (O&M) = (40,500 x Volume treated$^{-0.7706}$) x Volume treated x Duration

H.2.2 User-Supplied Additional Costs

The costs described above are displayed in the summary section of the individual technology screens. Below the cost summary on these screens, the SRT allows the user to enter additional project costs and other metrics. These additional, project-specific costs are added to the pre-calculated totals, and are displayed on the “output” screens.

H.2.3 Cost Factors for Energy Costs

The SRT includes calculations, with user overrides allowed, for the amount of fuel and energy used for each technology. In the Pump and Treat module, calculations are done for gasoline, diesel, electricity, and natural gas. The cost-converted energy metric is displayed in the "normalized" section of the SRT's output screens. The cost conversion is the sum of the amount of energy type multiplied by cost, for each type of fuel/energy used. The Tier 1 costs for each energy type are:

Energy Type	Cost	Cost Reference
Gasoline	$2.00 / gallon	Average regular grade price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Diesel	$2.00 / gallon	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Electricity	$0.10 kWh	Electricity Cost from EPA 2005, Cost-effective Design of Pump and Treat Systems (http://www.frtr.gov//pdf/optimization/gw_mon_cost-effective_design_030805.pdf)
Natural Gas	$11.00 / mcf	Average industrial natural gas price, January 2009 (http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm); website accessed 4/23/09.

H.2.4 User-Supplied Additional Energy

The SRT allows the user to enter additional, project-specific metrics, including energy in megajoules. To complete the normalized/cost-based calculation for energy, the conversion from megajoules to dollars uses factors for gasoline. The converted value is added to the energy costs above, and is displayed on the "output" screens, if the user chooses to view the normalized values.

H.3 NON-COST CALCULATIONS

The following assumptions apply to non-cost calculations in the Pump & Treat module:

- The number of trips during construction is assumed to be a minimum of 5 trips for the first 1,000 cubic feet of contaminated soil and 1 additional trip for each additional 2,000 cubic feet (Design Team).
- The number of trips post-construction is assumed to be 52 trips per year multiplied by the project duration (Design Team).
- Annual operating time is assumed to be 95% (8320 hrs/yr), as 100% operating time is unrealistic (Design Team). This factor is also used in the Soil Vapor Extraction module.
- An overall 95% efficiency factor is applied to account for the fact that 100% of contaminant cannot be removed (Design Team).

PUMP & TREAT VARIABLES & CALCULATIONS		
Value Name	**Units**	**Calculations & Assumptions**
User-required Input		
Airline miles flown by project team (total miles for all travelers)	Miles over project lifetime	--
Average Distance Traveled by Site Workers per one-way trip	Miles	--
Trips by Site Workers during construction	# over project lifetime	--
Trips by Site Workers after construction	# over project lifetime	--
Remediation Design (Purpose)	Choose: Remediation or Containment	--
Duration	years	--
Additional Technology Cost	Dollars ($)	--
Additional Energy Consumed	Megajoules	--
Additional CO_2 Emissions	tons	--
Additional Safety / Accident Risk	Lost hours due to injuries / illnesses	--

PUMP & TREAT VARIABLES & CALCULATIONS		
Tool-calculated Value or User Override		
Total Pumping Rate, Containment	Gpm	Containment pumping rate (capture zone equation) = Maximum plume width x Hydraulic conductivity x Aquifer thickness x Gradient x 2 x unit conversions
Total Pumping Rate, Remediation	Gpm	Remediation pumping rate = Total plume volume for all zones x unit conversion Assume 1 pore volume per year.
Number of Wells	Wells	Number of wells = Number of wells per acre x Plume area, where Number of wells per acre = Gravel, 0.2; Sands, 1; Silt, 5; Clay, 25 (RACER™)
Per Well Pump Rate	Gpm	Per Well Pump Rate = Total pumping rate / Number of wells, capped at 500 gpm to account for pump properties (Design Team)
Length of Manifold	Feet	Length of PVC for manifold = Total length of each zone + Number of wells x Maximum plume width / 4
Treatment Method	Activated Carbon, Air Stripper, or Air Stripper/Thermal Oxidizer	If maximum concentration < 1 mg/L, then Activated carbon. Otherwise, air stripper is default.
Beginning Plume Mass	Kilograms	Beginning plume mass = Sum of each zone of Area of donut x Aquifer thickness x porosity x representative concentration x unit conversions Note that plume areas are conceptualized using “donuts” (see graphic on GW Input screen) to avoid double-counting contaminant mass. Since the area of highest concentration is in the interior, that area must be subtracted from areas of subsequently lower concentrations.

PUMP & TREAT VARIABLES & CALCULATIONS		
Ending Plume Mass	Kilograms	Pore volumes recovered = Pump rate x Duration x unit conversions / original plume volume; used to calculate the concentration reduction factor (CRF): If pore volumes recovered < 3, CRF = (-0.2195 x PVr) + 1. If pore volumes recovered >=3, CRF = 1.3367 x PVr ^(-1.2424). Minimum CRF = 0.05. For Containment systems, CRF = 1. For Containment systems, starting plume mass and ending plume mass are assumed to be the same.
Plume Area, Original Plume	Acres	= Maximum plume length x maximum plume width x conversion factor
Plume Length, Original Plume	Feet	= Maximum plume length entered
Plume Volume, Original Plume	Million gallons	= Sum of plume lengths x plume widths x aquifer thickness x porosity
Dissolved Mass, Original Plume	Kilograms	= Sum of concentration x volume for each zone of "donut"
Plume Area, After Project	Acres	= Maximum calculated new plume length x new plume width
Plume Length, After Project	Feet	= Maximum calculated new plume length
Plume Volume, After Project	Million gallons	= Sum of calculated new plume lengths x plume widths x aquifer thickness x porosity
Dissolved Mass, After Project	Kilograms	= Sum of calculated new concentration x volume for each zone of "donut"
PVC	Pounds	= Depth to groundwater x aquifer thickness x Number of wells x 2.03 lbs/ft conversion factor
Steel	Pounds	= Steel pipe per well x number of wells x conversion factor + Other steel per well x number of wells + other system components Conversion factor = 10.79 lb/ft
Activated Carbon	Pounds	Amount of activated carbon, if required by treatment system, is based on average concentration in recovered groundwater (a function of pump rate, operating time and duration), and contaminant-specific parameters from Dobbs and Cohen, 1980. This value is calculated for O&M and both Capital and O&M projects.
Electricity	kWh	Amount of electricity over project lifetime = Power

PUMP & TREAT VARIABLES & CALCULATIONS		
		requirements x Operating time in hours / year x Duration (input above). This value is calculated for O&M and both Capital and O&M projects. Note: Operating time in hours / year is modified to be 95% (Design Team)
Diesel (Capital)	Gallons	Diesel is based on the amount of fuel for trenching plus drilling. Diesel is calculated for Capital and both Capital and O&M projects.
Diesel (O&M)	Gallons	Diesel for O&M is calculated based on transport for activated carbon.
Gasoline (Capital)		= Vehicle mileage (travel) x Miles traveled, where Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW) Miles traveled = Distance to site x 2 x Number of trips during construction Jet fuel is lumped into gasoline because of similar properties. Total jet fuel = Jet fuel use rate x weight x air miles input above. The default calculation assumes 50% is used in capital, and 50% used in O&M phases.
Gasoline (O&M)	Gallons	= Vehicle mileage (travel) x Miles traveled, where Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW) Miles traveled = Distance to site x 2 x Number of trips post-construction Jet fuel is lumped into gasoline because of similar properties. Total jet fuel = Jet fuel use rate x weight x air miles input above. The default calculation assumes 50% is used in capital, and 50% used in O&M phases.
Jet Fuel	Gallons	= Jet fuel use rate per passenger x Weight of passenger + luggage x Total air miles for all passengers, where Jet fuel use rate per passenger = 0.037 gal / 3800 mile

PUMP & TREAT VARIABLES & CALCULATIONS		
		Weight of passenger + luggage assumed to = 200 lbs
Natural Gas	mcf	If treatment method is Air Stripper/Therm Ox, amount of natural gas = Natural gas flow rate x Duration (input above) x Operation time in hours per year x unit conversions. Note that operation time in hours per year is multiplied by 95% (Design Team).
Cost (Capital)	Dollars ($)	Capital and O&M Costs are based on site data from USEPA 2001. Capital cost = [277189 x Volume$^{-0.781}$)] x Volume
Cost (O&M)	Dollars ($)	Annual O&M cost = [40500 x Volume$^{-0.7706}$)] x Volume
Tool-calculated Metrics		
CO_2 Emissions		= (PVC x 1.824 lb/lb / 2000) + (Steel x 2.948 lb/lb / 2000) + (Diesel x 25.8 lb/gal / 2000) + (Gasoline x 20.17 lb/gal / 2000) + (Activated carbon x 2.7 lb/lb / 2000) + (Natural gas x 122 lb/mcf / 2,000) + User-defined additional CO_2 CO_2 conversions from nrel.gov; Activated carbon conversion derived from Vignes, 2001 and Energy Information Administration (Jet fuel is lumped into gasoline volume)
NOx	tons NOx	= (PVC x 0.00318 / 2000) + (Steel x 0.002227 / 2000) + (Electricity x 3.66 / 2000) + (Diesel x 0.20922955 / 2000) + (Gasoline x 0.015078 / 2000) + (Natural gas x 86 / 2000)
SOx	tons SOx	= (PVC x 0.0105 / 2000) + (Steel x 0.003153 / 2000) + (Electricity x 6.89 / 2000) + (Diesel x 0.00020065 / 2000) + (Gasoline x 0.0001599 / 2000) + (Natural gas x 0.29 / 2000)
PM10	tons PM10	= (PVC x 0.00018 / 2000) + (Steel x 0.00005843 / 2000) + (Electricity x conversion factors) + (Diesel x 0.0099786 / 2000) + (Gasoline x 0.00129015 / 2000) + (Natural gas x conversion factors)
Total Energy Consumed	Megajoules	= (Electricity x 11 MJ/kWh) + (Diesel x 170 MJ/gal) + (Gasoline x 150 MJ/gal) + (Natural gas x 1

PUMP & TREAT VARIABLES & CALCULATIONS		
		MJ/mcf) + User-defined additional Energy (Jet fuel is lumped into gasoline volume)
Technology Cost	Dollars ($)	See Section 2.0
Change in Resource Service (plume reduction)	Million gallons	= Plume volume after project – Original plume volume
Safety/Accident Risk	Lost hours	= Total hours worked x Injuries per hour + Total vehicle miles traveled x Injuries per mile, where Total hours worked = Hours worked + Hours for travel (post-construction/site visit) Hours worked = 50% x Capital Cost / $80/hr labor rate (Design Team) Hours for travel = 10 + Distance to site x 2 / 40 mph (Design Team) Injuries per hour = 2.7 x 10^{-9} (derived from US Bureau of Labor Statistics, 2007) Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of post-construction trips Injuries per mile = 9.1 x 10^{-7} (NHTSA, 2005)
Safety/Accident Risk	Lost hours	= Total hours worked x Injuries per hour + Total vehicle miles traveled x Injuries per mile, where Total hours worked = Hours worked + Hours for travel (post-construction/site visit) Hours worked = 50% x Capital Cost / $80/hr labor rate (Design Team) Hours for travel = 10 + Distance to site x 2 / 40 mph (Design Team)

PUMP & TREAT VARIABLES & CALCULATIONS		
		Injuries per hour = 2.7×10^{-9} (derived from US Bureau of Labor Statistics, 2007) Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of post-construction trips Injuries per mile = 9.1×10^{-7} (NHTSA, 2005)

H.3.1 Key Factors / Rules-of-Thumb

In Tier 1, the tool uses several "Rules-of-Thumb" (RoT) in order to approximate sustainability metrics while limiting user inputs. These RoT are derived from a combination of published values and equations and project team experience. The following table provides the key RoT used in the Pump and Treat technology module of Tier 1.

PUMP AND TREAT RULES-OF-THUMB		
Value Name	**Value**	**Reference**
Activated Carbon, Miles Traveled for Disposal (roundtrip)	400 miles / trip	Design Team
Activated Carbon vs. Air Stripper	Use Activated Carbon or Air Stripper?	If maximum concentration < 1 mg/L, then Activated Carbon. Otherwise, Air Stripper is selected.
Activated Carbon, Conversion Factor	10 lbs GAC / lb contaminant	The default assumption is 10 pound of granular activated carbon for each pound of contaminant; based on Nyer 1993 ROT, p. 127
Activated Carbon, Miles Traveled for Disposal	400 miles / trip	Design Team
Activated Carbon, System Pump Power	10 hp	Design Team
Drawdown per Well	0.25 x Aquifer thickness	Design Team
Fuel Consumption Rate, Drilling	32 gal / day	Design Team (BW). Assumes drilling completed with smaller rig (4 gal/hr) for

PUMP AND TREAT RULES-OF-THUMB		
		8 hrs / day.
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Fuel Consumption Rate, Trenching	6.25 gal / hr	Design Team
Mileage, Vehicle for Activated Carbon Disposal	3 miles / gal	Design Team
Mileage, Vehicle for Transportation	15 miles / gal	Design Team (BW)
Natural Gas supplemental fuel flow rate	2.21 scfm	Kuo, 1999, p. 246, Example VII.2.5
Pumping Rate, Remediation	1 pore volume / yr	Design Team
Rate, Drilling	100 ft / day	Driller (Fugro) Correspondence
Rate, Trenching	300 ft / hr	Design Team
Steel, Length Pipe Per Well	10 ft / well	Design Team
Steel, Non-pipe Steel Per Well	50 lbs / well	Design Team
Steel, Treatment System, Activated Carbon	400 lbs	Design Team
Steel, Treatment System, Air Stripper	950 lbs	Design Team
System Operating Time	8,320 hrs / yr	Hours in one year = (8,760 hrs / yr) x 95% (Design Team; assume 95% operating time)
System Pump Power Requirements	5 hp	Design Team

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APPENDIX I: TIER 1 IN SITU CHEMICAL OXIDATION (ISCO) COSTS AND OTHER CALCULATIONS

I.1 BACKGROUND

This section describes the Tier 1 costs and other calculations used in the In Situ Chemical Oxidation (ISCO) module of the Sustainable Remediation Tool (SRT). For the purpose of this tool, ISCO refers to treatment of groundwater contamination through the injection of an oxidant (assumed to be sodium permanganate) to promote degradation of contaminants. SRT allows the user to select treatment area (source or source + plume) and frequency, but does not consider subsequent monitoring of groundwater quality within this module. A separate Long-term Monitoring module is available to evaluate that option, if desired.

Section 2.0 below addresses technology and energy cost calculations for this module. The calculations consider all costs to be in the Capital phase, as the treatment duration is assumed to be one year.

Section 3.0 below contains tables of non-cost calculations and the relevant assumptions / rules-of-thumb for those calculations.

I.2 COST CALCULATIONS

I.2.1 Technology Cost

Technology cost is based on unit cost of the plume volume treated.

Technology Cost Calculations for ISCO

The Tier 1 calculation for ISCO costs follows, and is based on Design Team experience:

- Technology Cost = Volume treated (in cubic yards) x $94 per cubic yard

I.2.2 User-Supplied Additional Costs

The costs described above are displayed in the summary section of the individual technology screens. Below the cost summary on these screens, the SRT allows the user to enter additional project costs and other metrics. These additional, project-specific costs are added to the pre-calculated totals, and are displayed on the "output" screens.

I.2.3 Cost Factors for Energy Costs

The SRT includes calculations, with user overrides allowed, for the amount of fuel and energy used for each technology. For the ISCO module, calculations are done for gasoline and diesel. The cost-converted energy metric is displayed in the "normalized" section of the SRT's output screen. The cost conversion is the sum of the amount of energy type multiplied by cost, for each type of fuel/energy used. The Tier 1 costs for each energy type are:

Energy Type	Cost	Cost Reference
Gasoline	$2.00 / gallon	Average regular grade price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Diesel	$2.00 / gallon	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.

I.2.4 User-Supplied Additional Energy

The SRT allows the user to enter additional, project-specific metrics, including energy in megajoules. To complete the normalized/cost-based calculation for energy, the conversion from megajoules to dollars uses factors for gasoline. The converted value is added to the energy costs above, and is displayed on the "output" screens, if the user chooses to view the normalized values.

I.3 NON-COST CALCULATIONS

The following assumptions apply to non-cost calculations in the ISCO module:

- All treatment occurs in the first year, so all costs are considered capital costs.
- Treatment sodium permanganate is assumed.
- Selecting "Treat Source Only" vs. "Treat Source + Plume":
  - Choosing "Treat Source Only" assumes that only Zone 1 input by the user is treated, and that that treatment completely removes contaminants. The final plume dimensions, after project completion, are based on this assumption as detailed below.
  - Choosing "Treat Source + Plume" assumes a reduction in concentration throughout the entire contaminated zone. All groundwater zones input by the user are considered. The final dimensions of the plume, after project completion, are assumed to be 90% of the original plume.

IN SITU CHEMICAL OXIDATION (ISCO) VARIABLES & CALCULATIONS		
Value Name	**Units**	**Calculations & Assumptions**
User-required Input		
Airline miles flown by project team (total miles for all travelers)	Miles over project lifetime	--
Average Distance Traveled by Site Workers per one-way trip	Miles	--
Trips by Site Workers during construction	# over project lifetime	--
Trips by Site Workers after construction	# over project lifetime	--
Treat Source Only or Source plus Plume?	Choose: Source Only or Source + Plume	--
Treatment Frequency	Choose: Once or Once with 2 followup applications	--
Length of pipe, per well	ft	--
Natural Oxygen Demand	Choose: Low, Average, or High	--

IN SITU CHEMICAL OXIDATION (ISCO) VARIABLES & CALCULATIONS		
Additional Technology Cost	$	
Additional Energy Consumed	Megajoules	--
Additional CO_2 Emissions	tons	--
Additional Safety / Accident Risk	Lost hours due to injuries / illnesses	--
Tool-calculated Value or User Override		
Number of injection points	#	= Area treated / (π x (20 ft)^2), where Area treated = If "Source + Plume" is selected, Area of all GW Zones summed; If "Source Only" is selected, Area of Zone (source) only Well spacing assumed to be radius = 20 ft (AFCEE *Principles and Practices for Enhanced Bioremediation*)
PVC	Pounds	= Length of pipe per injection point x Number of injection points x 2.03 lbs/ft conversion factor
Oxidant	Gallons	= Volume to treat x Soil bulk density x Natural oxygen demand x Unit conversion factors
Diesel	Gallons	= Fuel for drilling + Fuel for oxidant delivery <u>Fuel for drilling</u> = Length of pipe per injection point * number of injection points / Drilling rate x Drilling fuel consumption rate, where: Drilling rate assumed to = 100 ft/day (Fugro correspondence) Drilling fuel consumption rate assumed to = 10 gal/day (Design Team) <u>Fuel for oxidant delivery</u> = Total miles driven for oxidant delivery / vehicle mileage, where: Total miles = (Total mass of oxidant derived from volume to treat, soil bulk density, and natural oxygen demand) / (oxidant load delivery capacity assumed to be 3000 lbs per tote) x distance to oxidant supplier assumed to be 50 miles one-way x 2.

IN SITU CHEMICAL OXIDATION (ISCO) VARIABLES & CALCULATIONS		
		Vehicle mileage = 17.6 mpg, based on Design Team assumption for heavy-duty truck fuel consumption rate.
Gasoline	Gallons	= Vehicle mileage (travel) x Miles traveled, where Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW) Miles traveled = Distance to site x 2 x (Number of trips during construction + Number of trips post-construction)
Jet Fuel	Gallons	= Jet fuel use rate per passenger x Weight of passenger + luggage x Total air miles for all passengers, where Jet fuel use rate per passenger = 0.037 gal / 3800 mile Weight of passenger + luggage assumed to = 200 lbs NOTE: SRT reports gasoline and jet fuel together, under gasoline, on the Tier 1 screen and in summary metrics.
Cost (Capital)	Dollars ($)	= Volume Treated in cubic yards x $94 / cubic yard All costs assumed to be in the capital phase (Design team).
Tool-calculated Value		
Original Plume: Area	Acres	= Maximum plume length from Zones 1-4 x Maximum plume width from Zones 1-4 x 0.000023 acres/ft^2 conversion factor
Original Plume: Length	Feet	= Maximum plume length from Zones 1-4
Original Plume: Volume	Million gallons	= Total pore volume x 7.28 conversion factor / 1,000,000, where Total pore volume = Sum of pore volume of each treated zone (Area x thickness x porosity)
Original Plume: Dissolved Mass	Kilograms	= Sum of GW zone “doughnut” areas x Aquifer thickness x Porosity x Representative concentration

IN SITU CHEMICAL OXIDATION (ISCO) VARIABLES & CALCULATIONS		
		x conversion factors
Plume After Project: Area	Acres	If treating "Source Only", SRT assumes that the plume length and width is reduced by the length and width of Zone 1. So, area = (Maximum plume length from Zones 1-4 - Length of Zone 1) x (Maximum plume width from Zones 1-4 – Width of Zone 1) x 0.000023 acres/ft^2 conversion factor If treating "Source + Plume", the new plume area is assumed to be 90% of the original area. i.e., = Original plume area x 0.9
Plume After Project: Length	Feet	If treating "Source Only", the new plume length is calculated as above. i.e., = Maximum plume length from Zones 1-4 - Length of Zone 1 If treating "Source + Plume", the new length is assumed to be 90% of the original length. i.e., = Original plume length x 0.9
Plume After Project: Volume	Million gallons	= Plume after project area x Aquifer thickness x Aquifer porosity * 7.28 conversion factor / 1,000,000.
Plume After Project: Dissolved Mass	Kilograms	If treating "Source Only", the mass is estimated by the original mass, less the mass in Zone 1. i.e., = Original mass – (Area of Zone 1 x Aquifer Thickness x Aquifer Porosity) x geometric mean of Zone 1 original high and low concentration x 28.3 / 1,000,000 unit conversion factors. If treating "Source + Plume", the mass is estimated at 90% of the original mass. i.e., = Original mass x 0.9
Tool-calculated Metrics		
CO_2 Emissions	Tons	= (PVC x 1.824 lb/lb / 2000) + (Oxidant x 4 lb/lb / 2000) + (Diesel x 25.8 lb/gal / 2000) + (Gasoline x 20.17 lb/gal / 2000) + User-defined additional CO_2 CO_2 conversions from nrel.gov; Oxidant conversions

IN SITU CHEMICAL OXIDATION (ISCO) VARIABLES & CALCULATIONS		
		from Design Team (Jet fuel is lumped into gasoline volume)
NOx	tons NOx	= (PVC x 0.00318 / 2000) + (Diesel x 0.20922955 / 2000) + (Gasoline x 0.015078 / 2000)
SOx	tons SOx	= (PVC x 0.0105 / 2000) + (Diesel x 0.00020065 / 2000) + (Gasoline x 0.0001599 / 2000)
PM10	tons PM10	= (PVC x 0.00018 / 2000) + (Diesel x 0.0099786 / 2000) + (Gasoline x 0.00129015 / 2000)
Total Energy Consumed	Megajoules	= (Diesel x 170 MJ/gal) + (Gasoline x 150 MJ/gal) + User-defined additional Energy (Jet fuel is lumped into gasoline volume)
Technology Cost	Dollars ($)	See Section 2.0
Change in Resource Service (plume reduction)	Million gallons	= Plume volume after project – Original plume volume
Safety/Accident Risk	Lost hours	= [Total hours worked x Injuries per hour + Total hours worked x Injuries per hour due to oxidant risk + Total vehicle miles traveled x Injuries per mile] x Lost hours per injury, where Total hours worked = Hours worked + Hours for travel (post-construction/site visit) Hours worked = 50% x Capital Cost / $80/hr labor rate (Design Team) Hours for travel = 10 + Distance to site x 2 / 40 mph (Design Team) Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of post-construction trips Injuries per hour = 2.7 x 10^{-9} (derived from US Bureau of Labor Statistics, 2007)

IN SITU CHEMICAL OXIDATION (ISCO) VARIABLES & CALCULATIONS		
		Injuries per hour for oxidant risk = 1.65×10^{-5} Injuries per mile = 9.1×10^{-7} (NHTSA, 2005) Lost hours per injury = 48

I.3.1 Key Factors / Rules-of-Thumb

In Tier 1, the tool uses several "Rules-of-Thumb" (RoT) in order to calculate sustainability metrics while limiting user inputs. These RoT are derived from a combination of published values and equations and project team experience. The following table provides the key RoT used in each technology module of Tier 1.

IN SITU CHEMICAL OXIDATION (ISCO) KEY FACTORS / RULES-OF-THUMB		
Value Name	**Value**	**Reference**
Oxidant	4 lbs CO2 / lb	Design Team
Natural Oxygen Demand	Low (0.5 g/kg) Average (2.0 g/kg) High (20.0 g/kg)	Design Team, BW
Mass of Oxidant (Treating Once; Initial application)	Volume to Treat x Soil bulk density x Natural oxygen demand x unit conversion factors	Design Team, BW
Mass of Oxidant (Treating Once with 2 Followup Applications)	Each subsequent application requires half the mass of the initial application	Design Team, BW
Oxidant load delivery capacity	3,000 lbs per tote	Design Team, BW (Carus quote for RemOx L)
Distance to oxidant supplier	50 miles one-way	Design Team, BW
Injection Well Spacing	20 ft	Injection well spacing is assumed to be 20 feet; AFCEE *Principles and Practices for Enhanced Bioremediation*
Rate, Drilling	100 ft / day	Fugro correspondence
Fuel Consumption Rate, Drilling	10 gallons / day	Design Team, BW

IN SITU CHEMICAL OXIDATION (ISCO) KEY FACTORS / RULES-OF-THUMB		
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Vehicle mileage, heavy-duty trucks	17.6 mpg	Design Team
Vehicle mileage, travel	15 mpg	Design Team

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APPENDIX J: TIER 1 PERMEABLE REACTIVE BARRIER (PRB) COSTS AND OTHER CALCULATIONS

J.1 BACKGROUND

This section describes the Tier 1 costs and other calculations used in the Permeable Reactive Barrier (PRB) module of the Sustainable Remediation Tool (SRT). For the purpose of this tool, PRB refers to treatment of groundwater contamination through construction of a barrier wall perpendicular to the plume axis. SRT provides options for both source remediation (wall placement at the plume source area (Plume Zone 1) and containment (wall placement at the downgradient plume boundary) scenarios. Options are also provided for the user to select ZVI or mulch biowalls.

The PRB module addresses the construction of the barrier wall itself, installation of monitoring wells, and post-construction maintenance. Groundwater monitoring to evaluate remedy effectiveness should be evaluated separately in the Long-term Monitoring module.

Section 2.0 below addresses technology and energy cost calculations for the PRB module. Costs are calculated for both Capital (Year 1) and Operations and Maintenance (subsequent years) phases.

Section 3.0 below contains tables of non-cost calculations and the relevant assumptions / rules-of-thumb for those calculations.

J.2 COST CALCULATIONS

J.2.1 Technology Cost

Technology cost for PRB is calculated using formulas derived by the Design Team, and is based on the unit cost per square foot of the PRB.

<u>Technology Cost Calculations for PRB</u>

The Tier 1 calculation for Enhanced Bioremediation costs follows.

- Technology Cost for ZVI is $168 / square foot (capital cost), with no cost for O&M. This assumes no replacement of wall materials during the remediation program.

- Technology Cost for Mulch Biowall is $16 / square foot (capital cost). An additional $4 / square foot is added, assuming materials will be replaced every 5 years the remediation program is in place.

- The default case is that spoils disposal will be disposed of as non-hazardous waste. Additional costs are factored in if hazardous waste disposal is needed (volume of spoils for disposal, in cubic yards x $400/cubic yard).

J.2.2 User-Supplied Additional Costs

The costs described above are displayed in the summary section of the individual technology screens. Below the cost summary on these screens, the SRT allows the user to enter additional project costs and other metrics. These additional, project-specific costs are added to the pre-calculated totals, and are displayed on the "output" screens.

J.2.3 Cost Factors for Energy Costs

The SRT includes calculations, with user overrides allowed, for the amount of fuel and energy used for each technology. For the PRB module, calculations are done for gasoline and diesel. The cost-converted energy metric is displayed in the "normalized" section of the SRT's output screen. The cost conversion is the sum of the amount of energy type multiplied by cost, for each type of fuel/energy used. The Tier 1 costs for each energy type are:

Energy Type	Cost	Cost Reference
Gasoline	$2.00 / gallon	Average regular grade price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Diesel	$2.00 / gallon	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.

J.2.4 User-Supplied Additional Energy

The SRT allows the user to enter additional, project-specific metrics, including energy in megajoules. To complete the normalized/cost-based calculation for energy, the conversion from megajoules to dollars uses factors for gasoline. The converted value is added to the energy costs above, and is displayed on the “output” screens, if the user chooses to view the normalized values.

J.3 NON-COST CALCULATIONS

The following assumptions apply to non-cost calculations in the PRB module:

- Selecting “Remediation” vs. “Containment”:
  - The Source Remediation option assumes that the wall is placed at the source zone (Zone 1)
  - The Containment option assumes that the wall is placed at the downgradient boundary of the plume

PERMEABLE REACTIVE BARRIER (PRB) VARIABLES & CALCULATIONS		
Value Name	**Units**	**Calculations & Assumptions**
User-required Input		
Airline miles flown by project team (total miles for all travelers)	Miles over project lifetime	--
Average Distance Traveled by Site Workers per one-way trip	Miles	--
Trips by Site Workers during construction	# over project lifetime	--
Trips by Site Workers after construction	# over project lifetime	--
Remediation design (purpose)	Choose: Remediation, or Containment	--
Wall type	Choose: ZVI, or Mulch	--
Depth of wall	Feet	Must be greater than the depth to water (input on Groundwater Input screen)
Disposal type	Choose: Non-hazardous, or Hazardous	--

PERMEABLE REACTIVE BARRIER (PRB) VARIABLES & CALCULATIONS		
Remediation duration	years	--
Additional Technology Cost	Dollars ($)	--
Additional Energy Consumed	Megajoules	--
Additional CO_2 Emissions	tons	--
Additional Safety / Accident Risk	Lost hours due to injuries / illnesses	--
Tool-calculated Value or User Override		
Length of wall	ft	If the design purpose is Source Remediation, = width of plume Zone 1 If the design purpose is Containment, = the maximum width of plume Zones 2-4
Average COC concentration upgradient of wall	mg/L	= original plume mass / original plume volume x 1000 x 1000 / 28.316 unit conversion factors
PVC	Pounds	= Length of pipe per monitoring well, assumed to be equal to the wall depth x Number of wells + 2 x wall length x 2.03 lbs/ft conversion factor, where Number of wells = Wall length / 200 x 3 well transect per 200 ft wall length
Iron / Mulch	Pounds	Derived from type of wall selected by user, average concentration upgradient of wall, and seepage velocity
Substrate	Pounds	Mass of substrate over project lifetime = (Wall depth – Depth to groundwater) x Wall length x Wall thickness x 2 lbs substrate/ft^3 wall below water table x (Duration / 5) If duration > 5 years, assume rejuvenation of wall via substrate every 5 years (Design Team)
Diesel	Gallons	Diesel, considered in the Capital phase, includes fuel for drilling, trenching, loading/filling, delivery of wall materials, and disposal of spoils. <u>Fuel for drilling</u> = Length of pipe per monitoring well, assumed to be equal to wall depth x Number of wells / Drilling rate x Drilling fuel consumption rate,

PERMEABLE REACTIVE BARRIER (PRB) VARIABLES & CALCULATIONS		
		where: Drilling rate assumed to = 100 ft/day (Fugro correspondence) Drilling fuel consumption rate assumed to = 32 gal/day (Design Team) Fuel for trenching = hours to install wall x fuel consumption rate of 6.25 gal/hr, where Hours to install wall = wall length / trenching rate of 200 ft / day x 24 hours / day. Fuel for loading/filling = hours to install wall x fuel consumption rate of 10 gal/hour, where Hours to install wall = (total wall volume – volume spoils for disposal) * fluff factor 0f 1.3 / spread-compaction rate of 654 cu yds / hr Fuel for delivery/disposal = Total miles driven to deliver sand/iron or gravel/mulch, and disposal / fuel consumption rate of 8 mpg, where Miles for delivery is based on wall thickness and material ratios, which are, in turn, functions of average COC concentration upgradient of wall and the seepage velocity. Miles for disposal is calculated from the volume of trench spoils for disposal (volume of wall below water depth), dump truck volume, and disposal site. For wall rejuvenation via substrate (O&M) = Mass of substrate over project lifetime / 7.89 lb/gal / 5,000 gal/tanker x 1,000 mi/tanker one-way trip x 2 one-way trips/roundtrip / 8 mi/gal
Gasoline	Gallons	= Vehicle mileage (travel) x Miles traveled, where Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW) Miles traveled = Distance to site x 2 x (Number of trips) For Capital phase, the number of trips is the number

PERMEABLE REACTIVE BARRIER (PRB) VARIABLES & CALCULATIONS		
		entered for construction. For O&M phase, the number of trips is the number of post-construction trips.
Jet Fuel	Gallons	= Jet fuel use rate per passenger x Weight of passenger + luggage x Total air miles for all passengers, where Jet fuel use rate per passenger = 0.037 gal / 3800 mile Weight of passenger + luggage assumed to = 200 lbs
Cost (Capital)	Dollars ($)	If ZVI, Cost = Wall area x $168 If Mulch, Cost = Wall a x $16 This default case assumes spoils disposal is as non-hazardous waste. For hazardous waste disposal, additional costs are added (an additional $400 per cubic yard of spoils for disposal).
Tool-calculated Value		
Original Plume: Area	Acres	= Maximum plume length from Zones 1-4 x Maximum plume width from Zones 1-4 x 0.000023 acres/ft^2 conversion factor
Original Plume: Length	Feet	= Maximum plume length from Zones 1-4
Original Plume: Volume	Million gallons	= Total pore volume x 7.28 conversion factor / 1,000,000, where Total pore volume = Sum of pore volume of each treated zone (Area x thickness x porosity)
Original Plume: Dissolved Mass	Kilograms	= Sum of GW zone “doughnut” areas x Aquifer thickness x Porosity x Representative concentration x conversion factors
Plume After Project: Area	Acres	If the design (purpose) is for Source Remediation, SRT assumes that the entire plume will be treated by the end of the remediation program. That is, the area will display as 0. If Containment is the goal, the assumption is that 90% of the original plume area will remain.

PERMEABLE REACTIVE BARRIER (PRB) VARIABLES & CALCULATIONS		
Plume After Project: Length	Feet	If the design (purpose) is for Source Remediation, SRT assumes that the entire plume will be treated by the end of the remediation program. The length will display as 0. If Containment is the goal, the assumption is that 90% of the original length will remain.
Plume After Project: Volume	Million gallons	If the design (purpose) is for Source Remediation, SRT assumes that the entire plume will be treated by the end of the remediation program. The volume will display as 0. If Containment is the goal, the assumption is that 90% of the original volume will remain.
Plume After Project: Dissolved Mass	Kilograms	If the design (purpose) is for Source Remediation, SRT assumes that the entire plume will be treated by the end of the remediation program. The mass will display as 0. If Containment is the goal, the assumption is that 90% of the original mass will remain.
Tool-calculated Metrics		
CO_2 Emissions	Tons	= (PVC x 1.824 lb/lb / 2000) + (Diesel x 25.8 lb/gal / 2000) + (Gasoline x 20.17 lb/gal / 2000) + (Iron x 1.21 lb/lb / 2000) + User-defined additional CO_2 CO_2 conversions from nrel.gov (Jet fuel is lumped into gasoline volume)
NOx	tons NOx	= (PVC x 0.00318 / 2000) + (Diesel x 0.20922955 / 2000) + (Gasoline x 0.015078 / 2000)
SOx	tons SOx	= (PVC x 0.0105 / 2000) + (Diesel x 0.00020065 / 2000) + (Gasoline x 0.0001599 / 2000)
PM10	tons PM10	= (PVC x 0.00018 / 2000) + (Diesel x 0.0099786 / 2000) + (Gasoline x 0.00129015 / 2000)
Total Energy Consumed	Megajoules	= (Diesel x 170 MJ/gal) + (Gasoline x 150 MJ/gal) + User-defined additional Energy

PERMEABLE REACTIVE BARRIER (PRB) VARIABLES & CALCULATIONS		
		(Jet fuel is lumped into gasoline volume)
Technology Cost	Dollars ($)	See Section 2.0
Change in Resource Service (plume reduction)	Million gallons	= Plume volume after project – Original plume volume
Safety/Accident Risk	Lost hours	= Total hours worked x Injuries per hour + Total vehicle miles traveled x Injuries per mile, where Total hours worked = Hours worked + Hours for travel For Capital Phase: Hours worked = 50% x Capital Cost / $80/hr labor rate (Design Team) Hours for travel = (10 + Distance to site x 2 / 40 mph) x Number of construction trips (Design Team) For O&M Phase: Hours worked = 50% x O&M Cost / $80/hr labor rate + 35 hrs/500 ft wall x Wall length x (Duration / 5) (Design Team) Hours for travel = (10 + Distance to site x 2 / 40 mph) x Number of post-construction trips (Design Team) Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of post-construction trips + 1,000 mi/tanker one-way trip x 2 one-way trips/roundtrip x Mass of substrate over project lifetime / 7.89 lb/gal / 5,000 gal/tanker x (Duration / 5) Injuries per hour = 2.7 x 10^{-9} (derived from US Bureau of Labor Statistics, 2007) Injuries per mile = 9.1 x 10^{-7} (NHTSA, 2005)

J.3.1 Key Factors / Rules-of-Thumb

In Tier 1, the tool uses several "Rules-of-Thumb" (RoT) in order to calculate sustainability metrics while limiting user inputs. These RoT are derived from a combination of published values and equations and project team experience. The following table provides the key RoT used in each technology module of Tier 1.

PERMEABLE REACTIVE BARRIER (PRB) KEY FACTORS / RULES-OF-THUMB		
Value Name	**Value**	**Reference**
Wall Composition Ratio	If Mulch Wall, 30% gravel & 70% mulch If ZVI, Average concentration > 1 mg/L and Seepage velocity >100 ft/year, 50% sand & 50% iron Average concentration <1 mg/L and Seepage velocity < 100 ft/year, 60% sand & 40% iron Otherwise, 40% sand & 60% iron	Design Team
Dump truck volume	12 cu yd	
Fluff Factor	1.3	
Distance from site to gravel/sand/mulch source	20 miles one-way	
Distance to ZVI source	1,000 miles one-way	
Distance to disposal	20 miles one-way	
Trenching rate	200 ft/day	
Spread/compaction rate	654 cu yd/hr	
Rate, Drilling	100 ft/day	Fugro correspondence
Fuel Consumption Rate, Drilling	32 gallons / day	Design Team, BW; Assumes drilling completed with smaller rig (4 gal/hr) for

PERMEABLE REACTIVE BARRIER (PRB) KEY FACTORS / RULES-OF-THUMB		
		8 hrs/day.
Fuel Consumption Rate, Trenching	6.25 gal/hr	
Fuel Consumption Rate, Loading	10 gal/hr	
Vehicle Mileage, Delivery and Disposal	8 mpg	
Vehicle Mileage, Travel	15 mpg	
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team

J.4 REFERENCES

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APPENDIX K: TIER 1 LONG-TERM MONITORING / MONITORED NATURAL ATTENUATION COSTS AND OTHER CALCULATIONS

K.1 BACKGROUND

This section describes the Tier 1 costs and other calculations used in the **Long-term Monitoring / Monitored Natural Attenuation (LTM/MNA)** module of the Sustainable Remediation Tool (SRT). For the purpose of this tool, LTM/MNA can be used as a stand-alone module, or in conjunction with other remedies to evaluate sustainability metrics for the monitoring component of a remediation program.

Section 2.0 below addresses technology and energy cost calculations for this module.

Section 3.0 below contains tables of non-cost calculations and the relevant assumptions / rules-of-thumb for those calculations.

K.2 COST CALCULATIONS

K.2.1 Technology Cost

Technology cost is based on the well installation depth and characterization plus first year sampling (capital) and the number of subsequent sampling events (O&M). The cost equations were developed from RACER.

<u>Technology Cost Calculations for LTM/MNA:</u>

The Tier 1 calculation for LTM/MNA costs follows.

- Technology Cost (Capital) = (Depth of well x Number of wells x 200) + (Number of sampling events for characterization + Number of sampling events in the first year) x Number of samples per event * [(2.5 *Depth of well) + 2957]

- Technology Cost (O&M) = Trips post-construction + [Sampling events after the first year x (Duration – 1) x Samples per event x 2.5 x Depth of well] + 2957

K.2.2 User-Supplied Additional Costs

The costs described above are displayed in the summary section of the individual technology screens. Below the cost summary on these screens, the SRT allows the user to enter additional project costs and other metrics. These additional, project-specific costs are added to the pre-calculated totals, and are displayed on the "output" screens.

K.2.3 Cost Factors for Energy Costs

The SRT includes calculations, with user overrides allowed, for the amount of fuel and energy used for each technology. In the LTM/MNA module, calculations are done for gasoline and diesel. The cost-converted energy metric is displayed in the "normalized" section of the SRT's output screens. The cost conversion is the sum of the amount of energy type multiplied by cost, for each type of fuel/energy used. The Tier 1 costs for each energy type are:

Energy Type	Cost	Cost Reference
Gasoline	$2.00 / gallon	Average regular grade price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.
Diesel	$2.00 / gallon	Average diesel price (http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm). Website accessed 4/23/09.

K.2.4 User-Supplied Additional Energy

The SRT allows the user to enter additional, project-specific metrics, including energy in megajoules. To complete the normalized/cost-based calculation for energy, the conversion from megajoules to dollars uses factors for gasoline. The converted value is added to the energy costs above, and is displayed on the "output" screens, if the user chooses to view the normalized values.

K.3 NON-COST CALCULATIONS

The following assumptions apply to non-cost calculations in the LTM/MNA module:

- For the groundwater modules, estimates of the plume after project completion are provided. These values are used to calculate the natural resource metric.

  For Tier 1 of the LTM/MNA module, the calculation method uses a decay rate constant that can be entered by the user (default value is 0.23 / year). In Tier 2, the user has the option to enter the final plume characteristics (calculated outside of SRT) directly into the tool.

LTM/MNA VARIABLES & CALCULATIONS		
Value Name	**Units**	**Calculations & Assumptions**
User-required Input		
Airline miles flown by project team (total miles for all travelers)	Miles over project lifetime	--
Average Distance Traveled by Site Workers per one-way trip	Miles	--
Trips by Site Workers during construction	# over project lifetime	--
Trips by Site Workers after construction	# over project lifetime	--
Number of monitoring wells	#	--
Length of piping, per well	feet	--
Number of samples collected per sampling event	#	
Source zone point decay rate constant	1/year	Default is 0.23 /year
Additional Technology Cost	Dollars ($)	--
Additional Energy Consumed	Megajoules	--
Additional CO_2 Emissions	tons	--
Additional Safety / Accident Risk	Lost hours due to injuries / illnesses	--
Tool-calculated Value or User Override		
Number of characterization (baseline) sampling events	#	
Number of sampling events in the first year	#	1

LTM/MNA VARIABLES & CALCULATIONS		
Number of sampling events per year in subsequent years	#	4
Number of sample collected per sampling event	#	1
Duration	years	30
Beginning Plume Mass	Kilograms	Beginning plume mass = Sum of each zone of Area of donut x Aquifer thickness x porosity x representative concentration x unit conversions Note that plume areas are conceptualized using “donuts” (see graphic on GW Input screen) to avoid double-counting contaminant mass. Since the area of highest concentration is in the interior, that area must be subtracted from areas of subsequently lower concentrations.
Ending Plume Mass	Kilograms	Pore volumes recovered = Pump rate x Duration x unit conversions / original plume volume; used to calculate the concentration reduction factor (CRF): If pore volumes recovered < 3, CRF = (-0.2195 x PVr) + 1. If pore volumes recovered >=3, CRF = 1.3367 x PVr ^(-1.2424). Minimum CRF = 0.05. For Containment systems, CRF = 1. For Containment systems, starting plume mass and ending plume mass are assumed to be the same.
Plume Area, Original Plume	Acres	= Maximum plume length x maximum plume width x conversion factor
Plume Length, Original Plume	Feet	= Maximum plume length entered
Plume Volume, Original Plume	Million gallons	= Sum of plume lengths x plume widths x aquifer thickness x porosity
Dissolved Mass, Original Plume	Kilograms	= Sum of concentration x volume for each zone of “donut”
Plume Area, After Project	Acres	= Maximum calculated new plume length x new plume width
Plume Length, After Project	Feet	= Maximum calculated new plume length
Plume Volume, After Project	Million gallons	= Sum of calculated new plume lengths x plume widths x aquifer thickness x porosity

LTM/MNA VARIABLES & CALCULATIONS		
Dissolved Mass, After Project	Kilograms	= Sum of calculated new concentration x volume for each zone of "donut"
PVC	Pounds	= Length of pipe per well x Number of wells x 2.03 lbs/ft conversion factor
Diesel (Capital)	Gallons	Diesel is based on the amount of fuel for drilling. = Length of pipe per well x Number of wells / Drill rate of 100 ft/day x Fuel consumption rate of 32 gal/day
Gasoline (Capital)	Gallons	= Vehicle mileage (travel) x Miles traveled, where Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW) Capital Phase: Average distance traveled by site workers per one way trip x 2 x (Number of trips by site workers during construction + Number of characterization sampling events + Number of sampling events in first year) Jet fuel is lumped into gasoline because of similar properties. Total jet fuel = Jet fuel use rate x weight x air miles input above. The default calculation assumes 50% is used in capital, and 50% used in O&M phases.
Gasoline (O&M)	Gallons	= Vehicle mileage (travel) x Miles traveled, where Vehicle mileage (travel) assumed to = 15 mpg (Design Team, BW) O&M Phase: Average distance traveled by site workers per one way trip x 2 x (Number of trips by site workers after construction + (Number of sampling events in subsequent years x (Duration - 1)) Jet fuel is lumped into gasoline because of similar properties. Total jet fuel = Jet fuel use rate x weight x air miles input above. The default calculation assumes 50% is used in capital, and 50% used in O&M phases.

LTM/MNA VARIABLES & CALCULATIONS		
Jet Fuel	Gallons	= Jet fuel use rate per passenger x Weight of passenger + luggage x Total air miles for all passengers, where Jet fuel use rate per passenger = 0.037 gal / 3800 mile Weight of passenger + luggage assumed to = 200 lbs
Cost (Capital)	Dollars ($)	See Section 2.0
Cost (O&M)	Dollars ($)	See Section 2.0
Tool-calculated Metrics		
CO_2 Emissions		= (PVC x 1.824 lb/lb / 2000) + (Diesel x 25.8 lb/gal / 2000) + (Gasoline x 20.17 lb/gal / 2000) + User-defined additional CO_2 CO_2 conversions from nrel.gov (Jet fuel is lumped into gasoline volume)
NOx	tons NOx	= (PVC x 0.00318 / 2000) + (Diesel x 0.20922955 / 2000) + (Gasoline x 0.015078 / 2000)
SOx	tons SOx	= (PVC x 0.0105 / 2000) + (Diesel x 0.00020065 / 2000) + (Gasoline x 0.0001599 / 2000)
PM10	tons PM10	= (PVC x 0.00018 / 2000) + (Diesel x 0.0099786 / 2000) + (Gasoline x 0.00129015 / 2000)
Total Energy Consumed	Megajoules	= (Diesel x 170 MJ/gal) + (Gasoline x 150 MJ/gal) + User-defined additional Energy (Jet fuel is lumped into gasoline volume)
Technology Cost	Dollars ($)	See Section 2.0
Change in Resource Service (plume reduction)	Million gallons	= Plume volume after project – Original plume volume
Safety/Accident Risk	Lost hours	= Total hours worked x Injuries per hour + Total vehicle miles traveled x Injuries per mile, where

LTM/MNA VARIABLES & CALCULATIONS		
		Total hours worked = Hours worked + Hours for travel (post-construction/site visit) For Capital phase: = [(Sampling events for characterication + Sampling events in first year) x Number of wells x 1 x 2] + [Number of trips for construction x (10 + Distance to site x 2 / vehicle speed] For O&M: = [Sampling events after first year x (Duration – 1) x Number of wells x 1 x 2] + [Number of trips post construction x (10 + Distance to Site x 2 / vehicle speed)] Injuries per hour = 2.7×10^{-9} (derived from US Bureau of Labor Statistics, 2007) For Capital phase: Total vehicle miles traveled = (Distance to site x 2) x Number of construction trips + (Distance to site x 2) x Number of characterization trips + (Distance to site x 2) x Number of sampling trips For O&M: Total vehicle miles traveled = (Distance to site x 2) x Number of post construction trips + (Distance to site x 2) x Number of sampling trips x (Duration -1) Injuries per mile = 9.1×10^{-7} (NHTSA, 2005)

K.3.1 Key Factors / Rules-of-Thumb

In Tier 1, the tool uses several “Rules-of-Thumb” (RoT) in order to approximate sustainability metrics while limiting user inputs. These RoT are derived from a combination of published values and equations and project team experience. The following table provides the key RoT used in the LTM/MNA technology module of Tier 1.

LTM/MNA RULES-OF-THUMB		
Value Name	**Value**	**Reference**
Number of sampling events in the first year	1	Design Team
Number of sampling events per year in subsequent years	4	Design Team
Number of sample collected per sampling event	4	Design Team
Duration	30 years	Design Team
Fuel Consumption Rate, Drilling	32 gal / day	Design Team (BW). Assumes drilling completed with smaller rig (4 gal/hr) for 8 hrs / day.
Fuel Consumption Rate, Jet Fuel, Use Rate Per Passenger	0.0000097 gal / mile	Extra weight of fuel required for carrying 1 additional pound for 3,800 miles traveled on a Boeing 777 = 0.25 lbs (i.e. 0.25 * payload weight = weight of additional fuel required). 8/27/08, http://www.flyertalk.com/forum/showthread.php?t=712294
Fuel Consumption Rate, Jet Fuel, Weight of passenger + luggage	200 lbs	Used for jet fuel calculation. Design Team.
Mileage, Vehicle for Transportation	15 miles / gal	Design Team (BW)
Rate, Drilling	100 ft / day	Driller (Fugro) Correspondence

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