COST ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

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1.0 INTRODUCTION

1.1 Purpose and Intended Audience

This cost estimating tool is intended to assist Department of Defense (DoD) Restoration/Remedial Project Managers (RPMs) in evaluating the cost of implementing enhanced anaerobic bioremediation for chlorinated solvents in groundwater. These costs may be useful for comparing various system configurations, or for comparison to alternative remedial technologies (e.g., groundwater extraction, air sparging, permeable reactive iron barriers, or chemical oxidation). For example, this information may be useful to the RPM for comparison of remedial alternatives in feasibility studies, corrective measures studies, or engineering evaluation/cost analysis studies. Costs also may be compared between alternative systems for enhanced bioremediation; however, this cost estimating tool is not intended for design purposes. Costs calculated by this model should be considered order-of-magnitude estimates suitable for comparison purposes only.

1.2 Quick Start Guide

It is recommended that the user review this guidance manual prior to using the tool. However, to start using the tool quickly, extract the cost model Excel® template file and the user's manual to a "C:\Cost Estimating Tool" subdirectory. The cost model can be used in any subdirectory; however, the HELP function in the model will only link directly to the user's manual when the manual is located in the "C:\Cost Estimating Tool" subdirectory.

<u>To use the Cost Estimating Tool in Microsoft Excel®, the user must be able to enable the macros in the Cost Estimating Tool file.</u> The user may need to change the security settings in Excel® to be able to do this. To enable macros in Excel®, the user should open Excel®, click on the "Tools" pull down menu, scroll down to "Options", and select the "Security" tab. On the "Security" window, the user should select the "Macro Security…" button, then check the "medium" security setting and close the program. Then, when the cost tool is opened it will prompt the user to "enable macros" or "disable macros". Enable the macros to run the model.

Once the Excel® template file is opened, the user can fill in the required information (Model Input Sheets). Based on this input, the cost tool will calculate a life-cycle cost based on model assumptions and defaults, and produce a model summary report. When electing to save the model file, the program will prompt the user to select a subdirectory to save the file to, and to give the file a unique name.

Costs calculated by this model should only be considered order-of-magnitude estimates suitable for comparison purposes only. The user can further refine the cost estimate by reviewing the assumptions described in this user's manual and using the options provided in the model calculation sheets for user-specific input parameters.

1.3 Enhanced Anaerobic Bioremediation

Enhanced anaerobic bioremediation has emerged in recent years as a viable and cost-effective remediation strategy for chlorinated solvents in groundwater. Advantages include complete mineralization of the contaminants *in situ* with little impact on infrastructure, and relatively low cost compared to more active engineered remedial technologies. The addition of an organic substrate to an aquifer has the potential to stimulate microbial growth and development, creating an anaerobic environment in which rates of anaerobic degradation of chlorinated solvents may be enhanced.

A variety of organic substrates have been applied to the subsurface to promote anaerobic degradation of chlorinated solvents to innocuous end products. This cost estimating tool estimates life-cycle costs for commonly used substrates that can be injected into the subsurface either by installation of injection wells or by use of direct-push techniques.

1.4 Applicable Contaminants

The cost estimating model is designed to calculate order-of-magnitude cost estimates for enhanced anaerobic bioremediation of chlorinated solvents, including chloroethenes, chloroethanes, and chloromethanes. Enhanced anaerobic bioremediation may also be applicable to other compounds subject to anaerobic degradation reactions. These compounds may include chlorobenzenes, chlorinated pesticides (e.g., chlordane), polychlorinated biphenyls (PCBs), chlorinated cyclic hydrocarbons (e.g., pentachlorophenol), oxidizers such as perchlorate, explosive and ordnance compounds, dissolved metals (e.g., hexavalent chromium), nitrate, and sulfate. The user may in some cases use this cost estimating model for contaminants other than chlorinated solvents by providing alternate information for model input fields. However, this cost estimating model is primarily intended to develop life-cycle cost estimates for enhanced bioremediation of chlorinated solvents.

1.5 User Assumptions

The user of this cost estimating tool should have a basic understanding of the principles and practices of enhanced anaerobic bioremediation. The reader is referred to the following references for information regarding the application of enhanced anaerobic bioremediation.

- *Principles and Practice of Enhanced Anaerobic Bioremediation of Chlorinated Solvents* (Air Force Center for Environmental Excellence [AFCEE] et al., 2004)
- *Technical Protocol for Using Soluble Carbohydrates to Enhance Reductive Dechlorination of Chlorinated Aliphatic Hydrocarbons* (Suthersan et al., 2002)
- *Engineered Approaches to In Situ Bioremediation of Chlorinated Solvents: Fundamentals and Field Applications* (United State Environmental Protection Agency [USEPA], 2000)
- *A Systematic Approach to In Situ Bioremediation in Groundwater, Including Decision Trees on In Situ Bioremediation for Nitrates, Carbon Tetrachloride, and Perchlorate* (Interstate Technology and Regulatory Council [ITRC], 2002)

This cost estimating tool requires the user to provide model input parameters for basic site conditions, including contaminant distribution, hydrogeology, and groundwater geochemistry. The cost model uses practical default values to determine reasonable cost estimates in order to simplify the process. The user has the option to override the default values in order to tailor the model to specified conditions.

1.6 Model Summary Report

A model summary report provides the estimated life-cycle cost of an enhanced anaerobic bioremediation system developed from model defaults, user input, and selected options. ***This program is not intended for design purposes.*** The life-cycle cost produced should be considered an order-of-magnitude estimate only. The variability associated with system design, construction, and monitoring for enhanced anaerobic bioremediation applications is high. Costs are calculated using current dollars, and a total present worth cost is calculated using a discount rate that accounts for inflation and the cost of money (investment potential). Information provided in the summary report is described in Section 3.10.

2.0 USING THE COST ESTIMATING TOOL

2.1 Opening and Starting the Cost Model

This cost model follows the steps outlined in Figure 1. The user is required to provide basic information describing the site under consideration. The user is also required to make a number of decisions regarding the remedy including the configuration and size of the treatment system, the substrate to be used, and the duration of treatment and performance monitoring.

To open the model, the user should place the self-extracting file on a designated directory and extract the model template file. Next, the user should create a directory in which to save individual model cost estimates; the cost model prompts the user to use "C:\Cost Estimating Tool." The model may then be started by simply opening the Excel® template file.

To assist the user, a typical range of values is provided that are representative of reasonable enhanced anaerobic bioremediation scenarios. To facilitate using the tool, default values are provided, with an option for the user to modify the default value. Ranges and default values have been derived from practical applications of the technology. The cost models are designed to work in the ranges listed. Entering values outside the range *may* lead to irrational results, and is generally not allowed. Ranges for individual characteristics are described in Section 3.

When using the cost model, the user may access this model documentation by selecting the **HELP** button on any page of the model program. This user's manual can be searched by topic from the table of contents, and the user is encouraged to review this document in its entirety prior to using the cost estimating model.

2.2 Saving and Resetting the Cost Model

The user may save a current cost estimate model at anytime by selecting the save option from the main page. The user will be prompted for a subdirectory to save the file to and a unique file name for the cost estimate. The user may return to the specific cost model at a later time by selecting and opening that file. The user may reset the model defaults for each step by selecting the reset button on each page. Selecting the "Reset All" button on the main page will reset all model defaults for every step. If the user wishes to start a new cost model it is recommended they exit the program, re-open the model template file, and select "Reset All."

FIGURE 1
STEPS IN THE COST ESTIMATING PROCESS

Step 1: Site Description (Conceptual Site Model)
User Input
- Contaminant Data
- Hydrogeology
- Geochemical Data

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Step 2: Select System Configuration (Design)
User Input
- Treatment Configuration and Cell Size
- Substrate Type
  - Soluble Substrate Systems
  - Slow-Release Substrate Systems
- Design Life
- Number of Injection and Monitoring Wells

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Steps 3 through 9: Cost Estimation
Model Calculations
- Step 3: System Design
- Step 4: Capitol Construction
  - Soluble Substrate Systems
  - Slow-Release Substrate Systems
- Step 5: Operations and Maintenance
  - Soluble Substrate Systems
  - Slow-Release Substrate Systems
- Step 6: Substrate Requirements
- Step 7: Performance Monitoring
- Step 8: Reporting
- Step 9: Project Management, Markups, Fees, and Contingency

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Step 10: Model Summary Report
Model Output
- Calculated Cost for Each Model Step
- Total Estimated Life-Cycle Cost

2.3 Cost Estimating Categories

The cost estimating model computes a life-cycle cost of implementing enhanced anaerobic bioremediation that is subdivided into the following seven categories:

- ***System Design;***
- ***Capital Construction;***
- ***Operations and Maintenance;***
- ***Substrate Cost;***
- ***Performance Monitoring;***
- ***Reporting; and***
- ***Project Management, Markups, Fees, and Contingencies.***

The following sections describe these categories and how the cost model derives an estimated cost for each item. Model output is provided in the model summary report.

3.0 STEPS FOR COST ESTIMATION

This section describes 1) the model input required, 2) calculations and assumptions used, and 3) results provided for each of the 10 steps in the cost model.

3.1 Step 1: Model System Input – Conceptual Site Model

The first step in this cost estimating tool for enhanced bioremediation is providing model input for basic characterization of the site for which the application is intended. Step 1 asks for model input regarding contaminant constituents, aquifer parameters, and biogeochemical characterization. Input data should be representative averages or means for the entire treatment zone.

- **Contaminant Concentrations (Optional).** Data for contaminant concentrations is not required for calculating system costs, and is optional. The maximum range for contaminant concentrations is an approximate solubility limit for each compound.

- **Aquifer Description (Required).** Data characterizing the aquifer system is required for this cost model. Depth to groundwater, hydraulic gradient, hydraulic conductivity, estimated total porosity, and estimated effective porosity are required input. This information is used to calculate groundwater seepage velocity and groundwater flux through the treatment system. This data is then used by the model to determine the frequency of injection for soluble substrates (Step 5) and to calculate substrate requirements (Step 6).

- **Geochemical Characterization (Optional).** Data for geochemical characterization is not required for calculating system costs, and is optional. The ranges for geochemical parameters reflect values that may be encountered in common applications. If site-specific values are outside the listed ranges, then the reader should refer to guidance on whether the conditions are appropriate for application of enhanced anaerobic bioremediation.

Contaminant and geochemical data are used to calculate a site-specific substrate demand in Step 6 - Substrate Cost, an optional parameter provided for comparison to the model default (see Section 3.6). After the basic site conditions for the cost model are provided in Step 1, the user must proceed to Step 2 and provide input for the basic system design.

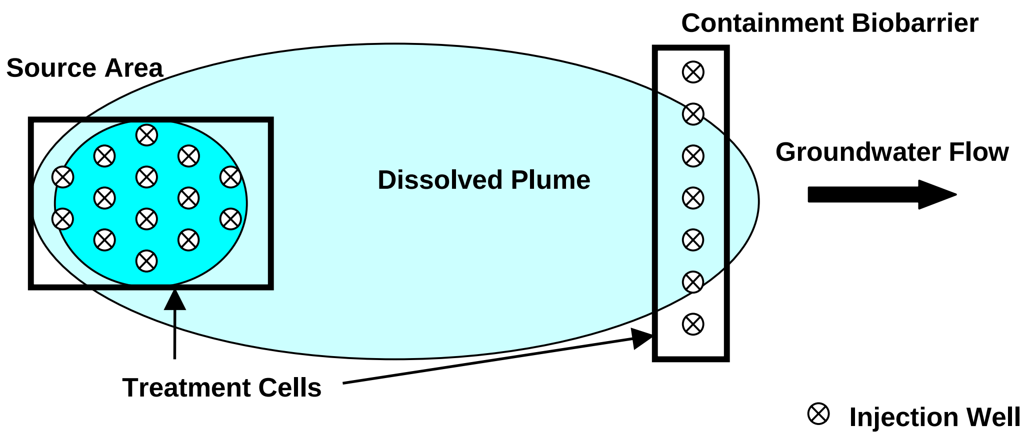
3.2 Step 2: Model System Input – System Design

Step 2 asks the user to input basic design criteria for the enhanced bioremediation system being considered. This step will have the greatest impact on bioremediation system life-cycle costs.

- **Proposed Remedial Configuration.** The user is asked to select either a source area/grid configuration or a biobarrier configuration (Figure 2). Many model assumptions are based on the treatment cell dimensions; the treatment cell dimensions should be appropriate for the source area/grid configuration or the biobarrier configuration selected.

- **Substrate Type**. This cost model allows the user to estimate costs for either soluble substrate systems, or for slow-release substrate systems. Substrate options for soluble systems include lactate, molasses, high fructose corn syrup, or ethanol. These are representative of common soluble substrate types being used for enhanced anaerobic bioremediation. For slow release substrates systems, the user is allowed to select from hydrogen release compound (HRC®), bulk vegetable oil, or a premixed commercial vegetable oil-in-water emulsion product (which are more costly than bulk oil). ***This cost estimating tool is not intended to endorse any substrate option or commercial bioremediation product.*** Substrate options are provided for comparison purposes only.

FIGURE 2
SCHEMATIC OF SOURCE AREA AND BIOBARRIER INJECTION CONFIGURATIONS



- **Treatment Cell Dimensions.** The user is asked to provide dimensions of the treatment cell size for the cost model. The area of the treatment cell is calculated by multiplying the width (perpendicular to groundwater flow) times the length (parallel to groundwater flow). The treatment cell dimensions are used to determine the default number of injection well/points. The practical aquifer thickness that a single injection well can be used to inject substrate is limited to 15 to 20 feet. For an aquifer thickness greater than 20 feet, the user should consider increasing the number of injection wells (determined per Injection Systems below).

- **Treatment Cell Hydraulics.** The model calculates groundwater seepage velocity, pore volume, and groundwater flux (per year) based on previous user input. No additional user modifications are allowed for this step. If modifications to these values are desired, the user must modify the aquifer description parameters in Step 1 (Model System Input – Conceptual Site Model).

- **Treatment Cell Design Life.** The user is asked to provide a system design life. A default value of 3 years is provided for comparison purposes. In practice, enhanced bioremediation applications may require from 1 year (e.g., a grid application for a low level plume), to 10 or more years (e.g., for a biobarrier system). The user is encouraged to input a representative system design life based on the site-specific conditions (e.g., size of plume, rate of groundwater flow, contaminant concentrations, and remediation goals).

- **Injection Systems.** The number of injection wells required for the treatment cell size provided by the user is calculated by default. The default calculation for the number of soluble substrate injections wells required is one well for every 900 square feet of treatment area in a grid configuration (approximately 30-foot spacing). For biobarrier configurations, the default is one well for every 1,800 square feet of treatment area. The default calculation for the number of slow-release injections points (i.e., using direct-push techniques) or injection wells (i.e., permanent wells) required is one well/point for every 100 square feet of treatment area in a grid configuration (approximately 10-foot spacing), and one well/point for every 200 square feet in a biobarrier configuration. Note that for biobarriers configurations, the model default calculation for the number of injection wells is approximately half that for grid configurations. For an aquifer treatment thickness greater than 20 feet, the user should consider increasing (e.g., doubling) the number of injection wells. The user has the option to input an alternate number of injection wells during this step.

- **Monitoring Systems.** Similar to the injection system, the number of monitoring wells is also provided by default. For small-scale applications of less than 5,000 square feet, the default number of monitoring wells is set to six. For moderate size applications between 5,000 and 25,000 square feet, the default number of monitoring wells is set to 10. For moderate- to large-scale systems between 25,000 and 100,000 square feet, the default number of monitoring wells is set to 15. For very large systems greater than 100,000 square feet (e.g., greater than 2 acres) the default number of monitoring wells is capped at 20 wells. The user has the option to input an alternate number of monitoring wells during this step.

Once user input is provide for Steps 1 and 2, the cost model will calculate a life-cycle cost using model default values in Steps 3 through 9. The user may go directly to the Model Summary Report in Step 10. Alternately, the user may review and modify the costs associated with Steps 3 through 9 to tailor the cost for their own purposes. ***When evaluating a number of alternative systems for cost comparison purposes only, it is recommended that the default values provided in Steps 3 through 9 not be changed in order to provide a consistent basis for the comparison between the alternative systems.***

3.3 Step 3: System Design Cost

System design typically includes development of remedial objectives, screening of site conditions for technology selection, design of an appropriate engineered bioremediation system, development of a health and safety plan, and development of a sampling and analysis plan. These items are typically presented in a site-specific work plan for regulatory approval. System design costs will be higher for larger enhanced bioremediation systems. A practical range for system design and development of a work plan for DoD sites is from $10,000 (minimum) for pilot-scale test systems to $100,000 (maximum) for large and complex applications.

This cost estimating tool uses a default value for system design of 10 percent of the overall system cost for 1) capitol construction, 2) operations and maintenance, 3) substrate, and 4) performance monitoring. The cost of these field application items is impacted by the scale of the system to be designed. System design costs are further assumed to be 95 percent labor and 5 percent other direct costs (ODCs). The user may input an alternative percentage for system design to modify the system design cost, if desired.

3.4 Step 4: Capital Construction

Capital construction costs include installation of bioremediation system components such as injection wells, mixing and delivery systems (e.g., pumps, meters, and piping), and monitoring well networks.

3.4.1 Construction of Soluble Substrate Systems

Construction of soluble substrate systems includes installation of the mixing and delivery system (including injections wells) and installation of the monitoring system. Actual injection of the substrate for soluble substrate systems is included under operations and maintenance.

- **Substrate Mixing Systems.** Soluble substrate systems typically employ either an automatic mixing and delivery system, or use a batch mixing method. Automatic systems require the use of storage tanks, mixers, programmable logic controllers to control mixing and delivery of the substrate, and distribution lines to each individual injection well. The default cost of an automatic mixing system is set to $25,000 in this cost model. Batch mode mixing is a simpler method where the substrate is mixed in a single portable tank, and the substrate is injected at each individual well directly from the mixing tank. While this system is simpler to build and operate, it may be more labor intensive. The default cost of a batch mode mixing system is set to $5,000 in this cost model. The user may modify these lump sum default costs.

- **Injection and Monitoring Well Installation Costs.** Costs for installation of injection and monitoring wells assumes a unit cost per well. For permanent wells, typical cost associated with hollow-stem augur drilling techniques are used for default values. Subcontractor costs are assumed to include drilling, installation, materials, and surveying. The cost of well installation typically increases with depth. Therefore, the model uses default calculations that include a base cost for fixed items (such as mobilization, well head completions, decontamination, and equipment rental) plus a unit cost per foot of well depth for a footage rate and materials. For wells from 10 to 30 feet in depth, the cost per well is calculated as a base cost of $1,000 plus a cost of $35 per foot of depth. For wells from 30 to 100 feet in depth, the cost per well is calculated as a base cost of $1,200 plus a cost of $40 per foot of depth. For wells greater than 100 feet, the cost per well is calculated as a base cost of $1,500 plus a cost of $50 per foot. The model limits the depth of treatment and monitoring to 200 feet. The user may add any additional costs on the line provided, or may modify the unit cost per well.

- **Capitol Construction Labor.** Labor for permitting and site access, installation of injection and monitoring wells, installation of the mixing and delivery system, and construction management and oversight is proportional to the number of wells installed. Default values for labor hours are 1 labor hour per well for permitting and site access; 6 labor hours per well for installation of injection and monitoring wells; 2 labor hours per injection well for installation of the mixing and delivery system; and 1 labor hour per well for construction management and oversight. The user may modify both the total labor hours per event for each line item, and the labor rate. A line is also provided for the user to add additional labor items.

3.4.2 Construction of Slow-Release Substrate Systems

Construction of slow-release systems includes either the use of direct-push methods for substrate injection, or installation of permanent injections wells (vegetable oil substrates only). Installation of the monitoring system is also included. Different from capitol construction of soluble substrate systems, the initial injection of the substrate for slow-release substrate is included under capitol construction. This is primarily because injection typically occurs only once, or at least infrequently, usually when the system is installed. When using direct-push injection, the substrate is delivered during probing of the injection point.

- **Type of Injection System.** The user has the option to either choose either the use of direct-push techniques for direct injection of a slow-release substrate, or installation of permanent injection wells. Permanent injection wells should only be selected for vegetable oil substrates. The number of injection points/wells is determined in Step 2 - System Design.

- **Installation of Injection Points/Wells and Monitoring Wells.** The default costs for installation of injection points/wells and monitoring wells assumes a unit cost per well. The cost for direct injection points is typically much less than the cost for permanent injection wells (installed by direct push or hollow stem auger), although direct-injection may not be feasible for some site conditions. The default unit cost for direct injection points is $500 per point. For permanent injection wells and monitoring wells, unit default costs are calculated the same as described above for installation of wells in soluble substrate systems.

- **Substrate Mixing Systems.** Mixing and delivery systems for slow-release systems are relatively simple compared to soluble substrate systems, and may often be rented from the product vendor. The default cost of a delivery systems is $3,000.

- **Capitol Construction Labor.** Labor hours for permitting and site access (e.g., mobilization, utility clearances, surveying), direct-push point installation or installation of permanent injection wells, substrate injection, monitoring well installation, and construction management and oversight are proportional to the number of injection wells/points and monitoring wells installed. Default values for labor hours are 1 labor hour per well for permitting and site access; 3 labor hours per point for installation of direct injection points or 6 labor hours per well for installation of permanent injection wells; 3 labor hours per injection well/point for injection of the substrate; 6 labor hours per well for installation of monitoring wells; and 1 labor hour per injection/monitoring well for construction management and oversight. The user may modify both the total labor hours per event for each line item, and the labor rate. A line is also provided for the user to add additional labor items.

3.5 Step 5: Operations and Maintenance

System operating costs include maintenance of frequently used injection systems or conducting repeated applications of substrate. Operating costs may include an evaluation of the effectiveness of the substrate delivery system, but performance monitoring costs are calculated separately in Step 7. System operating costs will be greatest for continuous recirculation systems or systems requiring frequent injection. Process monitoring (e.g., field measurements of dissolved oxygen [DO] and pH, and analyses for total organic carbon [TOC]) for systems using frequent substrate addition is used to optimize the rate of substrate loading to obtain more efficient anaerobic dechlorination of contaminant mass. For systems with slow-release substrates, operating cost are negligible unless additional substrate injection is required during the system design life.

3.5.1 Operations and Maintenance of Soluble Substrate Systems

Because soluble substrates require frequent injection, operations and maintenance costs are relatively labor intensive compared to slow-release substrate systems.

- **Frequency of Injection and Number of Injection Events.** The model calculates a default value for the frequency of injection based on the rate of groundwater seepage velocity (Step 2). The higher the rate of groundwater flow, the more frequently soluble substrates must be injected to maintain the reaction zone. If the seepage velocity is less than or equal to 0.1 feet per day (ft/day), then the default frequency is set to every 12 weeks (quarterly). If the seepage velocity is greater than 0.1 ft/day but less than 1.0 ft/day, then the default frequency is set to every 4 weeks (monthly). If the seepage velocity is greater than or equal to 1.0 ft/day, then the default frequency is set to every 1 week (weekly). The user may input an alternative injection frequency. The number of injection events is then calculated by dividing the system design life by the injection frequency.

- **Subcontractors and ODCs per Event.** The costs of materials and supplies for operations and maintenance is proportional to the number of injection wells. Default values are set to $50 per injection well for materials and supplies (excluding substrate). Analytical services for system monitoring (e.g., field measurements of DO and pH, and analyses for TOC) is assumed to be $500 per event. The user may modify these default values, and a line is provided for adding additional cost items.

- **Operations and Maintenance Labor.** Labor hours per event for mobilization/maintenance, system monitoring, and injection of substrate are assumed to be proportional to the number of injection wells installed. Default values for labor hours are 0.5 labor hour per well for mobilization/maintenance, 0.5 labor hour per well for system monitoring, and 2 labor hours per well for injection of substrate. The user may modify both the total labor hours per event for each line item, and the labor rate. A line is also provided for the user to add additional labor items.

Total operations and maintenance costs are summed by multiplying the cost per event times the number of injection events.

3.5.2 Operations and Maintenance of Slow-Release Substrate Systems

Operations and maintenance of slow-release substrate systems are typically much less than required for soluble substrate systems. Slow-release substrate will be depleted over time, with typical life-spans of 1 to 3 years. For a design life greater than 2 years, additional injections may be necessary.

- **Frequency of Injection.** The model uses a default value for injection of slow-release substrate of 2 years. The user may input an alternative injection frequency. The number of injection events is then calculated by dividing the system design life by the injection frequency. Note that the initial injection is included in the cost of capitol construction (Step 4). Only subsequent injections are included in the cost of operations and maintenance.

- **Subcontractors and ODCs per Event.** The costs of operations and maintenance is proportional to the number of injection points/wells. Default values are $50 per injection well/point for materials (excluding substrate), $500 per event for system monitoring analytical services (e.g., field measurements of DO and pH, and analyses for TOC), and $500 per point for a direct-push subcontractor (if used). The user may modify these default values, and a line is provided for adding additional cost items.

- **Operations and Maintenance Labor.** Labor hours per event for mobilization/maintenance, system monitoring, and injection of substrate are assumed to be proportional to the number of injection wells/points installed. Default values for labor hours are 0.5 labor hour per well/point for mobilization/maintenance, 0.5 labor hour per well/point for system monitoring, and 2 labor hours per well/point for injection of substrate. The user may modify both the total labor hours per event for each line item, and the labor rate. A line is also provided for the user to add additional labor items.

Total operations and maintenance costs are summed by multiplying the cost per event times the number of injection events.

3.6 Step 6: Substrate Cost

This cost estimating tool lists only the most common substrates used for enhanced bioremediation. Soluble substrates included are lactate, molasses, high fructose corn syrup, and ethanol. Slow release substrates include are Hydrogen Release Compound (HRC®), vegetable oil (bulk cost), and commercial vegetable oil emulsions. ***Inclusion of these substrates in this cost model does not constitute endorsement of any proprietary product or technology.*** The addition of nutrient amendments or application of bioaugmentation will increase the cost, but are not included in the cost estimating model.

Estimates and calculations of substrate requirements for the different substrate types is currently a subject of some debate. Users of soluble substrates typically use an empirically-based approach because they are able to modify the substrate loading rate on a more frequent basis until the desired geochemical conditions are achieved. Conversely, users of slow-release substrates typically rely on calculated substrate requirements because the product is commonly applied in a single injection event. Therefore, there is no uniform method for estimating substrate requirements among practitioners of the various substrate types. Furthermore, the use of safety or design factors that may range from 2 to 10 times the calculated substrate demand indicates that the degree of uncertainty in these methods is considerable. The user is referred to Appendix C of the *Principles and Practices Manual* (AFCEE et al., 2004) for further discussion.

An empirical approach is used for determining default substrate requirements in the cost model. Substrate costs are based on a specific quantity of substrate that could achieve an average substrate target concentration in the treatment zone over the design life of the application. The model calculates the total quantity of substrate that must be added to both the initial pore volume of the treatment zone plus the groundwater flux into the treatment zone (i.e., accounts for the rate of groundwater flow) over the design life to achieve the default concentration. The model makes no assumptions as to the mixing or concentration of the substrate product that is actually injected. Substrates are typically injected in a concentrated form, and mixing with groundwater is achieved by advection, dispersion, and diffusion.

The model default concentrations for the soluble substrates lactate, molasses, and fructose are 300 milligrams per liter (mg/L) of active ingredient, and 200 mg/L active ingredient for ethanol. For the slow release substrates HRC®, vegetable oil, and vegetable oil emulsion the default concentration is 400 mg/L of active ingredient. The user may modify the effective substrate concentration at their discretion. As mentioned, the amount of substrate required to maintain these concentrations is calculated based on the pore volume of the treatment zone and the groundwater flux through the treatment zone over the design life.

Alternately, the model estimates a molecular hydrogen demand (electron acceptor demand) and a corresponding substrate demand based upon the contaminant, hydrogeological, and geochemical data provided in the model input pages. ***The model calculates a site-specific substrate demand only for comparison to the empirical default values.*** The model uses example calculations presented in Appendix C of the *Principles and Practices Manual* (AFCEE et al., 2004). A safety factor of 2 is applied for soluble substrates, a safety factor of 3 is applied for HRC®, and a safety factor of 5 is applied for vegetable oil substrates. The slow-release substrate safety factors were selected based on comparison of model calculations to commercial calculation spreadsheets. ***These calculations are not intended for design purposes***, only to provide substrate costs for comparison purposes.

Substrate loading rates based on site-specific hydrogen demand are presented as an optional substrate “Demand”, listed next to the default value. The user is encouraged to compare this demand rate to the default rate. The user may input a user specified substrate loading rate, if desired.

The unit cost per substrate is based on published costs and vendor quotes. A range of costs is provided, and the user may enter a modified substrate unit cost at their discretion. In general, the greater the volume of substrate required, the lower the unit cost will be based on bulk purchasing and handling.

3.7 Step 7: Performance Monitoring

All bioremediation systems require performance monitoring to validate the effectiveness of the treatment in meeting remedial objectives. Performance monitoring typically involves collecting groundwater samples for field and laboratory analysis on a periodic basis over the design life of the application.

Performance monitoring protocols are similar for most systems, and typically require monitoring of a minimum of 6 to 10 monitoring wells for remediation of small plumes, and of up to 20 monitoring wells for larger applications. Performance monitoring costs are proportional to the number of monitoring wells used (established in Step 2). Performance monitoring costs are broken down into subcontractors, ODCs, and labor per event.

- **Subcontractors and ODCs per Event.** Subcontractor and ODC costs per event are broken down into laboratory analytical costs, measurement of field parameters, field meters (typically rented), and sampling supplies and shipping. A default value of $400 per sample for laboratory analyses is assumed, which includes typical costs for measurement of volatile organic compounds (VOCs), dissolved gases (methane, ethane, and ethene), TOC, volatile fatty acids (VFAs), nitrate + nitrite (as nitrogen), and sulfate. A default value of $100 per sample for field parameters is assumed, which typically includes DO, oxidation-reduction potential (ORP), specific conductivity, pH, ferrous iron, manganese, and hydrogen sulfide. This list of analytes is considered relatively extensive. Specialty analyses such as dissolved hydrogen, phospholipid fatty acids, or molecular screening analyses (e.g., for identification of *Dehalococcoides* species) are not included. The user may modify the default unit costs for performance monitoring subcontractor and ODCs, and a line is provided for the user to input additional costs for items such as the specialty analyses listed above. Finally, the model assumes that quality assurance/quality control samples are collected and analyzed at a rate of 10 percent of the number of monitoring samples.

- **Labor per Event.** Performance monitoring labor cost include mobilization/ demobilization to the field, groundwater sampling, and data management. Labor hours are assumed to be proportional to the number of well locations monitored. Default labor hours are 2 labor hours mobilization/demobilization per well, 5 labor hours sampling per well, and 2 labor hours data management per well. The model also assumes a labor rate of $75 per hour (direct labor plus overhead). The user may modify both the total labor hours for each line item per event, and the labor rate.

- **Number of Performance Monitoring Events.** The number of monitoring events is equal to the design life divided by the monitoring frequency, plus one event for baseline characterization (baseline characterization is not included in Step 4 - Capitol Construction or Step 5 - Operations and Maintenance). System design life is input in Step 2 – Model Input System Design. The default for monitoring frequency in the cost model is set to every 6 months (semi-annually), but performance monitoring may vary from as often as monthly to annually. Therefore, the user may input an alternative frequency for performance monitoring.

Total performance monitoring costs are summed as the cost per event times the number of monitoring events, and is reported on the Model Summary Report (Step 10).

3.8 Step 8: Reporting Cost

Performance reporting is required to address progress of the bioremediation system towards meeting regulatory compliance standards. Interim reports are typically required on a quarterly to annual basis, while final reports are generally required to gain regulatory approval for terminating system operation. Reporting costs are proportional to the size of the enhanced bioremediation system and the frequency and longevity of system monitoring. A practical range for reporting for DoD sites is from $10,000 (minimum) for small-scale, short duration pilot-scale tests to $100,000 (maximum) for large systems monitored over several years.

This cost estimating tool uses a default value for reporting of 10 percent of the overall system cost for 1) capitol construction, 2) operations and maintenance, 3) substrate, and 4) performance monitoring. The cost of these field application items are representative of the scale and complexity of the application, for which reporting costs can be assumed to be proportional. Reporting costs are further assumed to be 95 percent labor and 5 percent ODCs. The user may input an alternative percentage for reporting to modify the reporting cost, if desired.

3.9 Step 9: Project Management, Markups, Fees, and Contingency

Step 9 provides for project management costs, and allows the user to add costs for markups, fees, and contingency. Many Government contracts for environmental services include markups for subcontractor and ODC costs, and fixed fees (profit) on labor. This cost estimating tool allows the user to factor in these costs.

The model assumes that project management costs are 10 percent of project costs, excluding markups, fees, and contingency. The model assumes a 5 percent markup for subcontractor and ODC costs, and a 5 percent fixed fee is assumed for profit on estimated labor costs. The model default does not include a percentage for contingency, but the user may elect to add up to a 10 percent contingency for unanticipated costs. The user may modify the percentages used to calculate these costs at their discretion.

3.10 Step 10: Model Summary Report

3.10.1 Summary Report Output

Results of the cost estimating tool are automatically updated each time an input parameter is changed, and they are presented in the Model Summary Report in Step 10. An example summary report is shown on Figures 3A and 3B.

FIGURE 3A
EXAMPLE OF MODEL SUMMARY REPORT

Cost Estimate for Enhanced Anaerobic Bioremediation of Chlorinated Solvents

Model Summary Report

Project Name	**Example Case Study**
Project Location	**Anywhere, USA**
Proposed Remedial Configuration	**Source Area Or Grid**
Design Life (years)	**4**
	The Model reflects March 2005 Costs

Task		Category (Subtask)	Cost Type	Percent	No. Events	Amount
1		**System Design**		10.0%		
	A	System Design and Work Plan Preparation	labor	9.5%	1	$35,179
	B	Work Plan Production	ODCs	0.5%	1	$1,852
					Subtotal:	**$37,030**
SOLUBLE SUBSTRATES						
2A		**Capital Construction Soluble Substrate Systems**				
	A	Permitting and Construction Management	labor		1	$3,000
	B	System Installation	labor		1	$10,500
	C	Injection and Monitoring Well Construction	subcontractor		1	$37,500
	D	Delivery System	ODCs		1	$27,000
					Subtotal:	**$78,000**
3A		**Operations and Maintenance Soluble Substrate Systems**				
	A	Mobilization/Maintenance/Monitoring/Injection	labor		Varies	$117,000
	B	Analytical Cost	subcontractor		Varies	$26,000
	C	Materials and Equipment (excludes substrate)	ODCs		Varies	$26,000
					Subtotal:	**$169,000**
SLOW RELEASE SUBSTRATES						
2B		**Capital Construction Slow-Release Substrate Systems**				
	A	Permitting and Construction Management	labor		1	$0
	B	System Installation and Injection	labor		1	$0
	C	Injection and Monitoring Well Construction	subcontractor		1	$0
	D	Delivery System	ODCs		1	$0
					Subtotal:	**$0**
3B		**Operations and Maintenance Slow-Release Substrate Systems**				
	A	Materials and Equipment	ODCs		Varies	$0
	B	Subcontractor	subcontractor		Varies	$0
	C	Labor	labor		Varies	$0
					Subtotal:	**$0**
4		**Substrate Cost**				
	A	Life-Cycle Substrate Cost	ODCs		Lump Sum	$0
					Subtotal:	**$0**
5		**Process Monitoring**				
	A	Analytical Cost	subcontractor		9	$39,600
	B	Materials and Equipment	ODCs		9	$29,700
	C	Mobilization, Sampling, Data Management	labor		9	$54,000
					Subtotal:	**$123,300**
6		**Reporting**		10.0%		
	A	System Evaluation	labor	9.5%	1	$35,179
	B	Report Production	ODCs	0.5%	1	$1,852
					Subtotal:	**$37,030**
7		**Project Management/Markups/Fees/Contingency**				
	A	Project Management		10.0%	lump sum	$44,436
	B	Subcontractors and ODCs Markup		5.0%	lump sum	$9,475
	C	Labor Profit (Fixed Fee)		5.0%	lump sum	$12,743
	D	Contingency (percent of total costs less markups and fees)		0.0%	lump sum	$0
					Subtotal:	**$66,654**
					Total Project Cost:	**$511,014**
					Present Net Worth:	**$460,366**
					Discount Rate (1-10%):	**5.0%**

FIGURE 3B
EXAMPLE OF MODEL SUMMARY REPORT

Cost Estimate for Enhanced Anaerobic Bioremediation of Chlorinated Solvents

Model Summary Report - Cash Flow

Project Name	**Example Case Study**
Project Location	**Anywhere, USA**
Proposed Remedial Configuration	**Source Area Or Grid**
Design Life (years)	**4**

The Model reflects March 2005 Costs

Total Project Cost:	**$511,014**
Present Net Worth:	**$460,366**
Discount Rate:	**5.0%**

CASH FLOW BY YEAR

Year	Amount per Year	Cumulative
1	$221,644	$221,644
2	$89,359	$311,003
3	$89,359	$400,362
4	$110,652	$511,014
5	$0	$0
6	$0	$0
7	$0	$0
8	$0	$0
9	$0	$0
10	$0	$0
11	$0	$0
12	$0	$0
13	$0	$0
14	$0	$0
15	$0	$0
16	$0	$0
17	$0	$0
18	$0	$0
19	$0	$0
20	$0	$0
21	$0	$0
22	$0	$0
23	$0	$0
24	$0	$0
25	$0	$0
26	$0	$0
27	$0	$0
28	$0	$0
29	$0	$0
30	$0	$0

The summary report lists the cost for each of the cost model steps. Costs for each step are further broken down into subcontractor, ODC, and labor costs. This is largely to facilitate calculation of the markups and fees in Step 9, but also provides the user insight into whether different systems are relatively labor intensive, or equipment and materials intensive.

Breaking down the cost estimates of enhanced bioremediation systems into the different steps provides the user insight into how selection of different substrate types or system designs will impact overall costs for capitol construction, operations and monitoring, and substrate. Costs for system design, performance monitoring, and reporting are for the large part independent of the substrate type selected, and more dependent on the scale of the system.

3.10.2 Total Cost and Present Net Worth

Costs for each model step are estimated at current dollar value (as of March 2005). However, enhanced bioremediation systems may operate over periods of many years. The cost for operations and maintenance, for substrate, and for performance monitoring increases significantly as the design life of the system increases. Costs for initial design and capitol construction are relatively independent of the system life-cycle duration. To evaluate costs over time, the program provides a year by year cash flow value and a value for present net worth.

The following assumptions are used for calculating annual cash flow over the application design life:

- **System design** costs are assumed to be expended in Year 1.
- **Capital construction** costs are assumed to be expended in Year 1.
- **Operations and maintenance** costs are assumed to be expended equally for each year of the design life (i.e., each years cost equals the total operations and maintenance cost divided by the design life in years).
- **Substrate** costs are assumed to be expended equally for each year of the design life.
- **Performance monitoring** costs are assumed to be expended equally for each year of the design life.
- **Reporting** costs are assumed to be 50 percent expended in the final year of the design life, and 50 percent is assumed to be expended equally for all other years of the design life.
- **Project Management, Markups, Fees, and Contingencies.** Project management costs are assumed to be proportional to the annual combined cost for the above items. Markups, fees, and contingency costs are calculated for each individual year based on the annual costs calculated as described above.

Annual expenditures are then used to calculate present worth costs. The utility of using present worth cost, and guidance for estimating total present worth cost, can be found in USEPA (1994). Present worth cost uses a discount rate to determine what the future cost of the bioremediation application would be in today's dollars. The discount rate is the difference between the rate of inflation and the cost of money (i.e., investment potential). An annual adjustment (discount) factor of 5 percent is assumed in present-worth calculations, but the user may modify the discount rate (from 1 to 10 percent) on the model summary report page.

4.0 COST ESTIMATING MODEL HELP

Selecting the **<u>HELP</u>** button on any given page will direct the user to this users manual. References are provided in Section 5 for insight into how enhanced anaerobic bioremediation is practiced. There are many enhanced bioremediation methods that may not be represented in this model; the intent is to provide a comparison between the most common application techniques.

5.0 REFERENCES

Air Force Center for Environmental Excellence (AFCEE), Naval Facilities Engineering Service Center (NFESC), and the Environmental Security Technology Certification Program (ESTCP). 2004. *Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents*. Prepared by Parsons Infrastructure & Technology Group, Inc., Denver, Colorado. August.

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