

A STANDARD METHODOLOGY FOR COST EFFECTIVENESS ANALYSIS OF NEW
ENVIRONMENTAL TECHNOLOGIES

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ABSTRACT

This paper outlines a methodology that is being applied to assess the cost-effectiveness of new environmental technologies under development by the Office of Technology Development, Office of Environmental Management in the U.S. Department of Energy. Performance, total system effects, life-cycle costs, uncertainty, and environmental risk are all considered in the methodology to compare new technologies with existing or base-line technologies. An example of performance characterization is given in the paper. Sources of data for cost estimates and technology characterizations also appear in the paper.

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I. INTRODUCTION

The Department of Energy is facing a massive clean-up effort of waste sites that contain hazardous, radioactive, or mixed (i.e., hazardous *and* radioactive) materials. DOE has recognized that improvements in environmental restoration (ER) and waste management (WM) methods can potentially save the taxpayers billions of dollars as older, less effective technologies are displaced. Consequently, DOE has targeted significant funding to search for new technologies and to test and demonstrate them in a rapid and cost effective manner with the goal of applying them quickly to address environmental problems.

Los Alamos has been tasked by the Office of Technology Development (OTD) to develop a standardized methodology for cost effectiveness analysis of OTD-funded technologies. A simplified version of the methodology can be used by managers to screen technologies and the full version will be used throughout OTD-sponsored projects to perform cost-effectiveness analysis. Standardization will provide quality assurance for future OTD technology evaluations and furthermore helps ensure that an adequate and consistent level of cost information is reported during the demonstration of OTD technologies.

This report describes the methodology. We begin by describing our general approach to comparing new versus base-line technologies, then proceed to a step-by-step elucidation of process of cost effectiveness analysis. A forthcoming report to be issued as a guidebook will describe the methodology in more detail.

There exist many levels of technology evaluation where decisions are made for the allocation of limited research and development funds. The evaluation objective is to select for development or adaptation those technologies that are most likely to be significantly "better, safer, faster, and cheaper," the adjectives that summarize the goals of OTD. Technology cost is an important factor in these evaluations, both the cost for development and the expected cost of actually using the technology in the field, that is, the implementation cost. At the early stages of development, accurate costs are unknown. Only when the technology is actually demonstrated in the field do costs become clearer. Even then, the implementation costs of the final, commercialized technology may be significantly lower than the demonstration costs. Uncertainty of performance, cost, regulatory approval, and schedule also plays a major role in technology evaluation. Clearly, the evaluation process of new technologies is not trivial.

Several different types of screening and cost analysis that can occur during a technology's development. The first is decision analysis (e.g., scoring), which is recommended for use in early stages of technology selection and analysis. The scoring method is based on roughly estimated performance, cost, safety, and other factors. Usually a panel of technical experts are convened to screen various technologies using a list of weighted criteria that are applied in a reasonably consistent fashion. A second tool that can assist with technology selection that is often useful in later stages of development is linear programming, where the objective function (for example, complete the remedial action at minimum cost) is accomplished subject to various constraints. The constraints are usually related to performance and cost functions. A variation of linear programming is goal programming, in which more than one objective function must be satisfied.

At later stages of technology development, the more rigorous cost effectiveness analysis is undertaken. This entails comparing the relative performance and cost of two or more competing technologies to determine a life-cycle cost per unit of treated soil, or cost per unit of waste treated, etc. Only the costs (both social and private) of applying alternatives are included. This differs from benefit-cost analysis in which one attempts to quantify both the costs and benefits of alternatives. Portney and Krupnick (1989) analyzed information needs for assessing Superfund remediation efforts and recommended cost-effectiveness analysis as a satisfactory means of comparing remediation alternatives while avoiding the difficulties inherent in measuring the benefits of, e.g., a clean cubic meter of soil.

In our case, we compare a new technology with conventional or "base-line" technologies under various performance scenarios. The result of this analysis is an estimate of the cost difference of completing the remediation task with the new versus the base-line technology at a single, representative site. If an estimate is available of the number of sites where the new technology could be used, the total cost savings to DOE associated with the use of the new technology could be estimated. This total cost savings estimate can be compared to the technology's research, development, demonstration, testing, and evaluation cost to evaluate some of the benefits of DOE's investment in developing or adapting environmental technologies.

II. GENERAL APPROACH

The purpose of cost effectiveness analysis is an accurate comparison of the performance and cost of different technologies on an even basis. Of course, the fundamental challenge of the analysis is finding an appropriate way to compare technologies that upon initial examination often appear to be incomparable (colloquially known as "apples and oranges"). For example, the direct comparison of in situ air stripping with traditional pump and treat for removal of VOCs is inaccurate because the former technology strips VOCs not only from the groundwater but also from the vadose zone. In the case of in situ vitrification versus an excavation, treatment, and disposal alternative, the location of the disposal can cause the two alternatives to be incomparable. For example, if the waste is disposed at a different site, the original remediation site may become available for public use, which is clearly not the intent with in situ vitrification. Most ER technologies approach their task in different ways, which makes the job of the evaluator more difficult.

Our principal goal is to identify a level playing field with which to compare the technologies. This implies that all aspects of performance and cost of the technologies must be understood. Commercial firms that use the base-line technology and the new technology developers are important sources in arriving at this understanding. Discussions should occur between the evaluator and the above parties to develop scenarios for comparison where both technologies reach similar performance levels. For example, in situ air stripping removes VOCs from the vadose as well as the saturated zone. Therefore, one would construct a baseline

scenario that combines a pump and treat system (for groundwater treatment) and a vapor extraction system (for treatment of the vadose zone).²

In addition to performance, comparability in cost must also be defined. The technologies should be of similar scale and development. For example, it is preferable to estimate the decreases in costs that will occur when a new technology is commercialized and compare these costs to existing baseline technologies. Because of its experimental nature, the costs of a demonstration-stage technology are usually higher than when the technology is commercialized. Also, all system and life-cycle impacts of using one technology instead of the other must be costed and included. For example, in the case of in situ air stripping, it may be necessary to include additional monitoring wells relative to those required for pump and treat in order to identify the zone of influence of the injection and extraction wells to estimate the amount of groundwater being cleaned.

In order to capture all the issues related to performance, we adopt a "descriptive approach". In this approach we describe the new environmental technology in a detailed manner, so as to identify as many aspects of its performance as possible that may have a significant impact on the cost effectiveness of its future application on a broad scale. By virtue of a technology being "new," there are not extensive data available on its application and use. Scenarios are constructed showing reasonable possible future applications; the description of the technology performance provides the additional means for predicting how the technology might perform at many different sites.

The descriptive approach is also valuable because the new environmental technologies under evaluation are undoubtedly still evolving. By clearly identifying what they do now and discussing possible future developments, we can provide the reader with a foundation of information about the technology that will be of use for as long as possible. Therefore, our analysis is not simply a cost comparison, but actually reveals the strengths and limitations of the new technology within the remediation or waste management system. The intent of the cost effectiveness analysis is to be useful for managers of integrated demonstrations, OTD headquarters, DOE environmental restoration sites, and other public and private enterprises that may wish to adopt the technology.

Performance and cost data are gathered from multiple sources, including case-studies, commercial vendors, integrated demonstrations, etc. If cost data are not available on the new technology, conceptual cost estimating is used based on the technology developer's design. Sources of cost data and estimating methods are described further in a later section of this report.

²However, if regulatory requirements do not mandate treatment of the vadose zone, one would consider removal of VOCs from the vadose zone as a positive side-effect, or "externality" of in situ air stripping. In this case the baseline would be pump and treat only, but the analyst would be advised to value the benefits of vadose zone remediation as part of the cost savings from in situ air stripping. In the long-term, remediation of the vadose zone will prevent further contamination of groundwater by migration of pollutants from the vadose zone to the saturated zone.

Uncertainty in performance is captured through use of parameters in the scenarios that cover the range of possible performance. In this manner, estimates for different site geologies, wastes, etc. can be developed. Also, the break-even point at which the use of the new technology becomes cost-effective can be shown.

III. STEPS IN COST EFFECTIVENESS ANALYSIS

Cost effectiveness analysis is best accomplished in a step-by-step manner, with an emphasis in understanding the whole picture before emphasis is given to the details of cost analysis. Figure 1 presents the principal steps in schematic form and begins with the definition of the base-line and OTD technologies, i.e., the technologies to be compared. The remediation system in which these technologies operate is then described. This is a critical step because the technologies may impact the system in different ways, and the cost changes must be included in the analysis.

The next step in Figure 1 is to develop life-cycle cost estimates of the alternative technologies. These are the cradle-to-grave costs including the research, development, demonstration, testing, and evaluation costs (RDDT&E) plus the full-scale application costs for implementing the technologies in a typical system. The performance of the technologies is next described in detail, with an emphasis on how the costs of operation are affected by performance. Given the uncertain nature of the performance of many of the new technologies, we use scenarios based on varying values of parameters. This way, a range of performance can be estimated, and one can identify a break-even point at which the new technology becomes cheaper than the base-line technology.

With the cost data and performance scenarios in hand, the cost effectiveness analysis step can be completed. Appropriate discount rates are applied to the costs that occur over time, escalation factors may be applied, and the difference in system costs for the new technology case versus that of the base-line is computed. This cost effectiveness result will state what the savings would be under specific scenario conditions of using the new technology instead of the base-line at a single site. To compute the total cost savings of the new technology, one must have an estimate of the sites at which the new technology is applicable. It is preferable to estimate cost differences for applying the new technology in different environments. Then the total savings are roughly estimated by multiplying the number of sites by the cost savings per site. We now describe in detail each cost effectiveness step.

A. Definition of Technologies

The first step in the cost effectiveness process is to identify and define the technologies to be compared. The new technologies are funded by the Divisions of Research and Development and Demonstration, Testing, and Evaluation (which are generally combined as RDDT&E) and are generally chosen for cost effectiveness analysis by OTD managers and/or the integrated demonstration coordinator (IDC). The criteria for selection include: the technology is far enough along in the development process that accurate performance and cost data are available, for example, the Corps of Engineers' SCAPS; it is a high-visibility technology, such as in situ air

stripping; or the technology has reached a critical decision point, such as in situ vitrification which is almost ready for transfer out of OTD to ER.

Choosing the base-line technologies for comparison can be difficult because the RDDT&E technology may overlap with several of them. For example, the SCAPS technology analyzes the geology of a site (which might be compared with a cored hole), takes soil and water samples (to be compared with the split-spoon or Hydropunch), and measures resistivity (to compare with standard geophysical logs). In addition, the new technology may gather novel information that no base-line technology can duplicate. Finally, because the new technology is still in the development process, it may replace additional base-line technologies in the future. The analyst must work closely with the technology developers to identify the base-line technologies to be used. Also, the integrated demonstration technologists are useful contacts.

After the technologies are chosen, a full description is made for each, including the operational process, a review of documentation and case-studies of performance, and benefits and limitations in general terms. This is critical to making the evaluation report useful. The reader must understand the full context of how the technologies compare in general terms before cost specifics are described, and exactly where the new technology fits into the broad scheme of environmental technologies (i.e., what is the niche it fills?).

B. Definition of System

During this step, a study is made of how the technologies fit into the whole remediation effort or "system." For example, does the RDDT&E technology operate in the site characterization or remediation component? Cost effectiveness analysis is designed to capture the cost differences among the technologies. Consequently we examine the system-wide impacts of substituting the new technology for the base-line. If an activity in the system remains the same under each case, it is not included in the cost effectiveness calculation. For each of the following categories, analysis is made as to whether the technology substitution will have a cost impact. The detailed cost analysis will focus on those aspects that are different.

1 Site Preparation and Characterization

Substituting a new technology for a base-line technology in the remediation effort may require a change in the amount of site characterization that is needed before remediation gets underway. For example, in the case of in situ bioremediation, a careful assessment must be made of the micro-organisms present in the soils. Then an appropriate means of stimulating them must be identified. Also, the preparation of the site for the remediation may change depending on the technology to be used.

2 Ancillary equipment and process rates

Using the new technology may cause adjustments to be made in ancillary equipment such as the off-gas treatment system. For example, the in situ air stripping operation may pull significantly more amounts of VOCs from the saturated and unsaturated zones than the base-line technologies will. Of course, this depends on the performance scenario, which may be designed to have an equal VOC-removal rate for the two systems. Any additional equipment required or equipment of different capacity must be counted in the cost effectiveness

analysis. In addition, the maintenance schedule for equipment may become more (or less) intense when a new technology is substituted.

3 Monitoring and Post-remediation requirements

Monitoring costs can be a critical cost factor in cost effectiveness analysis. This is because monitoring occurs over a long time horizon, often decades, depending on local regulations. Installation of monitoring wells is expensive and the actual sampling process is labor-intensive and can add a significant costs, especially in remote areas. Laboratory expenses for sample analyses have been rising rapidly in past years, and with the current shortage of approved labs, this cost can only be expected to increase in importance.

Overall, careful attention must be paid to how the new technology will impact the required monitoring wells. The bioremediation technologies especially may require additional monitoring to keep track of the bacterial migration. In situ technologies also may need more monitoring to prove that remediation has occurred. For example, the in situ air stripping operation strips VOCs from both the vadose zone and the groundwater. The regulators may require that more groundwater monitoring wells be installed to prove that the groundwater is actually being cleaned. The base-line pump and treat system is very easy to monitor because one can measure the number of gallons per minute that are being cleaned by the tower air stripper.

4 ES&H requirements

This is a broad category that nevertheless can add significantly to the costs differences among technologies. The level of exposure of the remediation workers and the local population may be different in the substitute technologies; these differences must be costed and included in the cost effectiveness calculation. For example, in situ vitrification of a buried waste pit may preclude the use of tents and wind barriers required under an excavation,-treatment-and-disposal base-line. Whether or not the waste is radioactive will have profound effects on this category of costs.

5 Regulatory permit requirements and liability costs

This is a very difficult category to estimate accurately, given the present changeable environmental regulatory climate. Since most of the new technologies are not yet fully operational , and therefore are not accepted as completely viable by the regulatory agencies and the public, one would expect significantly higher expenses for obtaining permits for them. At the minimum, costs associated with additional public awareness meetings and regulatory paperwork should be considered in the cost comparison. It is probable that costs to obtain regulatory permits will change as experience with the relevant regulatory agencies increases. In addition, there is always the risk of encountering a "show-stopper" in this category, that would eliminate the new technology from being used at a particular site. Also, one must consider possible future liabilities that might result from changes in regulations.

6 Administrative requirements

Differences in the administrative burden associated with the technologies should be studied as well. The multiplicity of firms and contractors that are needed may be different between the technologies, especially if one technology is characterized by numerous complicated steps. For example, excavation, treatment, and

disposal may be administratively much more expensive than in situ vitrification because of the many additional steps and contractors required before the waste has been fully immobilized.

7 Residuals Treatment

Using a new technology may create different residual materials from the operations than the base-line technology. The proper disposal of hazardous, mixed, or radioactive wastes must be examined for both technologies to determine if any significant differences are present. Any cost differences in treatment, handling, transport, storage, and disposal must be included in the cost effectiveness analysis.

C. Characterize Performance

In this step the analyst attempts to gain a full understanding of the performance of the alternative technologies. Technology evaluation reports, demonstration results, and case studies are good sources for this information, as are the technology developers and users for the base-line technologies. The relative limitations and strengths of the alternatives must be described, and perhaps summarized in a table for ease of presentation. As an example of the process of completing this step of cost effectiveness analysis, we have inserted some relevant passages from the draft report of the cost effectiveness analysis of the Site Characterization and Analysis Penetrometer System (SCAPS) (Schroeder, et al., 1991).

SCAPS is an innovative environmental technology for characterizing soil types and detecting and delimiting the presence of contaminants in the subsurface. SCAPS is being developed by the U.S. Army Corps of Engineers at the Waterways Experiment Station (WES) in Vicksburg, Mississippi. Scientists at WES are leading a research and development effort to develop SCAPS for use in mapping areas of soil and groundwater contamination.

A cone penetrometer is a device for hydraulically pushing a small diameter (approximately 1.4 inch) instrumented cone tip and steel rods into the earth. The cone tip has sensors for measuring point penetration resistance and sleeve resistance. An empirical relationship between these physical strength measurements and soil type is used to derive soil classification for the layers through which the cone penetrometer has been pushed. Other sensors can also be present on the cone penetrometer, for example, a formation resistivity sensor.

In every site characterization investigation, the goal is to obtain information about both the natural subsurface environment and any non-indigenous contaminants that may now be present. The common and accepted approach to acquiring this subsurface information is to drill cored holes and install monitoring wells

Since the SCAPS cone penetrometer has been developed as a tool for initial site characterization, and since it acquires similar data on soil stratigraphy, and physical soil and water samples, it is natural to compare the cone penetrometer system to monitoring wells. Because of these similarities in purpose and collected data, we choose monitoring wells (with

continuous cores and sampling done during the drilling process) as the "baseline" technology for comparison with the SCAPS cone penetrometer.

Note, however, that we do not suggest that a cone penetrometer push and a monitoring well acquire the same information. Rather, we follow the intent of the SCAPS developers in considering the cone penetrometer as a complement to conventional drilling and sampling methods (Cooper, et al., 1991).

The strengths and limitations of both the SCAPS cone penetrometer system and monitoring wells are summarized in Table 1. Criteria such as geologic setting, drilling artifacts, crew exposure, sensors, and samplers are discussed. Each technology has different strengths, limitations, and intended uses. Table 1 illustrates the wide variety of factors involved in discriminating between the performance of the two different technologies.

Based on the above understanding of the performance of the alternatives, a series of performance scenarios are developed. The scenarios are based on the key performance factors that differentiate the technologies. In the case of SCAPS, the key parameter is the percentage of monitoring wells that can be avoided during a typical site characterization operation if the SCAPS is used. What follows is the explanation of scenario development from Schroeder, et al., (1991).

Representing all detailed factors and performance differences in a scenario is beyond the scope of this report. Instead, we will focus on the *major* differences encountered in using or not using the new technology, SCAPS, in a site characterization.

The following assumptions or approaches are used in the performance scenarios:

- All scenarios are assumed to be located in an area where the geology/soil conditions are amenable to the use of the SCAPS cone penetrometer system. SCAPS is intended for use in clayey or sandy soil; ...

- All scenarios are assumed to be located in an area where a screening sensor exists for the contaminant-of-interest. (This assumption may not be required, depending on the site. Since the cone penetrometer can also take water and soil samples, analysis of these samples may be sufficient in determining advantageous locations for the placement of monitoring wells.)

- The maximum depth considered for scenarios is 150 feet, the approximate depth limit of SCAPS. (Note that the cone penetrometer is still useful in areas where typical monitoring wells are deeper than 150 feet; the cone penetrometer sensors collect valuable information about the vadose zone.)

- A conservative approach is used in constructing the scenarios. While we attempt to be as fair as possible, many uncertainties and gray areas are encountered in constructing a performance scenario. Believing it prudent not to oversell the new technology, any biases are against SCAPS, and in favor of the baseline technology.

• We assume that by using SCAPS in site characterization, fewer monitoring wells are needed and the monitoring wells that *are* put in can be better located and better screened at appropriate depths. This is supported in field studies described in Smolley and Kappmeyer (no date) and Smythe et al. (1988).

This last assumption identifies an interesting and important issue in site characterization practice. In the conventional approach to site characterization (i.e., using monitoring wells only), some percentage of monitoring wells installed in a restoration project are not useful. Reasons why a monitoring well is not useful include:

(1). The monitoring well is so far off the plume it does not provide useful information. (Of course, a well just off the plume is useful because it helps to define the plume edges. Wells far beyond these wells are not useful.)

(2). The monitoring well is screened at the wrong depth. This is very likely during the early site characterization stage when the depth and location of aquifers is not known or well understood. This becomes less likely as the site becomes more well understood during the characterization process.

(3) There are problems in well construction. For example, if a perfect seal is not achieved with the annular packing, water may actually be running along the casing and coming from another zone other than the screened zone.³ The number of monitoring wells at a site deemed to be not useful can be staggering: general estimates were heard of 25% to 65% of monitoring wells not being useful.⁴ In the context of initial site characterization, 50% is probably not a bad number for the percentage of monitoring wells that are not useful.⁵ Thus, our premise is as follows:

In conventional site characterization (using monitoring wells only), some percentage of wells are not useful. This percentage is not known, but is in the range of 25 to 65%. Fifty percent is probably a reasonable figure to consider for initial site characterization. *By using the cone penetrometer system in site characterization, this percentage of "not useful" wells can be avoided.* SCAPS cone penetrometer data can be used to ensure that wells are located advantageously and screened at appropriate depths, and SCAPS fluid samples are taken from known depths.

Since the percentage of conventional wells that can be avoided by use of the cone penetrometer is not known, this percentage is treated as a parameter and is given a range of values in the economic analysis. (Schroeder, et al., 1991)

³"Problems in well construction" is listed here to illustrate a problem that may occur with well development. We assume competent drilling contractors are used.

⁴These estimates were obtained by contacting experienced personnel at Savannah River Laboratory, Los Alamos National Laboratory, and the Environmental Protection Agency. Published failure rates or figures on marginally useful monitoring wells were not found, but it is not surprising that this commonly found inefficiency in site characterization is not advertised in the literature.

⁵Reference: Savannah River Laboratory.

D. Develop Life-Cycle Cost of Alternatives

Life-cycle costing involves calculating the total of all cash flows for the complete time horizon over which the technology will be used. It can be thought of as the "cradle-to-grave" cost, because costs from the initial mobilization stage to the demobilization and long-term control and monitoring are included. Life-cycle costing measures the cost of equipment, materials, labor, and other requirements for all activities related to the technology. Because the technology use generally occurs over time, for example for a ten year VOC remediation effort, the future cash flows must be converted into present values to aid the technology comparison. This involves discounting. We assume all dollar values are in real terms, that is, inflation is assumed to be zero. However, there can still be real escalation rates applied to particular cost factors that are expected to change in cost over time relative to the other costs. For example, laboratory analysis costs may increase in real terms because of additional demand for site characterization analyses dictated by regulatory changes.

The level of detail of the cost estimate is dictated by the scenarios to be used in the cost effectiveness evaluation. For example, for analysis of a site characterization technology, different well depths might be used in the scenarios. Consequently, the cost elements that are depth-dependent must be detailed so they can be varied according to the scenarios. There is no need to estimate costs to a lower level than the scenarios dictate.

It is desirable to estimate the cost in two stages. First, an estimate is made of the RDDT&E cost plus the cost of implementing the technology alternatives ignoring the system-wide cost impacts. For example, this would be the cost of RDDT&E, and fabricating, setting up, operating, and maintaining an in situ air stripping operation. Second, all cost *impacts* throughout the system of using the new instead of the base-line technology are calculated, from site characterization to disposal of residuals. These are the cost differences caused by implementing one technology instead of another. Thus, the total system costs for both alternatives are not being estimated, but only the differences in those costs, as described in the system definition section above. Thus, the cost effectiveness comparison consists of comparing the life-cycle costs for the new technology itself with the cost of implementing the base-line technology, while accounting for the impacts on the system . . .

1 Relationship of Methodology to Other Efforts and Data Sources

Note that the cost estimations to support cost effectiveness analysis for environmental projects are significantly different from the typical cost estimation that occurs in a construction project. Preliminary guidance for cost estimation for DOE environmental restoration projects should be followed where possible to estimate the engineering or financial costs of alternatives (DOE, 1990). The methodology described in this paper builds upon the work of the Los Alamos and University of New Mexico team and others by recommending a means for technology comparison under uncertainty, heavily based on life-cycle performance issues and social as well as private costs.

Cost estimation to support our cost-effectiveness analysis may range from conceptual, "top-down" estimates to detailed, "bottoms-up" estimates. As previously mentioned, performance and cost data are gathered from multiple sources, including published case-studies, commercial vendors, integrated demonstrations, etc. If

cost data are not available on the new technology, conceptual cost estimating is used based on the technology developer's design. The tool recommended for conceptual estimates of environmental restoration projects is the Cost of Remedial Action (CORA) model developed by CH₂M Hill for the Environmental Protection Agency (EPA, 1990). Although CORA does not explicitly cover mixed and radioactive waste, the job factors for highest worker protection can be selected to estimate the extra costs associated with working in this environment. For detailed cost estimates of restoration alternatives, the M-CACES or Composer Gold cost estimating system, originally developed by the U.S. Army Corps of Engineers, is recommended (Building Systems Design, 1990). The large, detailed data base of unit prices used to support this system is being updated by Project, Time, and Cost to include some cost elements and prices for environmental restoration of mixed and radioactive wastes; these data are available in hard copy and will be in electronic form by early 1992 (personal communication, Gene Brooks, August, 1991). With Composer Gold, one can construct the typical engineering, *detailed cost estimate that would include the price and quantity of concrete, light fixtures, hinges, etc.* This level of detail is generally not feasible in cost effectiveness analysis of new or emerging technologies. Still, inclusion of this level of detail where possible allows the reader to see all of the assumptions that went into the cost estimate.

Other possible useful sources of information for technology characterizations and costs are listed below. All of these tools are under development and are not yet available. More information on the following and other sources of data appears in Youngblood, 1991a and 1991b.

- Remedial Technologies Information System (RTIS): a database under development by the Idaho National Engineering Laboratory;
- Remedial Action Assessment System (RAAS) and the Technology Information System (TIS): an expert system to help select remedial technologies (RAAS) and a supporting technology information system (TIS) (See Whelan, et al. (1990) for more information.); and
- HAZRISK: a model being constructed by the Independent Project Analysis Company to evaluate the cost and schedule risk for environmental restoration projects (See Independent Project Analysis, Inc. (1990) for more information.).

The new technology assessments and cost estimates will be provided to RTIS and TIS as they are completed.

The actual cost estimation involves obtaining unit costs and quantities for each of the major cost elements of the technology. There are many ways of dividing costs into categories⁶. For costing environmental technologies, we have defined broad categories as direct and indirect capital and operations costs as follows. These definitions are based on Chapters 14 and 15 of (Humphreys). The cost elements serve as guidelines for estimating the costs of constructing and operating the alternative technologies and also estimating the system-wide cost impacts.

⁶See Humphreys (1991), Part III, for examples.

2 Capital Cost

a. Direct Capital Costs

The direct capital cost of the technology includes "all permanent equipment, materials, labor, and other resources involved in the fabrication, erection, and installation of the permanent facilities." (Humphreys, 1991: 1991: p.365). Major upgrades to equipment or upgrades may also be counted as capital expense.

1 Materials

This includes the prices of all materials or parts used in fabricating the technology. The parts may be small (such as nuts and bolts) or large (such as a tower air stripper unit). Other relevant materials for a remediation technology might be containment tanks, piping, pumps, compressors, etc. Materials prices can be obtained from manufacturers or vendors or data bases, such as that maintained by the army Corps of Engineers. (Humphreys, 1991: 1991: p.375)

2 Equipment

This element is made up of the cost of the equipment that is used only in the construction or fabrication of the technology, such as a backhoe, crane, welder, etc. This is not equipment that is permanently part of the project; those items are part of the materials costs. If the equipment is leased, the lease costs are counted plus the fuel. If the equipment is owned by a contractor, the equipment costs are the "...ownership costs (investment , insurance, etc.) and operating costs (fuel, maintenance, repairs, etc.). The costs of operators for operating equipment, even though part of the operating costs, are included by most contractors in the direct labor costs." (Humphreys, 1991: p.375)

3 Labor

Labor costs are the total of the actual amounts paid to the personnel who perform the construction tasks such as laborers, engineers, painters, etc. The amount paid is composed of the actual wage rate times the number of hours worked plus the the labor burden (taxes, insurance, etc.) for each class of worker. (Humphreys, 1991: p.375)

4 Waste disposal

During the setup of the technology at a remediation site there are often residual waste products generated. This is especially true whenever drilling is needed; the drilling fluids and cuttings must be adequately disposed of. The cost of correct disposal of all wastes generated during the construction and through the initial start-up and check-out of the technology must be included here.

b. Indirect Capital Costs

Indirect capital costs "are all costs other than direct costs which do not become a permanent part of the facilities but are required for the orderly completion of the project. These may include, but are not limited to, construction management, start-up costs, fees, insurance, and taxes." (Humphreys, 1991: p.365)

1 Taxes

The tax cost associated with a capital project is dependent on the location and the tax-exempt status of the owner. Often, statutory wage taxes are included in this category, e.g., worker's compensation. (Humphreys, 1991: p.375)

2 General conditions

This category includes items required to perform the capital fabrication such as supervision, temporary buildings or trailers for the workers and equipment, sanitary facilities, electricity, potable water, etc. (Humphreys, 1991: p.376)

3 Financial Risk elements

This can be divided into two parts: profit and contingency. The profit is the amount charged by the contractor to cover his or her risks, and entrepreneurial skill and is subject to the market conditions in the location of the project, competition, and other factors. Contingency is included to account for uncertainties regarding cost and productivity. These include bad weather, machine breakage, labor strikes, scope uncertainty, etc. (Humphreys, 1991: p.376) Additional risk elements are considered below under a section entitled "uncertainty."

4 Overhead

Overhead includes the cost of support to the job from the home office and includes home office rent, communications, management personnel, etc. Overhead related to the specific job can be counted under general conditions. (Humphreys, 1991: p.376)

3 Operating Cost

"Operating costs differ from capital costs mainly in that operating costs must be paid repeatedly, in contrast to capital costs, which involve a one-time payment." (Humphreys, 1991: p.434) Calculating the operating cost of environmental technologies can be based on the following list of cost elements.

a. Direct Operating Costs

"Direct" operating costs implies that the costs are proportional to the throughput of the process. For example, the electricity used in vitrifying soil using ISV is a direct cost. The most accurate data for direct costs is usually the operating company's records. If those data are unavailable, the analyst can also use published price lists of materials vendors, industry guidelines, or data bases such as contained in CORA or M-CACES.

1 Materials

The cost of all materials required for operation of the technology are calculated under this cost element. For example, the methane used for in situ bioremediation to stimulate the bacteria would be considered a direct material expense to the technology. In an off-gas treatment technology, the cost of the activated carbon or National-Environmental-Policy-Act filters would be listed here. Other examples of materials costs are purchases of lubricating oils, computer paper, etc.

2 Labor

The analyst must define how many laborers are needed of each wage classification to operate the technology and convert that into the number of work hours. Then the appropriate wage rate plus burden is

applied. Actual costs of the operating firm should be used if possible. If not, industry standard wages adjusted for geographical differences can be used.

3 Utilities

The cost of electricity, natural gas, water, etc. that is used in the operation of the technology is included under this cost element. Again, actual records of utility costs from the operating company are the most acceptable cost source. If steam is used, generally a cost per thousand pounds is applied.

4 Maintenance

To keep the technology operating smoothly, regular maintenance is required. Usually a maintenance schedule is designed to monitor and prevent the failure of critical or weak components in the process. Maintenance cost includes the cost of materials and labor necessary to complete the task. Actual maintenance records for base-line technology operation may be available. For the new technologies, such data will be hard to find, so industry averages should be applied. Usually, these are expressed as a percentage of the investment involved in the activity. For example, maintenance for a complex plant with severe corrosive conditions might be 11% or more, whereas a mild environment may require as little as a 2 % maintenance budget. (Humphreys, 1991: p. 444)

5 Laboratory services

For regular evaluation of chemical samples and monitoring of the technology process, laboratory services are often required. Cost of sample analysis can be obtained from the laboratories currently working in the environmental arena. A difficulty is that the cost of analysis is dependent on the type and number of contaminants being determined.

b. Indirect Operating Costs

An "indirect cost" must be paid even if the operation of the technology has stopped. It is an ongoing cost to cover personnel and activities not directly related to the throughput of the activity.

1 Plant overhead or burden

This cost element includes overhead costs such as administration, indirect labor for repair shops, drivers, engineering, etc. Other overhead costs are for inspections, fire protection, accounting and clerical help, and communications. This is generally estimated as a percentage (50 to 70%) of the total expenses per year. (Humphreys, 1991: p. 449).

2 Insurance

The cost of maintaining insurance coverage for fire, tornado, explosion, etc. is included here.

4 Discount Rate

Discounting involves bringing future dollars into present value terms. A dollar today is worth more than a dollar next year by the amount of interest that could be earned in the interim. Therefore, the discount rate should reflect the opportunity of earning interest on the money over time.

Economic theory dictates that the real discount rate for government projects should be close to the historical real interest earned on long-term government bonds (Gramlich, 1981: pp. 95-108). However, for

evaluation of government projects there exist regulations that dictate the discount-rate to be used. For most governmental projects, the Office of Management and Budget (OMB) requires a real discount rate of 10% (Ruegg, 1987: Appendix H.). For Federal energy conservation and renewable energy projects the rate is 7% (ibid., p. 29). The Environmental Protection Agency requires a real discount rate of 5% be used for evaluating projects under its jurisdiction.

Given the disparity in the accepted discount rate, a range of discount rates can be used as a parameter in the cost effectiveness calculation. A low value of 5% and a high value of 10% are appropriate.

5 Escalation

Escalation is a means of building relative cost changes into the cost calculation. Generally a percentage rate is applied to particular cost elements to reflect the expected change in the cost of that item relative to the other elements. This is different than a general price increase across the whole economy, which is the inflation rate. Since the all monetary values are treated in real terms, any escalation applied must reflect a real change in cost. This may be appropriate for capturing the expected decline in price of the new technology as it matures--this would require a negative escalation on the new technology cost--or increases in regulatory costs expected in the future.

E. Uncertainty

Uncertainty is very prevalent in the environmental arena. At the site characterization stage, for example, there is major uncertainty in our understanding of the hydrology at specific remediation sites and the complexities are still beyond our modeling abilities. Much progress is being made in combining groundwater modeling, uncertainty analysis, and cost-effectiveness analysis by various researchers. Freese et al. (1990) contains a good description of the approach. Many sites are characterized by a varied geology and scattered clay lenses where VOCs have concentrated. In addition, even in so-called "routine" drilling operations, the uncertainties involved with striking cobbles or boulders adds to the cost analysis difficulties. These uncertainties with respect to the site characterization have profound effects on our ability to accurately estimate the cost of implementing environmental technologies.

Another level of uncertainty surrounds the type of waste that is located in the site under study. The material may be hazardous, mixed waste, or radioactive waste. It may be stored in buried drums, boxes, or tanks. It may be neatly stacked underground in trenches, or piled randomly in a pit. The level of documentation of many waste sites is low, and of course, uncertainty abounds. For the cost analyst, this creates a problem because the costs of using a technology at a site depend to a large degree on the type of waste located there. At a radioactive site, the worker protection costs and efficiency losses are very high.

A final area of uncertainty that is important to our analysis is related to the newness of the technologies being studied. The performance of RDDT&E technologies is often hard to estimate under controlled situations, and it is even more difficult within a scenario of a reasonable site. Yet performance is a key element of cost effectiveness analysis.

Because of the uncertainty in decisions it is becoming more necessary to document decisions and provide reasoning for the steps taken (Barrager and Gildersleeve, 1989). Methods of analysis can help for these reasons. Rather than making programmed or intuitive choices, "analysis involves a conscious, purposeful effort directed at determining the proper choice for these decisions (Holloway, 1979: p.4)." In the discussion that follows we review some of the methods for dealing with uncertainty in decision making. These methods are currently being analyzed for possible applicability to the standardized methodology for cost effectiveness analysis.

1 Sensitivity Analysis

One method of analysis is sensitivity analysis. Sensitivity analysis is useful for determining the worth of additional information about uncertain variables. That is, detecting which variables have the largest impact on the cost of the optimal solution when they are changed and whether more specific information about these variables is likely to change the optimal solution (Holloway, 1979: p.358). To determine these key variables cost parameters are varied over their ranges, one at a time, to investigate the effect of each on the total cost (Barrager and Gildersleeve, 1989: p.184). A diagram can then be made showing expected contribution for different values of the variable. If the range of positive expected contribution is small then additional information may be valuable to pin point the uncertain variable within this range (Holloway, 1979: p.359). This range also shows for which values of the variable the current solution is no longer beneficial and a new approach should be found. This is how "the sensitivity of a solution to changes in the data gives us insight into possible technical improvements in the process... (Bradley, et al., 1989: p.91)." All variables must be independent for sensitivity analysis to be accurate so only the effect of one changed variable at a time is considered (Barrager and Gildersleeve, 1989: p.186).

Although sensitivity analysis "determines crucial uncertainties... it does this without consideration of uncertainty" (Barrager and Gildersleeve, 1989: p.179). That is, it does not quantitatively deal with uncertainty. Sensitivity analysis deals with uncertainty in terms of ranges of values. It determines which variables ranges have the most effect on total cost and what the range of acceptable values is for each such variable. In this way, sensitivity analysis examines the uncertainties but does not attempt to predict their outcome. It is important for scenarios to not be sensitive to variations for a model to be useful. If a scenario is particularly sensitive it becomes necessary to consider uncertainties explicitly, as in risk analysis (Bradley, et al., 1989: p.302).

In the case of the SCAPS analysis described in the performance characterization section, we used parametric adjustment of the performance variables in a sensitivity analysis bounded by the possible range of the performance of the new technology relative to the base-line. We assumed that the old technology was reasonably well-understood and parametric changes were not needed for its performance.

2 Risk Analysis

Risk and uncertainty are inseparable. All decisions that must be made under uncertainty involve risks. If there is no uncertainty a decision becomes a programmed decision and there is no risk (Holloway, 1979: p.4).

Risk can be considered the probability of an event happening times the consequences if that event happens (Shorthouse, 1990-91: p.42). So where in sensitivity analysis uncertainty is represented by a range of numbers, the concept of risk breaks that range into discrete values which become the consequences and assign probabilities to each. Assigning a probability to these key variables is a way to "quantify the uncertainty associated with each key variable (Barrager and Gildersleeve, 1989: p.179)."

The risks included in analysis may be "direct threats to human safety, to the environment, or simply the chance of economic damage (Porter, et al.: p. 278)." Often, all of these risks will be expressed in financial terms (Shorthouse, 1990-91: p.42). Although sometimes as in the case of developing environmental protection standards, legal incentives are used instead (Bailey, 1990-91: p.34). Another factor which must be considered with the consequences is vulnerability. Vulnerability takes into account that the particular area where the event occurs may affect the consequences due to geography, geology, surrounding populations, etc. (Shorthouse, 1990-91: p.42).

"Risk analysis is a method of determining the probable outcomes of events that have varying possibilities of happening." These outcomes can be ranked according to effectiveness, benefits and anticipated costs in order to aid in decision making (Shorthouse, 1990-91: p.41). One method of performing risk analysis places a series of decisions or chain of events on a decision tree. Figure 2 supplies an example of a risk tree for deciding between three technologies for cleaning paint off of airplanes (Shorthouse, 1990-91: pp.48-51). There are two types of junctures. A square represents a decision branch where a choice must be made between two activities. After a decision is made the tree branches again with a circle at the node, into probabilities of different outcomes. Working backwards from the end of the tree the risk can be calculated for each possible branch. That is, the cost (or consequence) of each event times the probability of its taking place. This quantitative measure of the risk of an outcome is the expected value and can be used to rank the different paths. By providing an ordered list of alternatives "risk analysis and its associated procedures reduce uncertainty in decision making and enable appropriate changes to be made (Shorthouse, 1990-91: 52)."

The same type of tree can be utilized using the concept of risk, but not as a decision analysis technique. Instead of weighing alternate technologies the tree can have stages of discrete cost component ranges for one technology and associated probabilities. Each path through the tree will yield a possible cost for the activity. If all of these costs are computed they can create a cost frequency distribution for the project, accounting for the uncertainty involved in each key variable (Barrager and Gildersleeve, 1989: p.189-191).

The probabilities necessary for risk analysis can be derived in different ways. One possibility is through surveys, however these measure attitudes about outcomes, not actual facts. Another method is by researching statistical data and assuming that trends hold for the future and that data is available (Porter, et al.: p.279). Perhaps a better way to assign probabilities is presented by Barrager and Gildersleeve (1989). Experts were chosen and given formal interviews. They are presented with "a series of paired comparisons used to elicit probabilities." The uncertain variables were carefully defined and structured. The interviewers are specially trained to detect and counteract biases of judgement. With this approach the human elements are crucial to the

success of the analysis. "The analysis is doomed to failure if the analyst attempts to set probabilities rather than seek information from pertinent experts (Barrager and Gildersleeve, 1989: p.187-188)."

Another possible method of obtaining probabilities for cost components is creating probability distributions from a set of relative frequencies developed through Monte Carlo techniques. When using Monte Carlo a random number or range of random numbers is assigned to a particular outcome. It is not important which numbers are assigned to the outcome as long as the percentage of numbers assigned to each outcome is equal to the probability that the outcome actually happens. For example, in using Monte Carlo to simulate rolling a die, one could choose the numbers 0-4 to represent heads and 5-9 to represent tails. Or the numbers 0 and 1 can be used and all other numbers ignored. In both cases the probability of the numbers representing heads to come up is 0.5.

F. Environmental Risk

In this section we list some possible approaches that are being explored for inclusion in the cost effectiveness methodology. This section is based on a study by Portney and Krupnick (1989). Their delineation of these categories actually applied to environmental benefits, i.e., the improvement in health and other assets afforded by clean-up of a Superfund site. We borrow from their discussion to apply the same categories and estimation procedures to costs (damages to health and environmental assets) that might result from the residuals of applying two different remediation alternatives, or the differing probability of failure of two alternatives.

1 Human Health

a. Damage Functions

Environmental alternatives often provide different levels of short and long-term health risks to the workers and the public. For example, excavation and treatment of mixed or radioactive waste may impose far greater health risk to workers than in situ treatment. On the other hand, if the treated waste is to be transported off-site, and possibly some distance, for ultimate disposal, some risks to the public as well as the transportation workers will be incurred in this step. Additionally, in situ treatment that does not entail waste destruction (such as containment with grout linings and protective caps rather than in situ bioremediation of contaminants) may pose lowest health risks to the workers, but might impose long-term risks of migration or intrusion and ensuing public exposure in the long-term. Worker risks may already be quantified by the additional costs of worker protection required by the hazardous environment as well as the higher wages typically paid to induce people to work in a hazardous environment.

For public health risks, a pathway and exposure risk must be postulated to perform a risk analysis. The expected damages to human health would then be valued according to values recommended by the EPA for morbidity and mortality. Wage compensation, averting behavior, foregone earnings, costs of illness, and hedonic property values are alternative measures of damage functions.

b. Contingent Valuation

Contingent valuation involves conducting a survey to ascertain what a person or household would be willing to pay to *avoid* an environmental risk (or what they must be paid in order to *accept* an environmental

risk). Use of damage functions are likely to result in a lower value for health risks than use of contingent valuation (Krupnick, 1989). Although one cannot expect to perform a contingent valuation survey for each type of hazard one is considering, data in the literature from past surveys on related hazards might be used as proxy for willingness to pay or to accept (David Brookshire, personal communication, August, 1991).

2 Environmental Assets

If one used contingent valuation to assess to human health risk costs, the value assigned to a hazard by the public might include their monetary value of all of the environmental damages that will occur from a hazard, if the survey was appropriately constructed. Alternative measures of damage to environmental assets include cost of foregone recreation, if the remediated sites borders on a recreation area. service replacement, or property values.

3 Economic Assets

Environmental alternatives might pose different risks to economic assets, such as materials and property. For example, a decision to physically remove all waste from a site will have different long-term consequences on the economic value of the property than will a decision to leave the waste in place with protective caps and liners. The latter alternative would require long-term institutional controls and restrictions on land use. Damage to materials can be measured from replacement value or service values. Damage to property values equates to real estate value declines.

4 Production Assets

Such assets include crops, forests, fisheries, water-using industries, and municipal water supplies. For example, accelerator transmutation of radioactive waste, a means of decreasing the activity level and requirements for long-term isolation of high-level radioactive waste, could pose different environmental risks than a high-level waste repository, where the small probability exists for waste migration and resulting contamination of production assets. Admittedly, the time frame over which a repository might fail is so long that use of any economic discount rate will nullify the differences in these alternatives. A more clear-cut example is posed by contrasting pump and treat remediation of VOCs in groundwater with in situ remediation. Whereas many scientists doubt that pump and treat can ever restore groundwater to drinking-water standards, it is yet unknown whether in situ technologies can do so. If we assume that in situ treatment can, there are distinct differences in the costs to economic assets. Costs to economic assets can be estimated by using replacement values (e.g., the cost of an alternative drinking water supply if an existing water source cannot be restored), or opportunity costs.

G. Application of Uncertainty and Risk to Cost Effectiveness

The techniques described above are at this time being tested for possible inclusion in the standardized methodology for cost effectiveness analysis. The most likely method for handling cost uncertainty is the Monte Carlo method. For performance uncertainty, we have successfully used sensitivity analysis (as described in Schroeder et al. (1991). Decision trees can be useful, especially when defining possible technology applications

and outcomes, but the major drawback for using them in actual cost analysis cases is the need for probability estimates for the various events.

Despite the thoroughness taken with a cost and performance estimate there will always be uncertainty involved. This is especially true when dealing with new, developing technologies, and the heterogeneity of geological areas encountered with environmental remediation projects. "What companies need is documented justification for their decisions...Done properly, risk analysis satisfies this need (Shorthouse, 1990-91: p.53)." The steps taken to procure probabilities, and the fault trees used to reach decisions provide their own documentation. The ability to look back and review reasons for particular actions increases confidence in managerial decisions as well as reducing time wasted on controversy .

A choice for valuing environmental risk has not yet been made. If data are available, the authors prefer to use contingent valuation for environmental risk estimation because it may better reflect consumers' utility and it avoids the necessity of performing a risk analysis.

H. Conduct Cost Effectiveness Analysis

At this point in the analysis, we have identified the capital and operating costs for each alternative technology, along with the net system impacts, performance scenarios, uncertainties and risks. If the scenario is such that the technology alternatives remove differing amount of contamination, we must cost the alternatives in terms of a standard unit of measure, for example, pounds of VOCs removed or cubic feet of contaminated soil disposed. (Humphreys, 1991: p.125) This involves loading the capital costs over the lifetime of the project and then applying that cost to the unit of measure. That is, what is the capital cost associated with treated a cubic meter of soil. Also, the operating cost are put into the same terms. After the system impacts of using the particular technology are included, a true cost effectiveness picture emerges, where the comparison can be made of the two alternatives in terms of total cost per unit under the scenarios. Since the scenarios are designed to reflect a reasonable site situation for application of the technologies, one can multiply the cost per unit by the number of units involved in the scenario to result in an estimate of the cost savings associated with using one technology over the other at a site.

However, if the scenario has been designed so that both technologies operate at the same speed/performance level, the life-cycle costs can be directly compared to see which more cost effective. (Ruegg, 1987: p. 14) This style of analysis is often useful in determining the cost effectiveness of a well-defined project such as a heating system for a building that must satisfy established performance specifications.

I. Total Cost Savings

The goal of this step is to estimate the total cost savings possible from full implementation of the technology throughout DOE, then to compare this number against the total research and development funds (from the R&D and the DT&E Divisions of DOE) that need to be expended to bring the technology to the commercial stage. Using the cost savings at the site which results from the cost effectiveness analysis, one can apply this to the total number of sites in the DOE complex where the technology could be used. If possible, it is

preferable to determine cost-savings that are site specific and to apply them to the appropriate sites. This requires significant research into what sites would have a need for the technology. However, a data base of DOE environmental sites is now under development, and will be a very useful tool for this estimation process when completed. In the meantime, rough estimates of the number of applicable sites can be multiplied by the cost savings per site to give an estimated total cost savings.

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Table 1. Comparison of SCAPS with Monitoring Wells and Coreholes (from Schroeder et al., 1991)

Criteria	Cone Penetrometer System (SCAPS)		Monitoring Wells	
	Strengths	Limitations	Strengths	Limitations
Geologic Setting		Cannot be used in competent rock or cemented soils without pre-drilling [12]. Intended for use in clayey or sandy soil; can handle up to small gravel.	Different drilling technologies can be used according to the geologic conditions: hollow stem augering for unconsolidated materials, direct rotary drilling for consolidated formations, etc. [4].	
Depth		Depth limited to approximately 150 feet in normally compacted soil [12].	Not depth limited. Different drilling technologies can be used to attain the desired depth: hollow stem augering for moderate depths, direct rotary drilling for greater depths, etc. [4].	
Time	Less time required on site. A quick method for initial site investigations [10] [11].			More time required on site.
Drilling Rate	Approximately 3 feet/min [12]. Can push over 200 meters of holes a single day [1].		(Varies with drilling technique used.)	
Operations	Less intrusive than conventional drilling methods: small diameter (.4 inch) holes. This is particularly helpful when conducting work in residential and commercial areas [10].			
Surveying	SCAPS includes a suite of geophysical instruments for locating concealed obstacles and tied utility lines. Location and surveying equipment is also included [1].			Surveying equipment is generally not included as part of drilling operations.
Drilling Artifacts and Closure	No drill cuttings or drilling fluids to dispose of. Sealing and grouting of penetrometer holes is performed as hole is withdrawn [12].	Only one opportunity to obtain data; hole is sealed (grouted) as tool is withdrawn. However, a sensor could be permanently emplaced (left in the ground), with grout filling remainder of hole. Effect of cone penetrometer push on subsurface: causes densified material around the hole.	Hole is available to be completed as a well, and that can have a long lifetime of providing data such as water samples.	Drilling fluid is required for direct rotary drilling and contaminants are circulated with the fluid. Depending on waste environment, drilling fluids and cuttings must be disposed of as a hazardous waste. A completed monitoring well is often subject to regulations stipulating that it be monitored on a regular basis (possibly quarterly or yearly). This represents an ongoing expense. At some point in time, will probably incur the cost of abandoning the well. Effect of drilling on subsurface: must deal with effects of mud invasion in all subsequent measurements. May have possible microbial contamination from mud. Drilling a well creates about 16 times the volume of disturbed material as opposed to doing a cone penetrometer push.
Exposure to Dew	Minimizes crew's exposure to hazardous materials: separate push and data acquisition workspaces on the truck. Air quality can be controlled in the workspace [12].			Workers on the drill rig are more exposed in a hazardous environment, particularly if handling drilling mud. More costly worker protection is required.
Dew Size	0.4		0.5 or more	
Decontamination of Equipment	Allows for decontamination of surfaces and compartments exposed to hazardous wastes. Rods can be cleaned as they are retracted [2].			

Table 1 continued.

Criteria	Cone Penetrometer System (SCAPS)		Monitoring Wells	
	Strengths	Limitations	Strengths	Limitations
Data Management	Collects real-time data and allows partial on-site interpretation. Integrates data into unified database. Provides on-site visualization of subsurface conditions [12].			Data must be analyzed in the laboratory at a later time.
Data Collection: Lithology	<p>Strength properties are measured (sleeve friction and penetration resistance) and these data are used to empirically determine the soil classification. The continuous records produced by the probe are greatly superior to boring data for stratigraphic correlation across the site [2]. The sensor readings are typically made at approximately 2-cm depth intervals [1].</p> <p>Most major soil transitions noted by the cone measurements can be documented in the laboratory results [2].</p>	<p>An empirical relationship between measured strength properties and soil type is used to determine soil classification for the layers through which the cone penetrometer has been pushed. (See [2], Figure 4-10).</p> <p>No physical sample of subsurface material is taken during an initial push.</p> <p>Correspondence between the two classification systems is not exact [2].</p>	<p>Lithologic logs record characteristic properties of the various strata encountered in the borehole. (Actual logging procedure depends to some extent on the drilling method.) Most common type of lithologic log is the driller's description of the geologic character of each formation encountered [4].</p> <p>Samples should be taken at 5-ft intervals and at every change in formation materials. Samples usually consist of cuttings produced by the action of the drill bit. Sample cuttings can be sent to a laboratory for grain-size-distribution and lithologic analysis [4].</p> <p>During drilling, soil samples (such as split-spoon samples) can be taken. Laboratory testing of these soil samples yields a soil classification based on actual physical samples. The laboratory soil classification is based on sieve analysis and Atterberg limits (liquid and plastic limits) [2].</p> <p>Continuous cores can be taken during the drilling process.</p>	<p>Limited sampling (approximately 5 ft intervals) allows for poor correlation between holes. (Less vertical detail than the cone penetrometer.)</p> <p>Must wait for lab analysis of drilling cuttings.</p> <p>This kind of skip sampling (5 ft intervals) is standard practice when conducting exploratory borings, and serves to illustrate the tendency to minimize the number of samples taken as one measure to reduce costs of conventional drilling, sampling, and laboratory sample testing programs. However, this kind of sampling cannot provide a meaningful index of subsurface conditions when soil layers are thin, interbedded, and discontinuous. If a detailed and continuous record of soil conditions is not obtained then monitoring wells may not be correctly placed [2].</p>
Screening Sensors	<p>Screening sensors, or contact sensors, are those present on the cone penetrometer tool during an initial push. These tools provide detailed and continuous measurements at a rate of advance of 3 ft/min [12]. Examples are:</p> <ul style="list-style-type: none"> • <i>Electrical Resistivity Sensor</i> This basic screening detector can sense contaminants that alter the resistivity of the soil. The depth of investigation of the resistivity tool into the formation is about 5 cm. High vertical resolution is obtained, and no effects of mud invasion. • <i>Fiber-Optic Fluorometric Contaminant Sensor</i> Has been developed for use with SCAPS; was first used in detecting tracer compounds in groundwater. This sensor has also been successfully used to detect petroleum, oil, and lubricants (POL) contaminants at DoD sites [12]. The optical spectral measurements are based on laser-induced fluorescence. • <i>Fiber-Optic Sensor for TCE</i> [6] 	<p>Sensors provide only qualitative to semi-quantitative measurement of contaminant concentration. Sensors identify classes of compounds only [12].</p> <p>Detects moderate to high concentrations, but is not specific (i.e., cannot identify contaminant by type).</p>	<p>Resistivity logging tools can be used to obtain measures of formation resistivity (which has most often been used in the petroleum industry to evaluate hydrocarbon saturation). Various tool spacings (e.g., 16" normal) are available for obtaining different depths of investigations [9].</p>	<p>No sensors are carried along as part of the drilling process. Measurements of chemical contaminants must be done by insertion of subsequent logging tools or by taking physical water/soil samples and having them analyzed in the laboratory.</p> <p>Resistivity measurements show effects of mud invasion.</p>

Table 1 continued.

Criteria	Cone Penetrometer System (SCAPS)		Monitoring Wells	
	Strengths	Limitations	Strengths	Limitations
Soil Samples	<p>Soil samples can be obtained using samplers such as the Mostap Soil Sampler or Gouda Soil Sampler [1].</p> <p>Gives a high quality sample—not contaminated with drilling fluids.</p>	<p>Soil samples are not taken during the initial cone penetrometer push. Rather, the initial push identifies the depth-of-interest, then a soil sample is taken on a subsequent push.</p> <p>Soil samples are typically smaller than those provided from drilling [12].</p> <p>Soil samples must be analyzed in the laboratory.</p>	<p>Soil samples can be obtained during the drilling process, e.g., with continuous drive or split-spoon samples.</p> <p>Formation samples may be taken by various methods depending on the type of drill rig used. Certain methods will provide more representative samples [4].</p>	<p>With direct rotary drilling, samples are influenced by the drilling fluid [4].</p> <p>Soil samples must be analyzed in the laboratory.</p>
Water Samples	<p>Water samples can be obtained using samplers such as the QED Inc. Hydropunch Groundwater Sampler [1].</p>	<p>Water samples are not taken during the initial cone penetrometer push. Rather, the initial push identifies the depth-of-interest (aquifer), then a water sample is taken on a subsequent push [10].</p> <p>Water samples are typically smaller than those provided from drilling [12].</p> <p>Water samples must be analyzed in the laboratory.</p>	<p>Water samples can be collected at various depths during drilling [4].</p>	<p>The drilled hole must be turned into a monitoring well in order for continuous future water samples to be taken: the hole must be cased, well screen installed, completed, and developed. The methodology used in the sampling procedure is critically important if the true chemical nature of the groundwater contamination at that site is to be determined [4].</p> <p>Water samples must be analyzed in the laboratory.</p>
Other Data or Uses			<p>Pumping tests can be conducted in wells in order to determine the hydraulic parameters of the aquifer. The purpose of pumping tests is to provide data from which the principal factors of aquifer performance—transmissivity and storage coefficient—can be calculated [4].</p> <p>Numerous other well logs can be collected in the hole besides resistivity. Other logs routinely collected for environmental work are the Gamma and SP logs.</p>	
Placement of Sensors	<p>Installs monitoring/sampling devices [12].</p>		<p>Down-well monitoring instruments are being developed [6].</p>	

STEPS IN COST-SAVINGS ANALYSIS

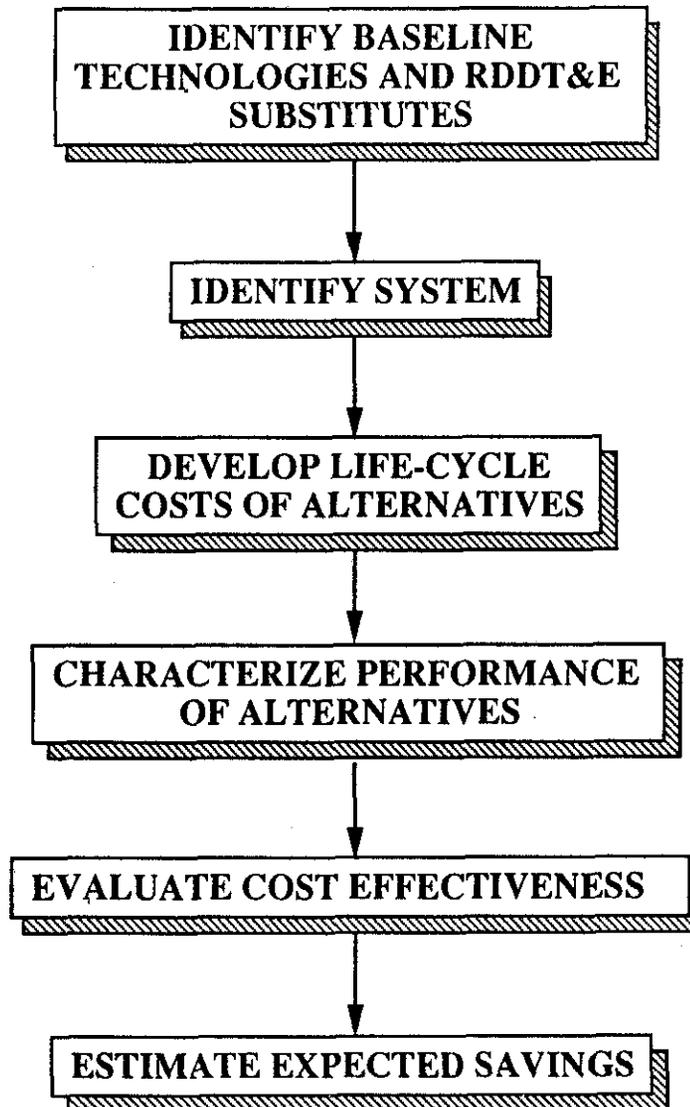


Figure 1. Steps in Cost Savings Analysis

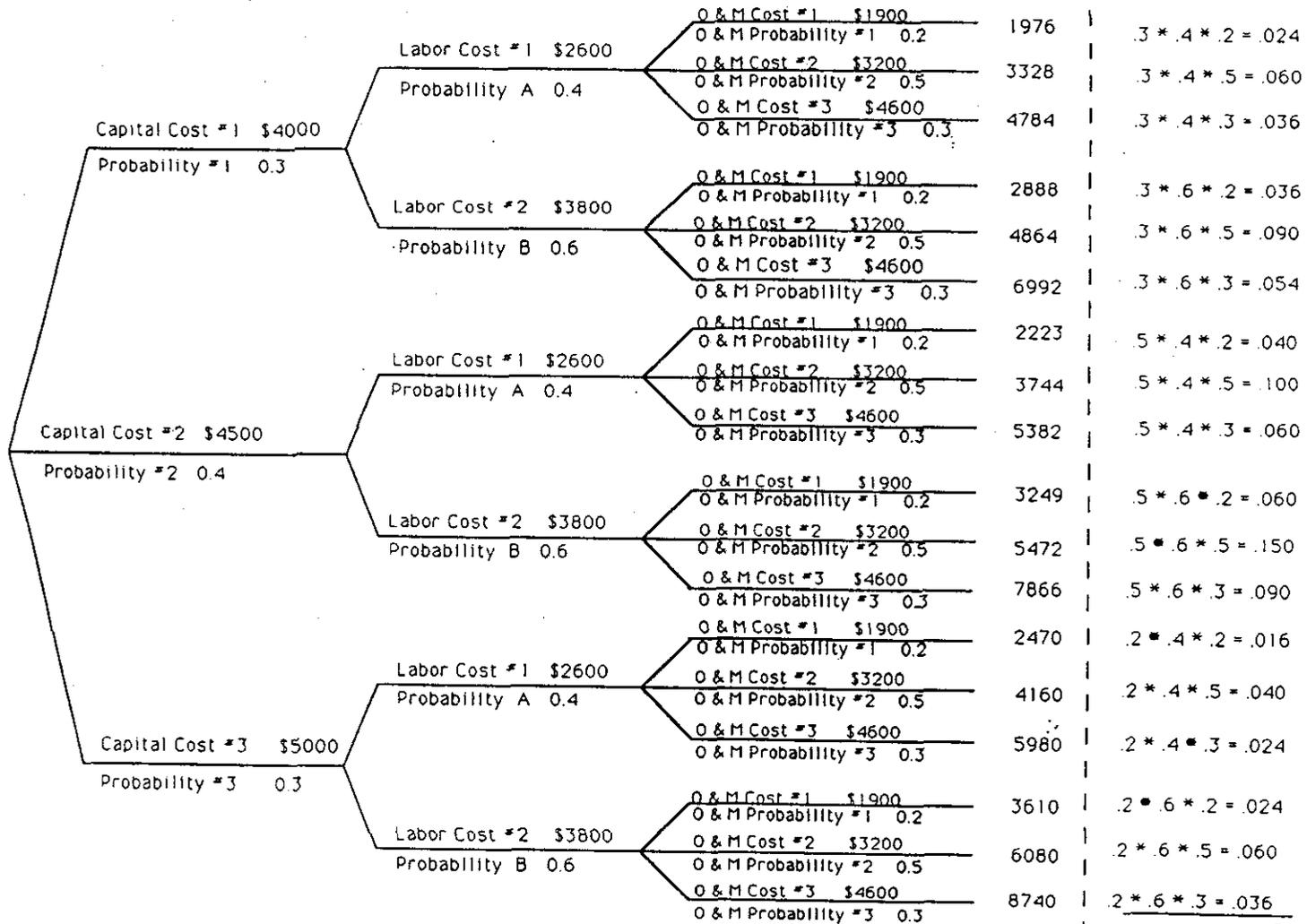


Figure 2. Decision Tree Example: Three options for cleaning paint off airplanes (adapted from Shorthouse, 1990-91)

