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A CERCLA-Based Decision Model to Support Remedy Selection for an Uncertain Volume of Contaminants at a DOE Facility

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Abstract

The Paducah Gaseous Diffusion Plant (PGDP) operated by the Department of Energy is challenged with selecting the appropriate remediation technology to cleanup contaminants at Waste Area Group (WAG) 6. This research utilizes value-focused thinking and multiattribute preference theory concepts to produce a decision analysis model designed to aid the decision makers in their selection process. The model is based on CERCLA's five primary balancing criteria, tailored specifically to WAG 6 and the contaminants of concern, utilizes expert opinion and the best available engineering, cost, and performance data, and accounts for uncertainty in contaminant volume. The model ranks 23 remediation technologies (trains) in their ability to achieve the CERCLA criteria at various contaminant volumes. A sensitivity analysis is performed to examine the effects of changes in expert opinion and uncertainty in volume. Further analysis reveals how volume uncertainty is expected to affect technology cost, time and ability to meet the CERCLA criteria. The model provides the decision makers with a CERCLA-based decision analysis methodology that is objective, traceable, and robust to support the WAG 6 Feasibility Study. In addition, the model can be adjusted to address other DOE contaminated sites.

A CERCLA Based Decision Model to Support Remedy Selection for an Uncertain Volume of Contaminants at a DOE Facility

1. Introduction

1.1 General Issue

The Department of Energy (DOE) and its predecessor agencies have been involved in the research, production and testing of nuclear weapons since the 1940s. During that time, numerous facilities, both government and privately-owned, were constructed or leased across the country to support these efforts. These facilities generated large quantities of radioactive and hazardous materials which, unfortunately, contaminated many of the facilities and surrounding areas. The DOE's Oak Ridge Operations Office, which is responsible for four such facilities, estimates that it will take from $8.9 to $9.6 billion to cleanup the four facilities in their area of responsibility by 2015 [http:www.em.doe.gov/add2006/ores.html: June 1997]. One such facility is the Paducah Gaseous Diffusion Plant.

The Department of Energy owns an active uranium enrichment facility in Paducah, Kentucky, known as the Paducah Gaseous Diffusion Plant (PGDP). The PGDP is located 10 miles west of Paducah, a city of approximately 31,000, and 3.5 miles south of the Ohio river. The Paducah facility was constructed in 1951 and began operation in 1952. The plant enriches the most abundant isotope of uranium, ^{238}U, to

^{235}U, a more fissile material. The enrichment process is complicated. It begins by converting naturally occurring uranium to uranium hexafluoride (UF_6) gas. The UF_6 feedstock is then pumped through micropores in a series of membranes to facilitate separation of the two isotopes, ^{238}U and ^{235}U. Diffusion through the micropores is mass dependent; however, because the difference in mass is so small, it takes a large number of separation membranes (over 1000) arranged in a cascade to capture a ^{235}U enrichment of several percent [DOE/OR/07-1243&D4, 1997: 4-4].

Most of the UF_6 was produced from feedstock, which came from the PGDP feed plant that processed both natural uranium and uranium from reactor tails. The uranium from the reactor tails included uranium that had been returned for re-enrichment from the plutonium production reactors at the DOE Hanford and Savannah River plants. The reactor tails received after 1975 were placed in storage rather than being processed and contained technetium-99 (Tc-99). These tails are believed to be the sole source of the Tc-99 that has been released into the environment at PGDP [DOE/OR/07-1243&D4, 1997: 4-4].

Since the plant's construction, trichloroethylene (TCE) has been used as a cleaning solvent to decontaminate equipment and waste material before disposal. TCE is a Dense Non-Aqueous Phase Liquid (DNAPL), an immiscible fluid with a density greater than water. TCE currently ranks 13th on the Agency for Toxic Substances and Disease Registry (ATSDR)/Environmental Protection Agency's Top 20 Hazardous Substances 1995 list [http://atsdr1.atsdr.cdc.gov:8080/cxcx3.html - Note that this list is updated periodically by ATSDR and EPA to meet the requirements of the

Comprehensive Environmental Response Compensation and Liability Act section 104]. Although TCE is not currently recognized as a cancer causing chemical, a partially degraded product originating from TCE, known as vinyl chloride, is carcinogenic and ranks number four on ATSDR's top 20 list. The use of TCE as a degreaser at PGDP ceased on July 1, 1993 [DOE/OR/07-1243&D4, 1997: 4-4]; however, it is unclear how much TCE was released to the environment over the years of its use at PGDP. Estimated spill volumes range anywhere from a minimum of 2,000 to a maximum of 500,000 gallons of TCE [Papatyi, 1997: 3-3].

Effective May 31, 1994, the PGDP was placed on the National Priorities List (NPL) by the U.S. Environmental Protection Agency (EPA). The Paducah Site Baseline Summary projects that as much as $255.714 million will be spent in remediation efforts from 1997 through 2006 and an additional $363.212 million will be spent from 2007 through remediation completion. This expected short term funding level totals $618.926 million, and assumes DOE receives the funds necessary for cleanup when needed [EI00000-0197]. The DOE's EM50 Subsurface Contaminants Focus Area has requested an analysis that will assist in the selection of remediation technologies, or groups of technologies, known as technology trains for their Waste Area Group (WAG) 6 site at PGDP. These technology trains can be used to remediate or clean up and control the level of contamination, such that the protection of human health and the environment will not be compromised by the principal contaminants of concern (PCOCs) at WAG 6, henceforth to be defined as TCE and Tc-99.

1.1.1 DOE Objectives

The primary objective of the DOE is to work with the EPA and Kentucky Department for Environmental Protection through a negotiated Federal Facilities Agreement (FFA). The draft FFA sets forth requirements to address releases of hazardous or radioactive substances by investigating solid waste management units (SWMUs) and areas of concern through an integrated remedial investigation/feasibility study process (RI/FS). Five SWMUs have been combined into a single Waste Area Grouping known as WAG 6. The objectives of the integrated RI/FS for WAG 6 at PGDP are to collect sufficient information on each SWMU, to evaluate the risk-based impact to human health and the environment, determine the nature and extent of contamination, and collect data for the support of the feasibility study (FS) [DOE/OR/07-1243&D4, 1997: ES-1]. In order to meet these objectives and ultimately determine whether the site remediation is possible, the decision makers turned to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and the nine technology performance criteria specified in the RI/FS processes described in the National Contingency Plan (NCP) [DOE/OR/07-1243&D4, 1997:1-11].

1.1.2 CERCLA and NCP Criteria

The Comprehensive Environmental Response, Compensation and Liability Act, commonly referred to as "CERCLA" or "Superfund", was enacted by Congress in 1980. CERCLA's enactment stemmed from an emerging realization, most directly associated with the Love Canal tragedy, that inactive hazardous waste sites presented great risk to public health as well as the environment, and that there were no existing regulations to address abandoned sites. CERCLA's primary intent was to address the past disposal of hazardous substances at these sites. CERCLA defines "hazardous substances" as those substances that are listed or designated under other environmental statutes; for example "hazardous wastes" under the Resource Conservation and Recovery Act (RCRA), "hazardous substances" under the Clean Water Act, "toxic pollutants" under the Clean Air Act, and "imminently hazardous chemical substances or mixtures" under the Toxic Substances Control Act (TSCA) [Lee, 1995: 227].

CERCLA requires the EPA to develop a ranking of the most hazardous waste sites across the nation. This ranking is known as the National Priorities List (NPL) and is updated yearly. In order to determine which sites belonged on the NPL, a hazardous ranking system was developed to score the sites. Once a site is placed on the NPL, it is subject to public comment and review.

In 1986, CERCLA was extensively amended with the Superfund Amendments and Reauthorization Act (SARA). In part, these amendments reflected Congress' great concern for federal facilities meeting the requirements of CERCLA, so they created an entire section, section 120, devoted to federal facility cleanup [Lee, 1995: 276]. Section 120 dictates that any federal facility that manages hazardous waste or has potential hazardous waste problems be scored under the hazardous ranking system to determine whether it should be placed on the NPL. If placed on the NPL, the facility must begin a remedial investigation/feasibility study (RI/FS) within six months of its listing. While the RI/FS is underway, the federal agency responsible for the site must work with the EPA and state where the site is located to ensure the RI/FS process is as complete and focused as possible [Lee, 1995: 276].

In order to accomplish the cleanup of hazardous waste sites, CERCLA refers to the methodology prescribed in the National Contingency Plan (NCP). When performing a CERCLA based response action or cleanup, the procedures set forth in the NCP must be followed by the EPA and the federal facility. The NCP establishes criteria for determining the appropriate environmental response by outlining the procedures to be followed in performing cleanups, remedial actions or removal actions. However, the guidance is often vague, and many times unclear, with numerous redundancies. Because the NCP fails to specify the type of remediation technology to employ at each type of hazardous waste site, technology selection is often a subject of intense debate in CERCLA proceedings [Lee, 1995: 232].

According to CERCLA and the NCP, there are nine performance criteria to be considered when comparing and selecting remediation technologies or technology trains. The nine criteria are divided into the following three distinct groups: Modifying Criteria, Threshold Criteria, and Primary Balancing Criteria and are presented in Figure 1.1[40 CFR S300.430(e)(9)(iii)]:

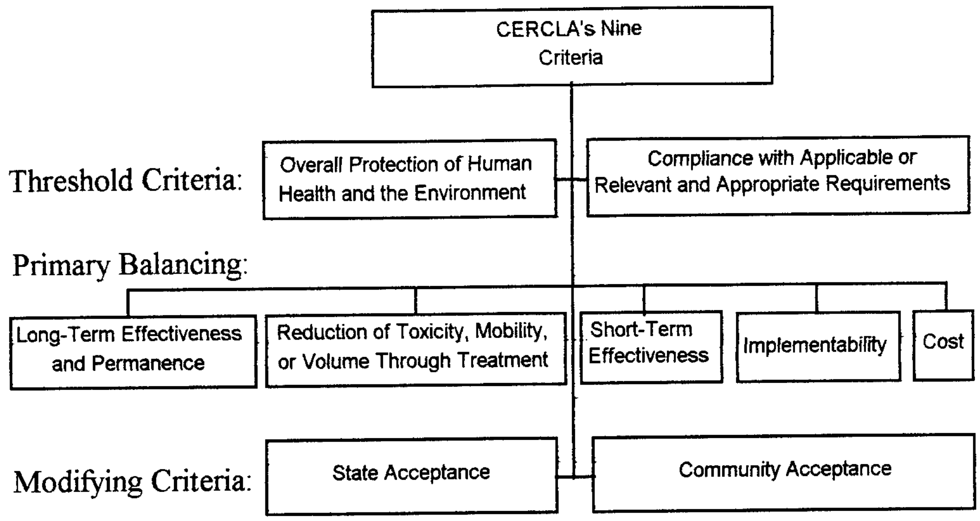


Figure 1.1 CERCLA criteria hierarchy [EPA/540/G-89/004, 1989: 6-7]

1.1.2.1 Threshold Criteria

The Threshold Criteria, consisting of the Overall Protection of Human Health and the Environment and Compliance with Applicable or Relevant and Appropriate Requirements (ARARs), are criteria that all remediation technologies considered must meet in order to be eligible for selection.

The Overall Protection of Human Health and the Environment criterion draws on the assessments conducted under other evaluation criteria, especially long-term effectiveness and permanence, short-term effectiveness, (both are primary balancing criteria) and compliance with ARARs. Compliance with ARARs mandates strict observance of all federal and state laws that have been identified earlier in the RI/FS process. When it is not possible to meet an ARAR, either the remediation technology/train is rejected (which is what was done at the site in this study) or allowable waivers can be obtained under the CERCLA process [EPA/540/G-89-004, 1989:6-6].

The Threshold Criteria serve to screen the candidate technologies/trains, as they are the first criteria considered. Therefore, in order for a remediation technology/train to even be considered for application, the technology/train must meet the Threshold Criteria.

1.1.2.2 Modifying Criteria

The Modifying Criteria, State and Community Acceptance, are considered after the remedial technology, or technology train, has been selected by the decision makers. These criteria encompass the review of the Remedial Investigation/ Feasibility Study (RI/FS) report and Proposed Plan, which details the remedial technology/train selected and proposes how it will be implemented. Both the public and the state, have the opportunity to review and comment on the report and the plan, prior to finalization. Once finalized, the remediation plan is known as the Record of Decision (ROD). The Modifying Criteria are the last criteria to be considered in the evaluation process, after the technological approach has been proposed, and thus will not be addressed in this research effort.

1.1.2.3 Primary Balancing Criteria

The five primary balancing criteria are grouped together because they represent the primary criteria upon which the analysis for selecting a remedial technology/train is based [EPA/540/G-89-004, 1989:6-6]. The approach taken in this research effort focuses specifically on these five criteria.

1.1.2.3.1 Long-Term Effectiveness and Permanence

The evaluation of remediation technologies under this criterion addresses the long-term effectiveness and permanence the technology can achieve. In addition, it evaluates the success of the technology/train in terms of reducing the remaining risk at the site after response objectives have been met. This criterion also focuses on the adequacy and reliability of controls necessary to manage treatment residuals or untreated wastes [EPA/540/G-89-004, 1989:6-8].

1.1.2.3.2 Reduction of Toxicity, Mobility, or Volume Through Treatment

The degree to which technologies employ recycling or treatment that reduces toxicity, mobility, or volume shall be assessed, including how treatment is used to address the principal threats posed by the site, is considered under this criterion [40CFR S300.430(e)(9)(iii)(D)]. This criterion is applied to each technology/train and considers the following factors [EPA/540/G-89-004, 1989:6-8]:

- The treatment processes the technology train will employ and the materials that will be treated.
- The amount of hazardous materials that will be destroyed or treated, including how the principal threat(s) will be addressed.
- The degree of expected reduction in toxicity, mobility, or volume measured as a percentage of reduction (or order of magnitude).
- The degree to which the treatment will be irreversible.
- The type and quantity of treatment residuals that will remain following treatment.
- Whether the alternative would satisfy the statutory preference for treatment as a principal element.

1.1.2.3.3 Short-Term Effectiveness

This criterion addresses the effects of a chosen technology during the construction and implementation phase until the remedial response (or cleanup) objectives are met. This criterion should be evaluated with respect to a technology/train's effect on human health and the environment during implementation of the remedial (or cleanup) action. Consideration should be lent to the following, applicable factors [EPA/540/G-89-004, 1989:6-9]:

- Protection of the community during remedial actions.
- Protection of workers during remedial actions.
- Environmental impacts.
- Time until remedial response objectives are achieved.

1.1.2.3.4 Implementability

This criterion assesses the technical and administrative feasibility of implementing a remediation technology/train as well as the availability of various services and materials required for its implementation [EPA/540/G-89-004, 1989:6-9].

1.1.2.3.5 Cost

The final balancing criterion assesses the cost of a remedial technology. Costs are expressed in net present cost and are broken into two categories: capital costs and operation and maintenance (O&M) costs. Capital costs include direct costs, such as construction and equipment costs, and indirect costs, such as permit or startup costs. O&M costs are post-construction costs that are required to execute the remedial action. Some examples of O&M costs are maintenance materials, disposal of residues, and operating labor costs.

Present worth analysis is used to evaluate cost outlays or expenditures, which occur over different time periods, by discounting future costs to a common base year. This allows the cost of all technologies to be compared on the basis of a single cost that represents the amount of money, if invested in the base year and distributed as required, would be sufficient to cover all costs associated with the remedial technology over its planned life [EPA/540/G-89-004, 1989:6-11,12].

1.1.3 Remediation Technologies and Technology Trains

The WAG 6 team, including the hydrogeologist, decided to attack the contamination by using three hydrogeologic zones: the unsaturated zone, saturated zone, and the aquifer. The decision makers decided that the remediation technologies/trains evaluated in this study will be designed to aggressively treat or remove the PCOCs (TCE and Tc-99) in all three zones. The mere containment of PCOCs is not considered an aggressive treatment and therefore containment is not considered a remedial option. Some technologies are designed to operate in only one zone. It is therefore sometimes necessary to implement more than one remediation technology so all three zones are treated. "Technology trains", or simply trains, are used to describe such a combination, where one remediation technology will treat both the saturated zone and aquifer, such as Pump and Treat, and another remediation technology will treat the zone, such as 6 Phase Heating. For consistency, the term technology train will be applied to all technologies or groups of technologies that are designed to treat three zones. In addition to evaluating technology trains, selected by the decision makers, this research effort also evaluates the no action alternative, that requires no aggressive action towards cleanup. The no action alternative, while not satisfying the Threshold Criteria, is used as a baseline in this study from which other alternatives or technology trains are compared.

1.2 Problem Statement

The DOE site manager must incorporate the criteria established in CERCLA and the NCP as part of the RI/FS process to select a remedy for a site contaminated with an uncertain volume of PCOCs. Challenges at the site include: an operational building located on top of the site, complicated hydrogeology, uncertain remediation technology performance, and uncertain volume of PCOCs.

1.3 Research Objective

The primary objective of this research is to provide the DOE and the Paducah decision makers with a decision analysis methodology that will provide insight into selecting a technology train that is being considered for remediating WAG 6, which is contaminated with TCE and Tc-99. A decision analysis model will be developed to quantify how well each technology train is expected to meet the CERCLA criteria. This model will also incorporate the uncertainties associated with volume; and hence, cost, time, and other affected measures used to quantify the overall utility of the technology trains.

1.4 Research Approach

This research effort begins by utilizing fundamental decision analysis principles of value-focused thinking and multiattribute preference theory, and employs such decision analysis tools as a value hierarchy, single dimensional value functions, the power-additive utility function, and sensitivity analysis. These principles and tools are all used with the aim of providing the best analysis possible of potential combinations of remediation technologies based on the CERCLA criteria. Value-focused thinking techniques are used to assist the decision makers in creating a CERCLA based, but site and PCOC specific, value hierarchy. Once this value hierarchy is created, evaluation measures can be identified and single dimensional value functions defined. Weights, or preferences, are elicited from the decision makers. Each technology train or alternative is scored against each measure, which ultimately allows for the quantification of the decision makers' values. This information is incorporated into a decision analysis model, along with life cycle costs and technology performance data. The model will rank the remediation technology trains based on their expected utility. A sensitivity analysis of model variables, including criteria weights, completes the research effort by providing the decision makers with additional information about the top technology trains.

The model created is a combined effort between MSE Technology Applications Inc.(MSE), Virginia Commonwealth University (VCU) and the Air Force Institute of Technology (AFIT). MSE is responsible for generating remediation technologies' life cycle costs and performance data for variable amounts (spill volume) of TCE. Cost and performance data were obtained from previous or current applications of remediation technologies and expert opinion was incorporated to tailor the data specifically to WAG 6.

1.5 Overview

Chapter 2 reviews the fundamentals of decision analysis and provides a brief discussion of the current literature related to the topic. Chapter 3 builds on the information in Chapter 2, by providing the decision makers' value hierarchy with associated weights, the single dimensional utility functions, and the decision analysis model. Chapter 4 discusses the results obtained from the model and provides a sensitivity analysis of the model. Chapter 5 concludes the research effort with recommendations that can be drawn from the analysis and suggests follow-on work at WAG 6. Detailed appendices are provided to facilitate communication of the entire process and exemplify the finer points of the research effort.

2. Literature Review

2.1 Introduction

There are three main objectives to this literature review. The first is to provide the reader with a brief introduction to decision analysis, including relevant concepts and theories that apply directly to this research. The second objective is to provide examples from the literature that demonstrate decision analysis techniques applied in the CERCLA arena. The final objective is to cite specific research that utilizes decision analysis techniques in the selection process of remediation technologies.

2.2 Decision Analysis

Decision analysis is a process which aids decision makers in structuring complex decisions, in identifying sources of uncertainty and representing that uncertainty in a systematic way, and in providing a framework, models and tools for handling decisions where there are multiple, and sometimes conflicting objectives [Clemen 1996: 4]. The flowchart, given in Figure 2.1 on the following page, exemplifies the typical decision analysis process. Note that the decision analysis process is iterative, allowing for continuous improvement. After insight is gained from the first run through the process, it is then possible to revisit the objectives, alternatives, and model that define the decision opportunity. The remaining portion of this section will provide a detailed review of this process, drawing directly on examples and suggestions for implementation from the literature.

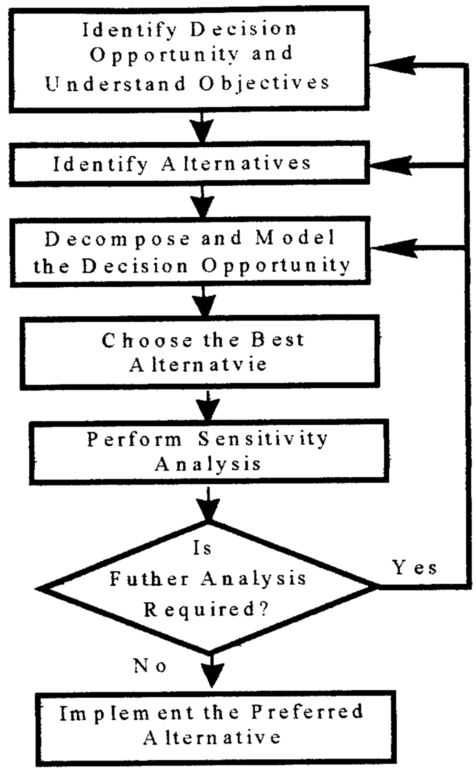


Figure 2.1 Modified Decision Analysis Process Flowchart [Clemen, 1996: 6]

2.2.1 Identifying Decision Opportunities and Understanding Objectives

The literature supports two trends of thinking in regards to identifying decision opportunities and defining objectives. The first approach is the standard or conventional approach to decision making. The focus of this approach is on generating alternatives and then considering objectives, criteria, or values to evaluate the alternatives. This traditional approach is termed "alternative-focused thinking" by Keeney, who claims this approach is "reactive, not proactive. Furthermore, it is backward; it puts the cart of identifying alternatives before the horse of articulating values" [Keeney, 1994: 33]. Another disadvantage to the traditional approach is in understanding the decision maker's objectives. Identifying and structuring objectives is a difficult task, and this approach fails to clearly specify how to perform that task, nor does it suggest how the objectives can be used to guide the decision maker's thinking [Keeney, 1992: 4].

The second approach is called "value-focused thinking", where leaderships' values are the primary focus of decision making, not alternative generation [Keeney, 1994: 33]. Value-focused thinking challenges the decision maker to consider why they are making the decision to begin with. Decisions are made with the intent of generating the most positive outcome. By using value-focused thinking, the decision maker's values are structured such that it is possible to construct a decision analysis model capable of identifying the alternatives that provide the greatest value to the decision maker.

There are numerous advantages to value-focused thinking. Value-focused thinking uncovers hidden objectives by exposing objectives not yet conceived. It leads to more productive information gathering, improves communication among decision makers, facilitates involvement of multiple stakeholders, enhances the coordination of interconnected decisions, generates better alternatives, and identifies more appealing decision opportunities [Keeney, 1994: 33]. One of the greatest benefits of value-focused thinking is that it includes a process for developing the decision makers' objectives. The process usually involves discussions with the primary decision maker(s), where Keeney's eight suggestions for identifying the objectives can be applied [Keeney, 1994: 35]: develop a wish list; identify alternatives; consider problems and shortcomings; predict consequences; identify goals, constraints, and guidelines; consider different perspectives; determine strategic objectives; and determine generic objectives.

Once a list of objectives has been generated, it is important to distinguish between fundamental or end objectives and means objectives. According to Clemen, means objectives help achieve other objectives while fundamental objectives are those that are important because they reflect what the decision maker really wants to accomplish [Clemen, 1996: 44]. To assist in identifying objectives, Keeney suggests implementing the "WITI test or Why Is That Important? test", where each objective is examined by asking that question. If the answer is that the objective is important only because of how it impacts some other objective, then it is a means objective. If the answer is that the objective is one of the reasons for interest in the decision opportunity, then it is a fundamental objective [Keeney, 1994: 34].

Fundamental objectives should be essential, controllable, complete, measurable, operational, decomposable, nonredundant, concise, and understandable. If they do not meet all of the above mentioned criteria, the objective should be defined differently or it could be considered a means objective [Keeney, 1992: 82]. Fundamental objectives can then be organized into value hierarchies, where the upper levels represent more general objectives or values and lower levels further define or describe the upper levels. It is very important to properly structure these value hierarchies because the lowest levels will be the basis from which various evaluation measures will be constructed to score or evaluate alternatives.

2.2.2 Developing Alternatives

A value hierarchy can provide a basis for designing good alternatives for the decision opportunity [Kirkwood, 1997: 23], because it is comprised of the fundamental objectives the decision maker is trying to accomplish. Understanding the objectives produces better alternatives, or to restate Keeney's earlier analogy [2-2], the horse is being placed in front of the cart. Specifically, alternatives should be designed that best achieve the values identified for the decision opportunity. There are a number of methods that are used in designing alternatives.

Keeney suggests thinking about how to better achieve fundamental objectives as a good start to developing alternatives. He recommends focusing on one objective and thinking of alternatives that might be very valuable if that were the only objective in the decision opportunity. This process is then repeated for every objective, after which there should be a broad range of potential alternatives. Next, consider two objectives at a time and try to generate alternatives that satisfy both, and then consider three objectives, and so on until all objectives are considered together. Examine the alternatives generated to see if it is possible to combine any into a single alternative [Keeney, 1994: 39].

Howard states that the most important method for creating alternatives is the strategy generation table [Howard, 1988: 684]. Strategy generation tables show how a total strategy can be specified by selecting among decisions in each of many areas, which could be thought of as individual decision variable settings. The table is constructed by listing all the alternatives (rows) under a specific objective (which represents the column). By combining all the columns, the table is formed and a strategy can then be mapped out across the columns. Strategy generation tables are especially useful when a structured procedure is needed to sort out reasonable alternatives to consider in more detail [Kirkwood, 1997:48]. In earlier work at WAG 6, a strategy generation table was constructed where the objectives are the cleanup of a particular hydrogeologic zone or zones (shown by the columns in Table 2.1) and the alternatives are the various technologies that work in the given zone (shown as the rows in Table 2.1) [Papatyi, 1997: 3-9]. A strategy or technology train is the combination of any given technology for one zone matched with any given technology from another zone. From Table 2.1, a valid technology train would be 2 Phase - 6 Phase - Pump & Treat (P&T) - Biological Polisher (Bio), and the maximum number of trains that could be formed would be the eight shown.

Table 2.1 Example Strategy Generation Table for Technology Trains

Unsaturated Hydrogeologic Zone Technologies		Saturated and Aquifer Zone Technologies		Combinations or Trains
SVE	none	P & T	Bio	SVE - P&T - Bio
				SVE - P&T - none
2 Phase	none	P & T	none	2 Phase - P&T - Bio
2 Phase	RF Heating			2 Phase - P&T - none
2 Phase	6 Phase			2 Phase - RF Heating - P&T - Bio
				2 Phase - RF Heating - P&T -none
				2 Phase - 6 Phase - P&T - Bio
				2 Phase - 6Phase - P&T - Bio

Keeney also suggests maximizing all objectives within a decision opportunity to reach the ideal alternative. Once this ideal has been identified, it can then be analyzed to determine which constraints are holding one back from this preferred alternative [Keeney, 1992:221].

Clemen suggests creativity techniques such as fluent and flexible thinking, idea checklists, brainstorming, and metaphorical thinking to enhance alternative generation [Clemen, 1996: 203-206]. The essence of his discussion is that creativity is essential in alternative development because the alternatives themselves ultimately determine the boundaries of the decision opportunity.

2.2.3 Decompose and Model the Decision Opportunity

The decomposition and modeling of the decision opportunity can be accomplished a variety of ways. Influence diagrams or decision trees can be used to represent or model the decision opportunity. Probability can be used to model the uncertainty inherent in the decision and hierarchical models can be used to understand the relationships among multiple objectives. Since these models are mathematical, they can be subjected to analysis, which can greatly enhance the decisionmaking opportunity. The following subsections highlight specific steps in the construction of a decision analysis model; they are also the steps that were employed in this research effort and their specific application to the WAG 6 site at the PGDP will be presented in Chapter 3.

2.2.3.1 Value Hierarchies

As stated previously, value hierarchies should reflect the fundamental objectives of the decision opportunity. The upper levels of a value hierarchy represent the more general objective or values of the decision maker(s). The lower levels further decompose the general objectives until they reach a level where they can be evaluated through an evaluation measure. Thus, the general idea of a value hierarchy is to ensure that each objective is measured through one or more evaluation measures.

According to Kirkwood, value hierarchies should be complete, nonredundant, decomposable, operable and small in size [Kirkwood, 1997; 16]. A value hierarchy is complete when each tier (or level), taken together as a group, covers all the concerns necessary to evaluate the overall objective of the decision. Nonredundancy means that no two lower level objectives, or evaluation measures can overlap by their definition. Taken together, these two properties are often expressed as "collectively exhaustive and mutually exclusive" [Kirkwood, 1997; 17]. Decomposability or independence ensures that the preference for the score of one evaluation measure does not depend on the score of any other evaluation measure. Operable refers to the value hierarchy being understood by the user and small in size conveys the point that a smaller value hierarchy is more easily communicated.

Consider the following example from CERCLA, where a fundamental objective is for a remediation technology/alternative to achieve Short-Term Effectiveness [40 CFR S300.430(e)(9)(iii)(E)]. CERCLA continues to decompose this fundamental objective into four lower-level, fundamental objectives or "subcriteria"; as depicted by the single, solid lined boxes in Figure 2.2, which demonstrates the Short-Term Effectiveness hierarchy. CERCLA stops at this point, allowing the decision makers and stakeholders the flexibility to design their own, unique evaluation measures of these objectives. The evaluation measures, in the dashed boxes, and weights are those that were derived as part of Grelk's research effort for Idaho's National Engineering Laboratory [Grelk; 1997: 3-3].

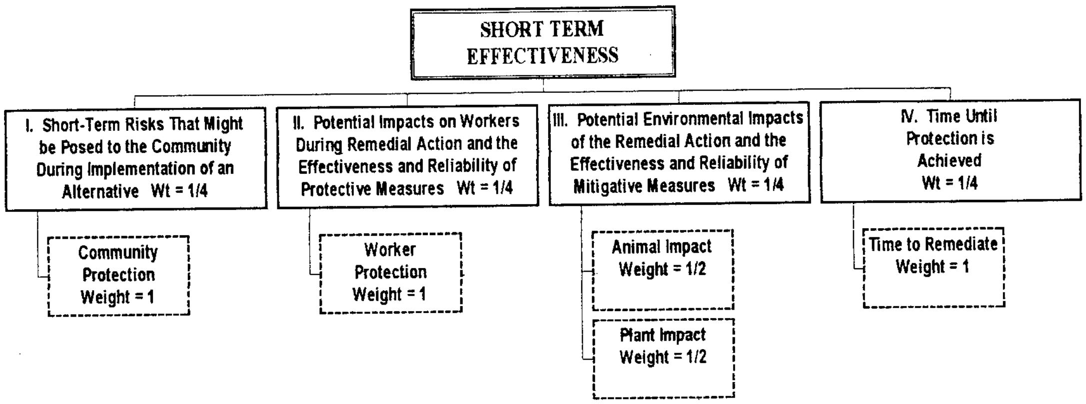


Figure 2.2 Short-Term Effectiveness Hierarchy

2.2.3.2 Evaluation Measures

Evaluation measures allow the qualitative nature of the value hierarchy to be transformed into a quantitative tool capable of determining how well an alternative does with respect to each objective considered within the decision opportunity. Evaluation measure scales can be classified as natural or constructed and either direct or proxy [Kirkwood, 1997: 24]. A natural scale is one that is used widely and commonly interpreted by all. Profit is a natural scale that is widely used in business decisions. Constructed scales are those developed for a particular decision opportunity that measures the degree of attainment of an objective. Direct scales directly measure the degree of attainment of an objective; again, profit is a good example. A proxy scale reflects the degree of attainment of its associated objective, but does not directly measure the objective itself. The Gross National Product (GNP) is an example of a proxy scale for the economic state of our nation [Kirkwood, 1997: 24]. The type of scale used can depend on the preference of the decision makers and stakeholders. The most critical factor in scale construction is that it must be precise, specific, and pass the "clarity test" [Howard, 1988: 688]. The clarity test asks whether a clairvoyant, who was capable of foreseeing the future, would be able to determine, unequivocally, what the score or outcome would be for each evaluation measure. No interpretation or judgment should be required of the clairvoyant [Clemen, 1996: 75]. The tradeoff lies in the effort spent to develop the scales, ease of assessing each alternative against the scale, and then communicating the results obtained.

2.2.3.3 Multiattribute Preference Theory

Once these evaluation measures have been created, combining their scores becomes the next issue. It is impossible to combine scores with different units of measure. For example, consider Figure 2.2, where one evaluation measure was the Time to Remediate. The natural, direct scale for this evaluation measure would be time, with units of measure as years. Another evaluation measure from Figure 2.2 is Community Protection, which represents how a remediation alternative affects the surrounding community. Community Protection is a constructed, proxy scale, with units of measure being the action taken at the site (containment, "in situ" treatment, excavation, etc.) [Grelk, 1997: B-11]. How could these two incommensurate evaluation measures ever be combined or even compared? By placing a unitless, dimensionless function over each evaluation measure, known as a single dimensional value or utility function, the scores can be transformed into either values or utilities, both of which are unitless. Once the scores have been converted to either values or utilities, they can be combined and compared against one another, hence the significance of multiattribute preference theory.

Multiattribute preference theory addresses decisions where there are multiple objectives, which may be competing, by quantifying the objectives through evaluation measures; developing weights for the objectives, which in turn assigns weight to each of the evaluation measures; and translating the objective evaluation measure scores into common, dimensionless units of measure, such as values. These values are then combined through an overall value function, to generate a single, overall value for an alternative or technology train, which represents how well that alternative meets the decision maker's objectives [Grelk, 1997: 2-12].

Multiattribute preference theory provides the decision maker an opportunity to examine and compare alternatives against competing objectives. Consider the five competing objectives listed as CERCLA balancing criteria in Figure 1.1: long-term effectiveness and permanence, reduction of toxicity, mobility, and volume, short-term effectiveness, implementability, and cost. Any remediation technology train considered for implementation at any CERCLA site must be evaluated against these competing criteria [40 CFR S300.430(e)(9)(iii)]. CERCLA also leaves the relative importance, weighing, or balancing of each criteria up to the decision makers, providing only that "The balancing shall emphasize long-term effectiveness and reduction of toxicity, mobility, or volume through treatment" [40 CFR S300.430(f)(1)(ii)(E)].

According to multiattribute preference theory, transforming the evaluation measures' scores into dimensionless units requires the use of single dimensional value or utility functions. Single dimensional utility functions are derived from the decision maker through a series of lottery questions where uncertainty and probability are addressed. Because estimates of probabilities are subjective in nature, it is often difficult to assess utilities with a group of decision makers. Single dimensional value functions are also derived from the decision maker(s), but do not incorporate uncertainty or probability and hence are easier to assess. The purpose of a single dimensional value function is to transform scores from evaluation measures into unitless, dimensionless numbers that can ultimately be combined and compared. There are two basic types of single dimensional value functions: monotonically increasing or monotonically decreasing.

Grelk's work presents some examples of single dimensional value functions that were used in environmental remediation technology selection. Figure 2.3 represents a monotonically increasing value function because as The Percent of Principal Threat i Mass Treated (the actual evaluation measure's score) increases, so does the value to the decision maker, thereby demonstrating a positive slope [Grelk, 1997, B-19]. In other words, if there is no treatment of principal threat i's mass, then there is no value gained for the decision maker. If 100% of the principal threat is treated, then that corresponds to the greatest value the decision maker could gain which would be ten in this example A monotonically increasing function need not be linear, like the one shown in Figure 2.3, nor continuous, but must exhibit a positive

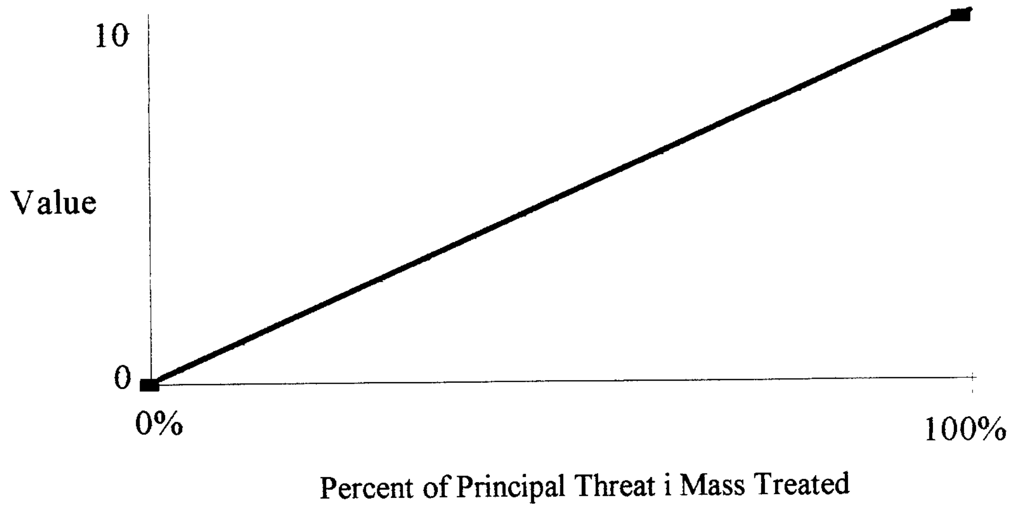


Figure 2.3 Example of a Monotonically Increasing Function

slope, or "trend". The only requirements are that the function assigns the worst score on an evaluation measure a value of zero, the best score on an evaluation measure a value of ten, and the function accurately conveys the decision makers' attitudes.

The other type of value function is the monotonically decreasing function which accounts for the "more is not always better" situation. Consider the evaluation measure depicted in Figure 2.4, where the Number of Major System Components is a proxy measure for how complicated a system is to construct and operate [Grelk1997, B-4]. In this case, the larger the evaluation measure score, the lower the value for the decision maker, thereby the negative slope or "trend" in value. A monotonically decreasing function need not be linear, as shown in Figure 2.4, nor continuous, but must exhibit a negative slope, or trend. The only requirements are that the function anchors the worst score on an evaluation measure at a value of zero, the best score on

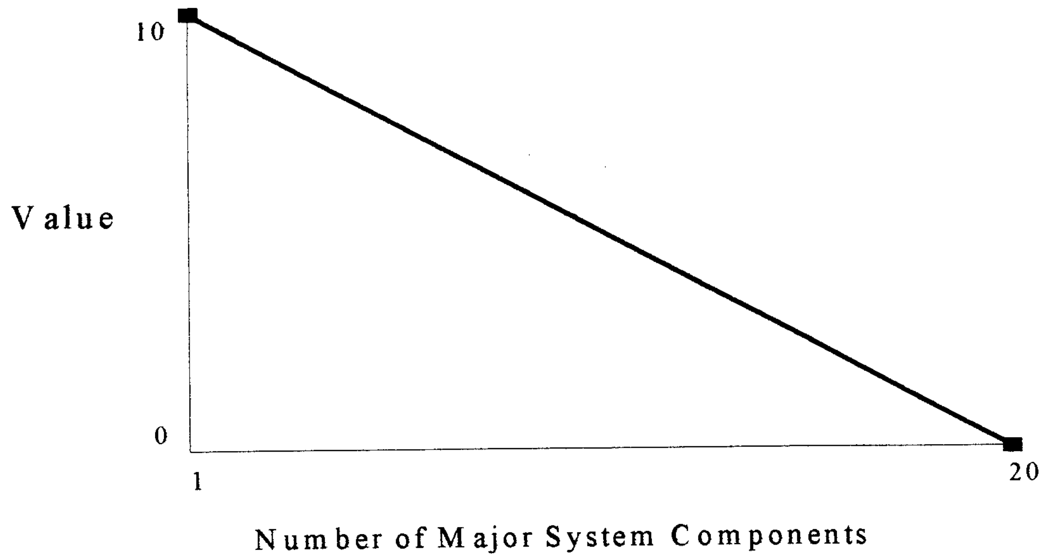


Figure 2.4 Example of Monotonically Decreasing Function

an evaluation measure at a value of ten, and the function accurately conveys the decision makers' attitudes.

2.2.3.4 Assessing Weights

Assigning weights in a multiple objective analysis is necessary if the decision makers feel that some objectives are more important than others, which is often the case. Weights are assigned to each level of the value hierarchy, where the sum of all the weights for any particular level must equal one. Consider Figure 2.2 where the subcriteria weights (horizontally) sum to one and the evaluation measures' weights (vertically) sum to one under each subcriteria. This restraint forces the decision maker to make tradeoffs between the objectives; if one objective is to have more weight, it must come at the expense of at least one other objective's weight. There are a variety of ways to determine weights; such as direct assessment, pricing out, swing weighting, and lottery comparison techniques [Clemen 1996: 546].

The direct assessment of weights requires the decision makers to assign weights to each objective based on their own personal judgment, previously established organizational policy, or law. This method requires consensus among the decision makers and is recommended only when there is sufficient guidance or there are decision "rules" that can be referenced or agreed upon. As mentioned previously, CERCLA does not provide much assistance in this area, so this research effort solicited weights directly from the decision makers, who were able to develop some basic decision rules to assist them in consistently applying weights to their value hierarchy.

2.2.3.5 Overall Value Function and the Power Additive Utility Function

An overall value function combines the values from the multiple evaluation measures into a single measure of the overall value of each alternative [Kirkwood, 1997: 53]. There are various forms that can be used for the overall value function; however, it is important that the form chosen adequately reflect the decision maker's preferences, and can be easily understood by the decision maker [Grelk 1997: 2-27]. The value function form that has been generally used in practice is the additive form [Kirkwood, 1997: 230]. The additive value function is a weighted average of the single dimensional value functions assigned to each evaluation measure and is presented on the following page [Kirkwood, 1997: 230]:

$$v(x) = \sum_{i=1}^{n} \lambda_i v_i(x_i) \qquad \textbf{(2.1)}$$

where the total value is represented by v(x), i =1 to the n^{th} single dimensional value function, and λ_i represents the weights to the corresponding single dimensional value functions, $v_i(x_i)$. A critical assumption is made in using this function: the objectives must be mutual preferential independent [Kirkwood, 1997:238]. Mutual preferential independence implies that a decision maker's preferences associated with one objective are independent of the preferences associated with all the other objectives. Applying the additive value function allows for the combination of values obtained from the evaluation measures and produces one overall value for each alternative, which allows comparison between alternatives and ranks alternatives as to how well they meet the objectives.

Combining the single dimensional values with their associated weights through an additive value function produces a deterministic ranking of alternatives that does not account for uncertainty or risk. By utilizing the power-additive utility function, it is possible to convert values calculated using a multiattribute value function into utilities, which captures the decision maker's attitude toward risk through the use of a multiattribute risk tolerance factor (ρ_m). The power-additive utility function is expressed as [Kirkwood, 1997: 161]:

$$u(x_1, x_2, \ldots, x_n) = \begin{cases} \dfrac{1-\exp[-v(x_1,x_2,\ldots,x_n)/\rho_m]}{1-\exp(-1/\rho_m)}, & \text{when } \rho_m \neq \text{infinity} \\ v(x_1,x_2,\ldots,x_n), & \text{otherwise} \end{cases} \qquad \textbf{(2.2)}$$

where $u(x_1, x_2,\ldots,x_n)$ is the overall utility for the evaluation measures $x_1,x_2,\ldots,x_n$, $v(x_1,x_2,\ldots,x_n)$ is an additive value function and must be less than or equal to one, and ρ_m is the multiattribute risk tolerance factor.

The multiattribute risk tolerance factor quantifies the decision maker's degree of aversion to taking risks [Kirkwood, 1997: 162]. Kirkwood assures that the exact value of ρ_m rarely impacts the ranking of alternatives. In fact, he suggests conducting a sensitivity analysis for ρ_m that covers the range from 0.2 up to infinity. If the ranking of alternatives does not change over this range, then "...you should not need to consider the multiattribute risk tolerance any further, and hence you do not have to assess the specific value of ρ_m" [Kirkwood, 1997: 162]. In other words, from Equation 2.2 above, values convert directly to utilities. If the alternative rankings do change, then an assessment of ρ_m must be made in order to conduct an expected utility analysis.

2.2.4 The Final Four

The first of the final four steps in Figure 2.1 is choose the best alternative, which is the alternative with the greatest utility or expected value, calculated from the analysis. The second step is to perform a sensitivity analysis to answer "what if" questions (e.g."If we change this weight, does the model recalculate a different optimal alternative?") [Clemen, 1996: 7]. The third step asks the question "Is further analysis required?", reinforcing the iterative nature of the process. Clemen suggests that a better term for the entire process might be a "decision-analysis cycle" because often many iterations are needed. The final step is simply to implement the best alternative generated from the analysis [Clemen, 1996: 7].

2.3 Decision Analysis Applications in the CERCLA Arena

Decision analysis (DA) is well developed in disciplines such as military science, medicine, business, and engineering, but with respect to CERCLA, it is more difficult to identify DA applications. Most modeling applications tend to concentrate on the prediction of a variable like contamination concentrations rather than on participation in the decision making process [Jennings, 1994: 1133]. The table below briefly describes the specialized DA models developed over the past fifteen years in reference to CERCLA and is primarily based on the work by Jennings as arranged by Papatyi [Papatyi, 1997: A-1].

Table 2.2 Models Used in CERCLA Applications

Model	Agency	Objective	References
HRS (Hazardous Ranking System)	EPA	Model used to determine National Priority Listing of a site.	Wu & Hilger, 1984: 797-807
MEPAS (Multimedia Environmental Pollutant Assessment System)	DOE	Model used to assess wildlife endangerment issues at DOE sites	Harz & Whelan, 1988: 295-299 Droppo & Hopes, 1990: 193-205
RAAS (Remedial Action Assessment System)	DOE	Model used for Feasibility Study to provide alternatives guidance	Hartz & Whelan, 1988: 295-299

Model	Agency	Objective	References
HAZRISK	DOE	Model used in cost estimate development and scheduling for hazardous waste cleanup projects	Hudson & Shangraw, 1990: 241-244
POS (Program Optimization System)	DOE	Model used to optimize distribution of remediation budgetary resources	Merkhofer, Cotton, Longo, 1988: 39-43
DPM (Defense Priority Model)	Department of Defense	Model used to estimate the risk to human health and the environment and assess funding priority	Expert, 1997
HARM (Hazard Assessment Risk Model)	US Air Force	Model used as a predecessor to DPM	Hushon, 1990: 206-216
ENVEST/ RACER	US Air Force	Model used to estimate cost of remediation projects	Expert, 1997
FLEX (Flexible Linear Expert)		Model used to evaluate chemical compatibility of liners	Rossman & Siller, 1987: 113-127
HERPM (Human Exposure Potential Ranking Model)	NY Dept of Health	Model used as a ranking tool that establishes relative priorities for investigation and remediation of sites	Smith, Patrick, & Hudson, 1987: 158-161
DRASTIC (Depth, Recharge, Aquifer, Soil, Topography, Impact, Conductivity)	EPA	Model used to preliminary assess hazardous waste sites, acronym -Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone media, and hydraulic conductivity	Allert, Bennet, Lehr, Petty, & Hackett, 1987
CORA (Cost of Remedial Action)	EPA	Model used as a costing tool for remedial actions	Chenu & Crenca, 1990: 162-175
PAST (Potential ARAR's Selection Tool)		Model used to assist in the development of ARARs	Greathouse & Clements, 1991

2.4 DA Applications in the Technology Selection Process at DOE Facilities

Upon review of the current literature, the Department of Energy appears to have the lead in utilizing decision analysis techniques when making decisions regarding remediation technology selection.

In 1994, Evans Duffield, Massman, Freeze, Stephenson, and Buss, completed a DA effort that incorporated a risk-cost based economic model, hydrogeological uncertainty model, and hydrogeological simulation model for the DOE's Savannah River site. The fundamental objective of their research was to determine the lowest cost remediation alternative and determine the largest cost contributors to the remediation of the site. They examined six technologies and concluded that the lowest cost technology was pump and treat. They also concluded that operation and maintenance costs were the largest cost contributor due inpart to the sheer volume of ground water that had to be treated [Evans Duffield, Massman, Freeze, Stephenson, and Buss, 1994].

In 1995, Timm used a rather simplistic approach to remediation technology selection at the DOE Rocky Flats facility, where cost and schedule, tempered with some regulatory requirements and future land use considerations, comprised the fundamental objectives of the value hierarchy. No weights were assigned. Alternatives were generated based on their ability to be implemented and included probabilistic data regarding the amount of time required for implementation. Each alternative was screened for technical feasibility and ability to meet time schedules. The alternatives that remained after screening were then evaluated based on: critical elements that could potentially lead to significant changes in either cost or schedule and life cycle costs and their variability. "The results enabled the DOE to select and defend a remediation alternative that saved million of dollars" [Timm, 1995: 46].

Early in 1995, the MSE/AFIT/VCU team formed and began producing Life Cycle Cost modeling, remedial technology selection, and risk analysis using DA models for the DOE. Two very applicable works to this research effort are summarized as follows:

Grelk completed a notable example of DA applied research in remediation technology selection in his 1997 AFIT thesis for the Department of Energy's Idaho National Environmental Laboratory. The DA process followed by Grelk is similar to the one described in Section 2.2, only it was deterministic, which means it did not account for any uncertainties or probabilities. The results of the analysis presented a ranking of 28 remediation technology trains along with a sensitivity analysis, which provided further information for the decision makers to consider when selecting a technology train. Perhaps the greatest contribution of Grelk's work was the development of a set of CERCLA based evaluation measures complete with their corresponding single dimensional value functions [Grelk, 1997: 5-5].

Concurrent to Grelk's work, Papatyi also completed DA research in remediation technology selection in his 1997 AFIT thesis for the Department of Energy's Paducah Gaseous Diffusion Plant. Papatyi's work focused on evaluating 58 technology trains considered for remediating the WAG 6 site. He used three evaluation measures: total net present value, year finished with remediation, and percent contaminant removed and then developed single dimensional utility functions for each evaluation measure. Basing his initial analysis on dominance and utility, he screened down the 58 trains to 7. From the 7, he selected the top three trains based upon total utility; which were Dynamic Underground Stripping, 2Phase and Oxidation, and LASAGNA and Oxidation.

As Papatyi himself noted, his research was limited by using only three evaluation measures, and not the CERCLA criteria. He also noted that the uncertainty regarding the spill volume at the site should be reflected in the performance data, making it scalable [Papatyi, 1997: 5-5]. It is the intent of this research effort to address these concerns by establishing a CERCLA based value hierarchy for WAG 6 and using scalable performance data based upon a probability distribution of spill volume to identify the best remediation technology or train for the site.

3. Methodology

3.1 Introduction

After reviewing the techniques applied in the literature review, value-focused thinking and multiattribute preference theory constitute the best approaches for creating a decision analysis model for remediation technology selection at WAG 6. The advantage of value-focused thinking is that it incorporates the decision makers' preferences so that the resulting ranking of alternatives (trains) is based completely on their values. Multiattribute preference theory provides the decision maker an opportunity to evaluate and compare alternatives against competing objectives, which is very applicable when addressing CERCLA's balancing criteria.

This chapter begins by reviewing WAG 6 site specific data, continues with the developing of alternatives or trains, building of the WAG 6 CERCLA value hierarchy, constructing the evaluation measures and single dimensional value functions, assessing weights, applying the additive value function and power-additive utility function, and concluding with a brief description of the modeling assumptions.

3.2 WAG 6 Site Characteristics

As mentioned previously, the Paducah Gaseous Diffusion Plant (PGDP) was placed on the National Priorities List on May 31, 1994. Because of this listing, PGDP is subject to CERCLA criteria for cleaning up or remediating its hazardous waste sites. The principal contaminants of concern (PCOCs) at Waste Area Group (WAG) 6, which is located primarily around and under the C-400 building, are trichloroethylene (TCE) and technetium-99 (Tc-99).

Unfortunately, there is a lack of information regarding the actual quantity of these contaminants. TCE spill estimates range from 2,000 to 500,000 gallons [Papatyi, 1997: 3-3]. The highest known concentration of TCE in the groundwater at the site is 890,000 ppb; the current regulatory limit is 5 ppb [DOE/OR/07-1234&D4, 1997: 5-20]. The activity of the Tc-99 ranges from 0 piC/L to 43,922 piC/L; the current regulatory limit is 900 piC/L but this may be relaxed to 3,900 piC/L [Davis, 1997].

Based on limited field data, historical records, and interviews with past site workers, a cumulative probability distribution of the volume of TCE spilled was generated and is shown in Figure 3.1.

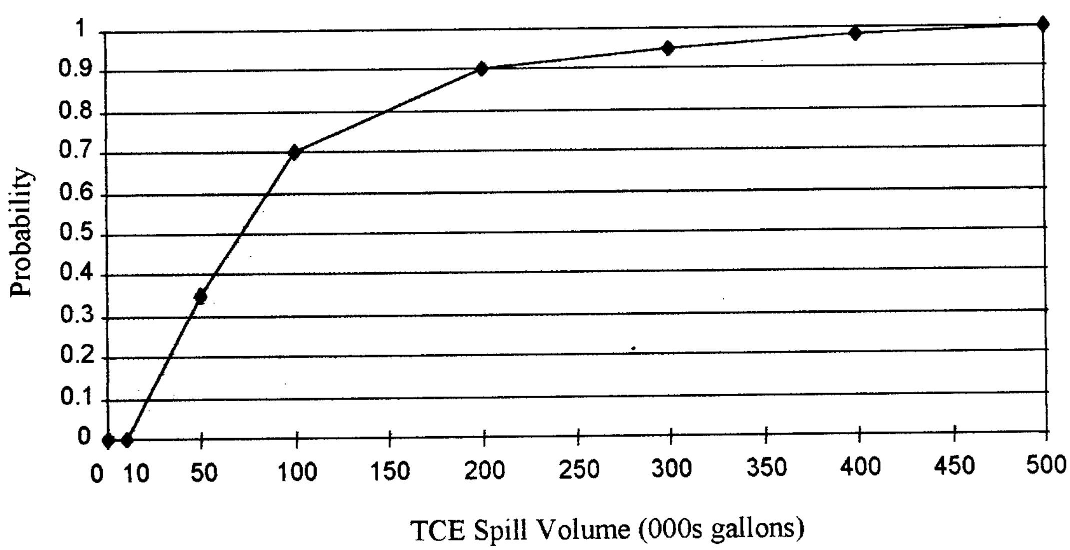


Figure 3.1 Cumulative probability distribution of TCE spill Volume

From this distribution, through discretization, discrete probabilities were calculated for spill volumes of 50,000, 100,000, 200,000, 300,000, 400,000, and 500,000 gallons and used by MSE for calculating cost and performance data. Appendix A details the mathematical/statistical procedure of discretizing a continuous distribution through moment matching. The results obtained from the analysis in Appendix A are summarized in Table 3.1. The expected value or mean of this spill distribution is 98,750 gallons.

The probabilities in Table 3.1 are used in the decision analysis models and their application will be further discussed at that point.

Table 3.1 Discrete Probabilities Assessed for TCE Spill Volumes

TCE Spill Volume (gallons)	Probability
50,000	0.74
200,000	0.20
300,000	0.03
400,000	0.02
500,000	0.01

"Understanding the geology and hydrology of a hazardous waste site is the crucial first step in accurately identifying and selecting an efficient remedial technology" [Barry, 1997]. Figure 3.2 is a conceptual spill model, created by Papatyi, which exemplifies the geologic complexity of the WAG 6 site [Papatyi, 1997: 3-4].

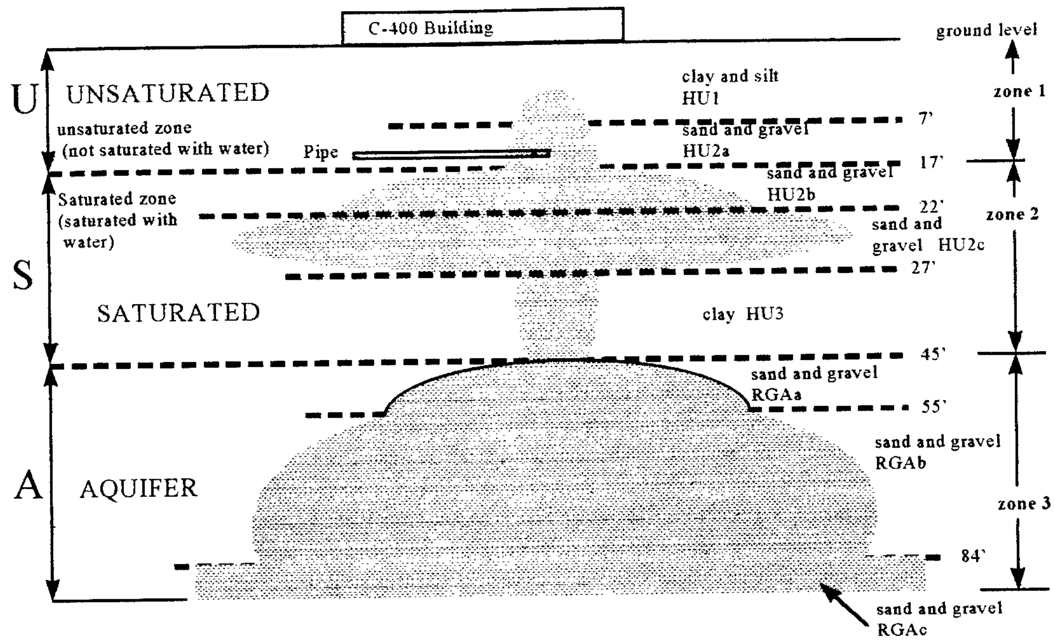


Figure 3.2 Conceptual Spill Model of the TCE Contaminant Plume

Notice there are eight hydrologic units (HU1, HU2a, RGAa, etc.), each representing nonhomogeneity (differing soil compositions) in the subsurface. These differing soil compositions promote nonhomogeneous contaminant migration through the subsurface. Figure 3.1 is a conceptual visualization of this concept; where, for example, the HU3 clay hydrologic unit tends to retard the spill, forcing it to pond on top of the clay unit, because clay is rather impermeable. The spill only passes through the clay unit when there are fractures or nonhomogeneities in the clay's composition.

The decision makers decided to combine the eight hydrologic zones presented in Figure 3.1 into three operational zones: the unsaturated (U) - zone 1, the saturated (S) - zone 2, and aquifer (A) - zone 3. Recent discussions with the site geologist have supported this hydrogeologic simplification and categorization. He described the saturated zone as the zone where pore volumes are saturated with water, but the hydraulic conductivity is too low for the region to serve as a water supply [Davis, 1997].

As the site characterization/remedial investigation continues at WAG 6, new data are collected, improving the understanding of the subsurface composition of the site. Recent geologic corings have shown that the clay layer (HU3) may not be 18 feet thick as originally estimated, but rather insignificant or nonexistent, thus providing little or no buffer for the aquifer. This new information seems to better explain how ground water samples from zone 3 became so contaminated [Davis, 1997].

3.3 Developing Alternatives or Trains

The decision makers decided to evaluate only aggressive technologies capable of remediating both TCE and Tc-99; no "containment only" technologies are considered in this analysis. Because of the geologic complexity of the site, only three technologies were found that could remediate all the contamination affecting all three zones: Dynamic Underground Stripping (DUS), Dual Phase, and Unterdruck-Verdampfer-Brunnen (UVB). However, there are three technologies that could work in the unsaturated and saturated zones and there are six potential technologies that could work in the aquifer. By combining these two groupings, a train, capable of remediating all three zones could be formed. Table 3.2, on the following page, demonstrates how the 18 trains are formed.

Table 3.2 Example Strategy Generation Table for Technology Trains

Unsaturated &Saturated Hydrogeologic Zone Technologies (Zones 1&2)	Aquifer Zone Technologies (Zone 3)	Number of Combinations or Trains
2 Phase	Pump and Treat	2Phase & Pump & Treat
6 Phase	Permeable Treatment Zone	2Phase & Surfactants
LASAGNA	Cosolvents	etc.
	Surfactants	
	Redox	
	Oxidation	3 * 6 = 18

In addition to the 18 trains developed above, the decision makers wanted to consider one specific train of Radio Frequency Heating in zones 1 and 2, and Oxidation in zone 3 as well as the No Action Alternative, when there is no remedial technology employed at the site. The No Action Alternative is used as a benchmark in this analysis. Table 3.3 lists all the trains evaluated in this analysis. In addition, Appendix C gives a brief description of how each of the candidate technologies works.

Table 3.3 Technology Trains Evaluated

Train Number	Train Description
1	DUS
2	UVB
3	Dual Phase
4	2 Phase and Pump & Treat
5	2 Phase and Permeable Treatment Zones
6	2 Phase and Cosolvents
7	2 Phase and Surfactants
8	2 Phase and Redox
9	2 Phase and Oxidation
10	6 Phase and Pump & Treat
11	6 Phase and Permeable Treatment Zones
12	6 Phase and Cosolvents

Train Number	Train Description
13	6 Phase and Surfactants
14	6 Phase and Redox
15	6 Phase and Oxidation
16	LASAGNA and Pump & Treat
17	LASAGNA and Permeable Treatment Zones
18	LASAGNA and Cosolvents
19	LASAGNA and Surfactants
20	LASAGNA and Redox
21	LASAGNA and Oxidation
22	Radio Frequency Heating and Oxidation
23	No Action Alternative

3.4 WAG 6 CERCLA Value Hierarchy

Because WAG 6 is on the NPL, the remedial technology selection process must address the criteria established in CERCLA. The CERCLA criteria are divided into the following three distinct groups: Modifying Criteria, Threshold Criteria, and Primary Balancing Criteria [40 CFR S300.430(f)(1)]. The Modifying Criteria, State and Community Acceptance, are not included in this analysis, because they should be considered after the Record of Decision (ROD) has been released to the public for review. The Threshold Criteria, consisting of the Overall Protection of Human Health and the Environment and Compliance with Applicable or Relevant and Appropriate Requirements (ARARs) are threshold objectives that all evaluated remediation trains *must* meet in order to be eligible for selection. Therefore, in order for a remediation train to be considered and used in this analysis, it will have already been examined to ensure it has met the Threshold Criteria.

A primary intent of this research effort is to describe the five Balancing Criteria of CERCLA in the context of WAG 6 and determine which subcriteria and evaluation measures ensure that these criteria are met. Figure 3.3 identifies the five CERCLA primary balancing criteria, denoted by the bolded boxes, and associated subcriteria as expressed in the Code of Federal Regulations (CFR). However, some of these subcriteria may not directly apply to WAG 6 or may not be mutually preferentially independent from one criteria or subcriteria to the next.

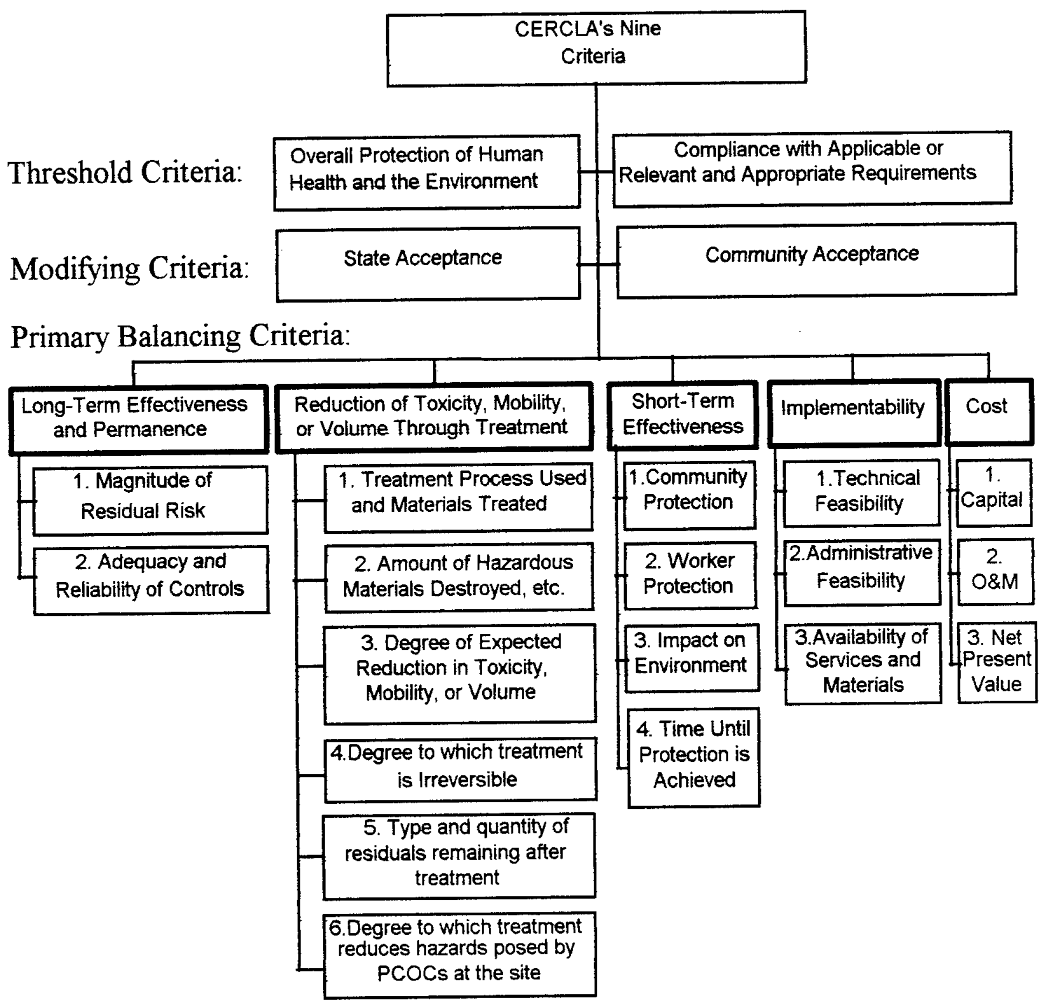


Figure 3.3 CERCLA criteria and subcriteria hierarchy [40CFR S300.430(e)(9)]

The WAG 6 team analyzed the CERCLA subcriteria of the five primary balancing criteria in reference to WAG 6, assured mutual preferential independence among the criteria as described in section 2.2.3.5, used EPA guidance for clarification [EPA/540/G-89/004], and developed evaluation measures and single dimensional value functions for each of those subcriteria which directly apply to WAG 6. Figure 3.4 depicts the WAG 6 CERCLA criteria and subcriteria hierarchy.

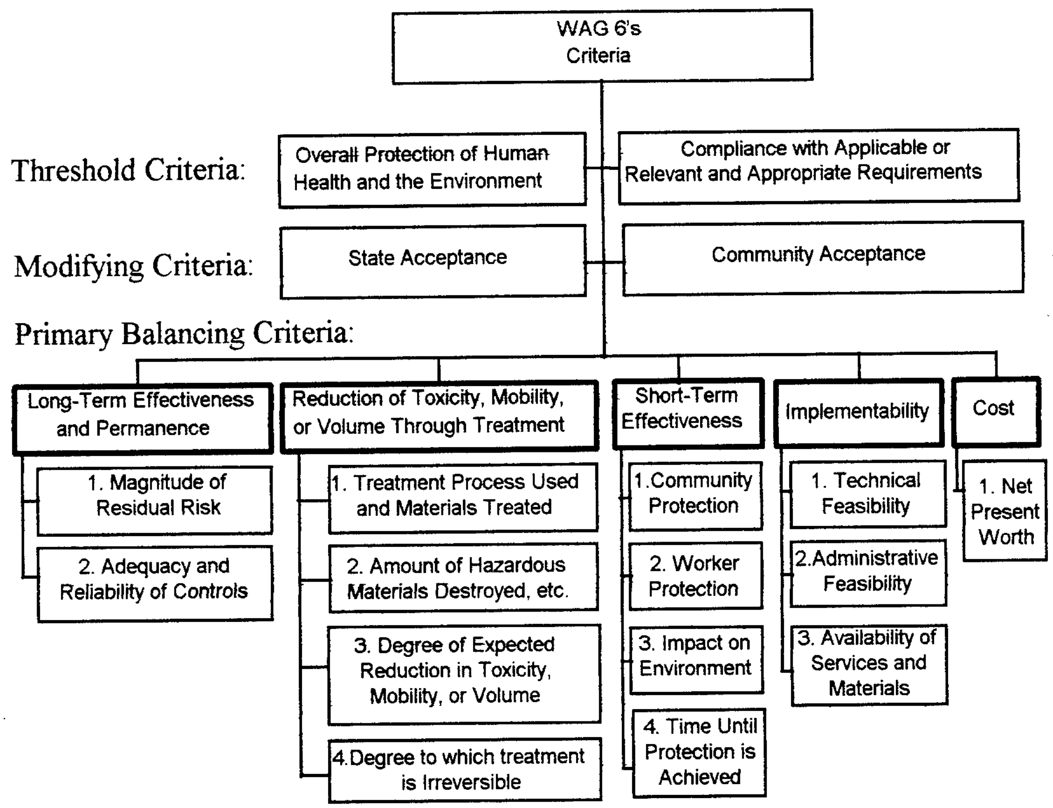


Figure 3.4 WAG 6's CERCLA based criteria and subcriteria

The two hierarchies (Figures 3.3 and 3.4) are predominantly the same. There is a slight difference in the cost subcriteria, where the WAG 6 hierarchy combines the subcriteria into one, net present cost. The WAG 6 team defines net present cost as the discounted sum of capital costs and annual O&M costs. Another distinction between the two hierarchies is that the WAG 6 hierarchy has only four subcriteria under the Reduction of Toxicity, Mobility, or Volume Through Treatment (TMV) criterion. The WAG 6 team thought subcriterion 5 under TMV (Figure 3.3) is redundant with what was addressed with subcriterion 1 under the Long-Term Effectiveness and Permanence criterion and they wanted to ensure mutual preferential independence. In the same way, they thought that subcriterion 6 under TMV (Figure 3.3) is redundant with subcriterion 3 under TMV, which already addressed the reduction of hazards.

3.5 Evaluation Measures, Scores, and Single Dimensional Value Functions

CERCLA provides limited guidance on the development of evaluation measures. It suggests whether high or low scores associated with an evaluation measure are preferred, but does not provide guidance as to the shape of the evaluation measure's single dimensional value functions.

Appendix B presents the WAG 6 CERCLA value hierarchy and discusses the development of each of the 28 evaluation measures that were used to score the trains. A list of the 28 evaluation measures is provided in Table 3.4 below:

Table 3.4 WAG 6 CERCLA Criteria/Subcriteria & Evaluation Measures

WAG 6 Subcriteria	Evaluation Measure
Long-Term Effectiveness & Permanence	
1. Magnitude of Residual Risk	1. HM Remaining in the Subsurface
	2. Percent of TCE Left in Subsurface
	3. Activity of Tc-99 in Ground Water
2. Adequacy and Reliability of Controls	Replacement of Technical Components

WAG 6 Subcriteria	Evaluation Measure
Reduction of Toxicity, Mobility, or Volume Through Treatment	
1. Treatment Process Used & Materials	PCOCs Addressed in the Treatments
2. Amount of HM Destroyed, etc.	1. Percent of TCE Destroyed, etc.
	2. Percent of Tc-99 Destroyed, etc.
3. Expected Reduction in TMV	1. Reduction of Toxicity Through In-situ
	2. Reduction of Mobility for TCE
	3. Reduction of Mobility for Tc-99
	4. Reduction in Volume of TCE zone
	5. Reduction in Volume of Tc-99 zone
4. Degree That Treatment is Irreversible	1. Percent of TCE Irreversibly treated...
	2. Percent of Tc-99 Irreversibly treated..
Short-Term Effectiveness	
1. Impact on Community Protection	Community Protection
2. Impact on Worker Protection	Worker Protection
3. Impact on the Environment	1. Surface Releases
	2. Subsurface Injection of Foreign Matls.
4. Time Until Protection is Achieved	Year Until Protection is Achieved
Implementability	
1. Technical Feasibility	1. Ability to Construct
	2. Number of System Equivalents
	3. Number of Successful Applications
	4. Effect/Impact on Future Remediation
	5. Exposure Risk from Unmonitored Path
2. Administrative Feasibility	Level of Effort to Obtain Permits
3. Availability of Services & Materials	1. Treatment/Storage/Disposal Options
	2. Minimum Number of Contractors/Sub
COST	
Net Present Cost	Net Present Cost Dollars

Each train listed in Table 3.3 was evaluated against each of the above evaluation measures using a scoring packet shown in Appendix D. Every technical expert on the WAG 6 team was asked to score each train individually, then the group of technical experts came together and discussed the scores until consensus was reached. This procedure was repeated until each train was scored and the technical experts were in agreement on the scores assigned. While the scoring was being conducted, the technical experts were not provided a copy of the corresponding value functions to avoid any bias in the scoring process. Only after all the scores were obtained, were they transformed into values through the appropriate single dimensional value functions.

Since CERCLA provided no direct guidance on the shape of the single dimensional value functions, the WAG 6 team determined an initial decision rule; single dimensional value functions would be linear across the possible range of values, which would, in their view, accurately reflect CERCLA's intentions for most of the evaluation measures. Thus, many of the single dimensional value functions are linear with either an increasing or decreasing slope, as appropriate. Appendix B describes the single dimensional value functions that were developed for each evaluation measure, and provides the rationale for their shape when they differ from the initial decision rule. These functions are critical as they convert evaluation measure scores into unitless values, which can be combined and compared as part of multiattribute preference theory described in Chapter 2.

3.6 Assessing Weights

The WAG 6 team obtained weights for each tier of the value hierarchy to reflect the relative importance of each primary balancing criteria, subcriteria, and evaluation measures, through direct assessment. The weights at each level of the hierarchy must sum to one, and so the overall weight attributed to the CERCLA value must also be one, as explained previously in Chapter 2. CERCLA contributes the following guidance for balancing (weighting): "The balancing shall emphasize long-term effectiveness and reduction of toxicity, mobility, or volume through treatment." [40 CFR S300.430(f)(1)(ii)(E)]. The team interpreted this to mean that half the weight of the primary balancing criteria should be split between Long-Term Effectiveness and Permanence and Reduction of Toxicity, Mobility, or Volume Through Treatment (hence their weight of 1/4 each). The remaining half of the weight was divided equally amongst the remaining three balancing criteria (hence their respective weights of 1/6 each), as shown below in Figure 3.5.

Unfortunately, CERCLA does not go on to distinguish or provide additional guidance for balancing/weighting the subcriteria. The WAG 6 team members asserted that since CERCLA accounted for no distinction, neither should they.

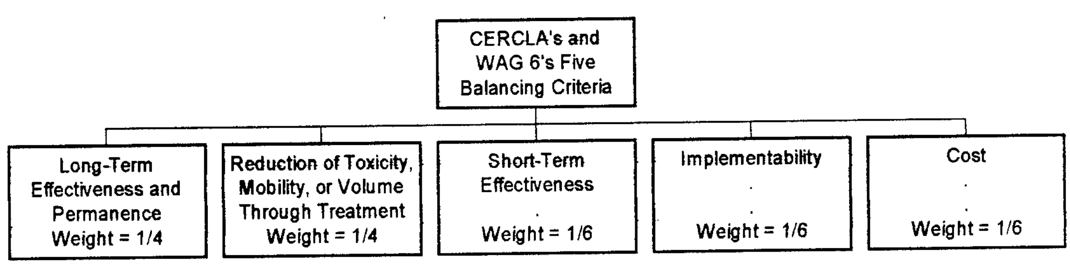


Figure 3.5 WAG 6 Hierarchy Showing Balancing Criteria Weights

The remaining weights for the subcriteria level of the hierarchy, the solid lined boxes in Figure 3.6, are equally divided and still sum to one.

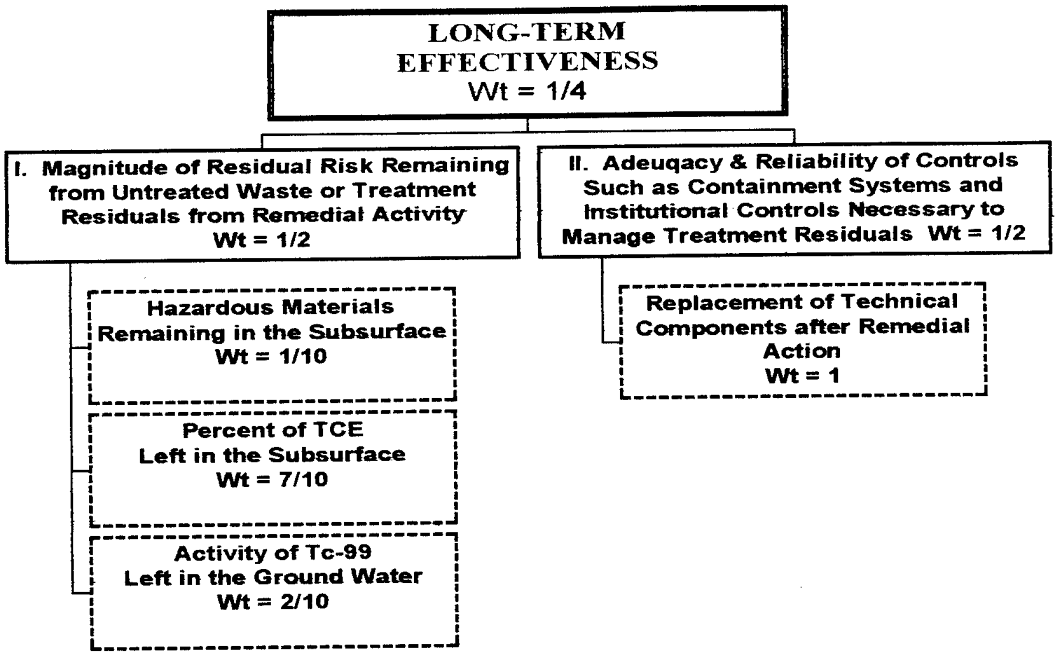


Figure 3.6 Long-Term Effectiveness Hierarchy and Weights

The next level of weights are those assigned to the evaluation measures, the dashed boxes in Figure 3.6. In the case where there is only one evaluation measure, the default weight is one (see Replacement of Technical Components after Remedial Action in Figure 3.6). Where there are several evaluation measures, the weight is again split equally, except where there is a distinction between TCE and Tc-99. Referencing CERCLA (40 CFR S300.430(f)(1)(ii)(E)), it goes on to say, "The balancing shall also consider the preference for treatment as a principal element and the bias against off-site land disposal of untreated waste." The WAG 6 team members interpreted this to mean that treating a waste was three times more valuable than disposing of it. Hence, TCE, which can be treated or destroyed, and does not need to be disposed of off-site in a landfill, weighs 7/10 (over 3 times the weight for Tc-99). Tc-99 cannot be readily destroyed, however, and in high concentrations it must be landfilled so it receives a weight of 2/10. The remaining weight of 1/10 was then assigned to the evaluation measure for hazardous materials remaining in the subsurface.

Note that the overall weight for any evaluation measure is the weight assigned to that evaluation measure, multiplied by all the criterion weights above it in the CERCLA hierarchy. For example, to calculate the overall weight for the evaluation measure of the Percent of TCE Left in the Subsurface, simply multiply 7/10 * 1/2 * 1/4 = 7/80 (see Figure 3.6).

3.7 Application of Additive Value and Power-Additive Utility Functions

Now that the evaluation measures, single dimensional value functions, weights, and scores are assessed, they must be combined into a single measure of the overall value for each alternative [Kirkwood, 1997:53]. As Grelk's work pointed out, the form of the overall value function must be easily understood by the decision maker, and allow extensive sensitivity analysis [Grelk 1997: 2-27]. The additive value function is merely a weighted average of the single dimensional value functions assigned to each evaluation measure and it is used extensively in practice [Kirkwood, 1997: 230]. It applies well in this decision opportunity because one of the primary assumptions made in the construction of the WAG 6 hierarchy was that the criteria and subcriteria are mutually preferentially independent. This assumption allows us to use the additive value function [Kirkwood, 1997: 230], presented as Equation 3.1.

$$v(x) = \sum_{i=1}^{n} \lambda_i v_i(x_i) \qquad \textbf{(3.1)}$$

where the total value calculated is represented by $v(x)$, and $v_i(x_i)$ is the single dimensional value function for measure i, and λ_i represents the weights for measure i.

It is assumed also that:

$$\sum_{i=1}^{n} \lambda_i = 1 \qquad \textbf{(3.2)}$$

Mutual preferential independence was briefly introduced in 2.2.3.5, where it was defined by a decision maker's preference for one objective not impacting their preference for any other objectives. As an example of applying this concept to the WAG 6 hierarchy, the decision makers viewed the subcriteria: Amount of Hazardous Substances Destroyed (under Long-Term Effectiveness) and Magnitude of Residual Risk (under Reduction of TMV) as mutually preferentially independent, by creating unique definitions and bounds for each of these subcriteria. The Amount of Hazardous Substances Destroyed is interpreted to mean the volume of only the PCOCs that will be destroyed, treated, or recycled through use of the technology train [Appendix B; B-12]. The Magnitude of Residual Risk is defined as any hazardous material left within the subsurface, this includes treatment residuals, degradation products, or unreacted materials [Appendix B; B-5]. Although some of the evaluation measures developed for these two subcriteria may be similar, the objective that they are measuring is perceived to be unique and independent by the decision maker.

Appendix B provides additional documentation on what the criteria and subcriteria were defined to be by the decision maker and how they were ultimately measured.

3.7.1 Uncertainty

The deterministic decision analysis models use the additive value function to produce a ranking of alternatives or trains that does not account for the uncertainty or risk associated with unknown contaminant volume. The power-additive utility function converts multiattribute values into utilities, which captures the decision maker's attitude toward risk through the use of a multiattribute risk tolerance factor (ρ_m). The power-additive utility function is expressed as [Kirkwood, 1997: 161]:

$$u(x_1, x_2, \ldots, x_n) = \begin{cases} \dfrac{1-\exp[-v(x_1, x_2, \ldots, x_n)/\rho_m]}{1-\exp(-10/\rho_m)}, & \text{when } \rho_m \neq \text{infinity} \\ v(x_1, x_2, \ldots, x_n), & \text{otherwise} \end{cases} \quad \textbf{(3.3)}$$

where $u(x_1, x_2, \ldots, x_n)$ is the overall utility for the evaluation measures $x_1, x_2, \ldots, x_n$, $v(x_1, x_2, \ldots, x_n)$ is an additive value function which calculates the overall value for evaluation measures $x_1, x_2, \ldots, x_n$, and ρ_m is the multiattribute risk tolerance factor.

For the deterministic analysis, the overall CERCLA values for each train are assessed at different spill volumes using the additive value function expressed as Equation 3.1, when modified to account for s different spill volumes becomes [Kloeber, 1997]:

$$v_s(x_{js}) \quad \sum_{i=1}^{28} \lambda_i v_i(x_{ijs}) \quad \textbf{(3.4)}$$

where s is either 50, 100, 200, 300, 400, or 500 thousand gallons, j = Train 1 through 23, and i = 1 through the 28th single dimensional value function. $v_i(x_{ijs})$ are the values from each single dimensional value function at the corresponding spill volume, s, for all trains. The values $v_s(x_{ij})$ are actual outputs of the deterministic models described in section 3.8. These values are then combined using the discrete probabilities presented in Table 3.1, which accounts for the uncertainty associated with the TCE spill volume, to calculate a single expected value representing a train's ability to meet the overall, fundamental CERCLA objective. This combination is completed using the following generic equation [Kloeber, 1997]:

$$V(x_j) = E[v_s(x_{js})] = \sum_{s} p_s v_s(x_{js}) \qquad \textbf{(3.5)}$$

where j ranges from Train 1 to Train 23, $V(x_j)$ = the expected value of train x_j, p_s = probability associated with a spill volume of s amount (from Table 3.1), and $v_s(x_{js})$ is the CERCLA value of the train at that corresponding spill volume, s from Equation 3.3. Appendix E presents the spreadsheet used to calculate $V(x_j)$ based on the data generated from the deterministic models.

Using the trains' expected values calculated above in Appendix E and the relationship established in Equation 3.2, the total utility of each train can be derived, provided the multiattribute risk tolerance factor, ρ_m, is known. The multiattribute risk tolerance factor is a measure of the decision maker's aversion to risk. However, in the case of multiple decision makers, it is often difficult to assess risk aversion. Therefore, an analysis of the sensitivity of ρ_m, can assist in determining whether it is necessary to ascertain an actual value for ρ_m. Using the theory supplied by Kirkwood, where ρ_m, varies between 0.2 and infinity, the trains' values are converted to utilities and ranked [Kirkwood, 1997: 161]. If the ranking changes at different values of ρ_m, then an attempt to quantify ρ_m directly from the decision maker must be made. However, if the rankings do not change, then the value of ρ_m is inconsequential and it can be assumed that the decision maker is multiattribute risk neutral. Appendix F demonstrates the analysis performed on ρ_m, which concludes that the value of ρ_m is irrelevant in this decision opportunity and so the train values generated from the decision models can also be interpreted as the train utilities.

3.8 The Decision Models: Deterministic and Probabilistic

Two different decision analysis software packages were used to model this decision opportunity: Logical Decisions® (LDW) and DPL™. LDW centers on value focused thinking concepts and allows the user to construct value hierarchies and enter data into a "familiar" spreadsheet format. LDW also produces numerous display options for deterministic results. DPL, utilizing decision trees and influence diagrams, handles uncertainty and probability better by allowing for sequential decisions and an unlimited number of key uncertainties and effects to be added. Grelk's work summarized the strengths and weaknesses of both software packages in his Table 3.4 [Grelk, 1997: 3-26].

Because of LDW's superiority in presenting deterministic results, 6 LDW models were created, one specific to each of the spill volumes expressed in Table 3.1. This was possible because cost and time data were provided by MSE at the same spill volumes. Appendix H provides the LDW model used to evaluate the trains at a spill volume of 50,000 gallons, this model is similar to the other 5 models, only the evaluation measure scores in cost, performance and time were changed to reflect the impact of differing spill volumes.

LDW facilitates further analysis that delves deeper than just overall rank based on the overall train values. It will actually demonstrate how well each train performs against each evaluation measure so that a decision maker can consider tradeoffs. LDW also supports weight sensitivity analysis by allowing the user to vary any criterion weight from 0% to 100% and then automatically recalculates the other weights, in the same original proportion, providing the overall value of the train, based on this one weight change.

Based on the deterministic analysis, it is possible to screen down the number of trains to where a more detailed probabilistic analysis can be performed. Probabilistic analysis is better supported by DPL and so three separate models were constructed that addressed uncertainty in time, cost, and overall CERCLA value based on the initial uncertainty in TCE spill volume. The DPL models can be viewed in Appendix I.

3.8.1 DA Modeling Assumptions

Because of the complexity of the decision opportunity, several assumptions were made in this research. The primary intent of the assumptions listed is to simplify the decision making and analysis; yet include enough information so that the analysis is objective, traceable and robust. The following list of assumptions were used in the development of the DA models:

1. The WAG 6 criteria and subcriteria are mutually preferentially independent. Section 3.7 addresses this assumption, which seems to be defensible because the criteria and subcriteria were constructed with this point in mind. Without this assumption, the additive value function would be invalid.

2. All alternatives or trains evaluated in this analysis meet CERCLA's Threshold criteria. Decision makers selected and reviewed the candidate trains to ensure that threshold criteria were met and that the technologies were aggressive, not purely containment focused.

3. The only uncertainty accounted for in this decision opportunity is volume of contaminant. Volume is not the only uncertainty, but it is a key technical uncertainty that impacts all trains and therefore must be addressed. Once the top trains have been identified in this effort, decision makers can determine where to focus additional resources to address other technical uncertainties; such as site constraints, technology performance, etc.

4. Removal efficiency for Tc-99 will be assessed by the aquifer technology, which assumes that the majority of Tc-99 is in the regional ground water aquifer. Since Tc-99 is soluble, this is a reasonable assumption. As additional information becomes available through the RI, it may be necessary to modify this assumption. However, the latest geological corings, indicate that the protective clay layer above the aquifer may

be absent. If this is correct, then the Tc-99 has a direct conduit to the aquifer, which supports the original premise that the majority of Tc-99 is in the aquifer. Appendix G highlights the standard decay function used to determine the concentration of Tc-99 for the trains evaluated in this analysis.

5. All technology trains are evaluated at 90% removal efficiency of TCE. The only exception to this is when a train exceeds 30 years to reach the 90%. Any train that requires more than thirty years is considered to add zero value with respect to time, as demonstrated by the single dimensional value function derived for time [Appendix B; B-24]. For those trains that exceed 30 years (Trains 2, 3, 4, 10, 16 and 22), 90% removal efficiency for TCE is not assumed. Rather, using linear interpolation (the 60% efficiency, cost and time data is the lowest efficiency data provided by MSE), an efficiency is calculated for the thirty year point. Net Present Cost for these trains is assumed to be at the 60% efficiency level because linear interpolation is not applicable.

3.8.2 Life Cycle Cost Modeling Assumptions

The following list of assumptions were made by MSE in deriving the Net Present Cost and train performance data from the Life Cycle Cost (LCC) model. LCC Model outputs are provided in Appendix M.

1. The unsaturated and saturated zones are fixed so that only the aquifer length is varied when addressing different TCE spill volumes. The technical expert considered the DNAPL in regards to the hydrogeologic model presented in Figure 3.2, and determined that this is a reasonable assumption [Davis, 1997].

2. Performance curves that are used to assess a trains' ability to remove or treat the contaminant are taken directly from the vendor. This assumes that the vendor, who is trying to sell the technology, is providing accurate information on the technology's performance.

3. Permeable Treatment Zones (PTZ) and In situ Redox times include the assumption that it takes one year for their installation. Their performance is assumed to be 0% at the time of installation and is then based on ground water flow, which is currently estimated at 22,400 gallons/day. These are thought to be the best technical assumptions that can be made in this situation.

4. Tc-99 is treated, using ion exchange, only by those trains that pull water out of the aquifer, such as pump and treat. All other trains assume a natural decay rate as shown in Appendix G.

5. Any technology that uses only a mechanical means of extraction from the aquifer, relies on dissolution calculations, which penalizes the technology with a longer time until remediation is achieved.

6. Cost estimates for technology trains (Trains 4-9) that incorporate the 2 Phase technology should be considered optimistic.

3.9 Summary

Figure 3.7 succinctly expresses the methodology followed in this effort, the roles of the key participants, and how the data was melded together. The WAG 6 team, comprised of AFIT/VCU and the decision makers, is responsible for the generation of the CERCLA hierarchy and weights (presented in detail in Appendix B).

The team also provides the restraining hydrogeologic model which impacts the technology trains selected for evaluation. The LCC Model provides net present cost and performance information for each technology train evaluated. Finally, AFIT collects all the information generated and translates it into decision analysis software for complete evaluation as presented in Chapter 4.

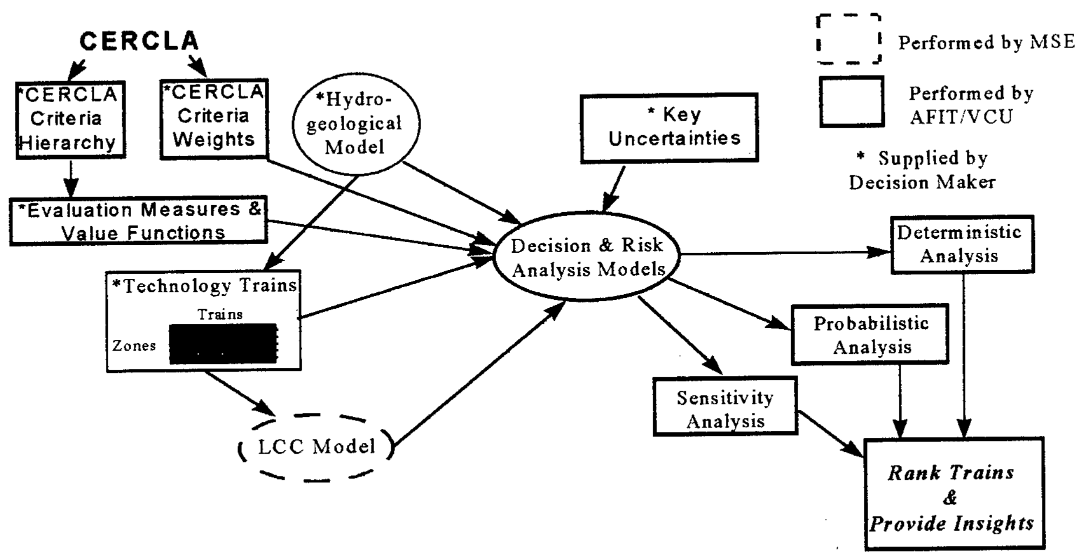


Figure 3.7 Decision and Risk Methodology Used for Train Selection

4. Results and Analysis

4.1 Introduction

This chapter presents the results from the deterministic and probabilistic models developed in Chapter 3. First, the deterministic results are presented, which highlight the trains that best meet the CERCLA criteria for the various spill volumes identified in Table 3.1. This is followed by a discussion of required CERCLA analysis, sensitivity analysis of criteria weights, and a comparison of all the trains' rankings at the two spill volume extremes. From this deterministic analysis, the top four trains will be selected for further evaluation through probabilistic analysis.

The probabilistic analysis will present the results from the models that initially explore how the utility of the top four trains are affected by the uncertainty found in volume. Specifically, overall CERCLA utility, net present cost and time will be examined for the influence of uncertainty in volume.

4.2 Deterministic Results

Six models were built to account for the six different spill volumes associated with this site. In the figures that follow, it will be helpful to remember that Train 23 is the "No Action Alternative" and may be used as a reference point to compare against all other trains. Figure 4.1 demonstrates the train rankings for a TCE spill volume of 50,000 gallons, which represents the lower end of the spill distribution. Figure 4.1 also shows how well each train meets each of the five CERCLA balancing criteria. The maximum value a perfect train can achieve is a value of ten.

Upon examining Figure 4.1, a few observations can be made. First, there is little difference in overall value for the top 4 trains. The highest rated train, Train 7 = 7.709, and the fourth ranked train, Train 1 = 7.576, have a total difference of 0.133. The top trains do equally well in the Reduction of Toxicity, Mobility, and Volume balancing criterion (TMV Reduction) and fairly equally in Long-Term Effectiveness and Permanence (Long-Term Effect). There is a more notable difference in Net Present Cost and Implementability criteria values, as demonstrated by Trains 7 and 21. Train 7 (2Phase & Surfactants) receives a higher value in Implementability than Train 21, LASAGNA and Oxidation. However, Train 7 does not receive as much value in the Net Present Cost criterion, which indicates it costs more.

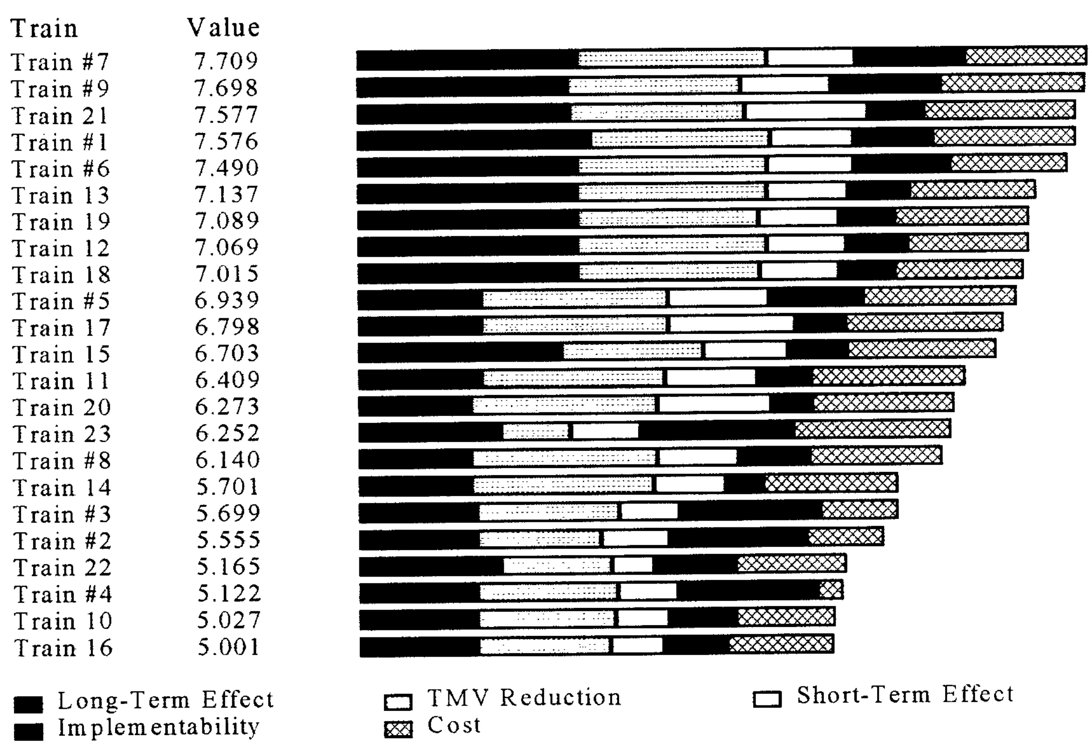


Figure 4.1 Overall CERCLA ranking for 50,000 gallon spill

Appendix J provides further quantification of each trains' balancing criteria's values at each different spill volume. Table 4.1 demonstrates this information for the 50,000 gallon spill scenario, the same information was used to create Figure 4.1. The maximum value a train can receive for any criterion is ten.

Table 4.1 Overall CERCLA and Balancing Criteria Values for Trains 1-23 at a 50,000 gallon spill site

Trains Ranked High to Low	CERCLA VALUE Goal	Long-Term Effect Goal	TMV Reduction Goal	Short-Term Effect Goal	Implement-ability Goal	Cost Goal
7	7.709	9.231	7.958	5.625	7.003	7.828
9	7.698	8.848	7.271	5.750	7.005	9.242
21	7.577	8.897	7.334	7.843	3.541	9.679
1	7.576	9.731	7.625	5.250	5.066	9.071
6	7.490	9.231	7.979	5.500	6.097	7.510
13	7.137	9.231	7.958	5.125	3.866	8.004
19	7.089	9.231	7.625	5.125	3.625	8.457
12	7.069	9.231	7.979	5.000	3.866	7.692
18	7.015	9.231	7.646	5.000	3.539	8.191
5	6.939	5.231	7.813	6.376	6.077	9.603
17	6.899	8.444	5.891	5.250	5.265	9.351
15	6.798	5.231	7.813	8.001	3.175	10.000
11	6.703	8.487	5.945	5.375	3.782	9.371
20	6.409	5.231	7.688	5.876	3.416	9.748
23	6.273	4.731	7.813	7.249	2.590	8.937
8	6.252	5.999	2.966	4.502	9.603	10.000
14	6.14	4.731	7.813	5.124	4.546	8.332
3	5.701	4.731	7.688	4.625	2.412	8.501
2	5.699	5.000	5.999	3.877	8.931	4.925
22	5.555	4.999	5.212	4.376	8.724	4.955
4	5.122	5.000	5.928	3.877	8.864	1.644
10	5.027	5.000	5.801	3.377	4.246	6.327
16	5.001	5.000	5.570	3.377	3.999	6.758

Figure 4.2 shows the variability of the ranking due to spill volume uncertainty by demonstrating the overall CERCLA ranking for a 500,000 gallon spill site. Not

only do the overall train rankings change, but there is more variability among the top trains in Long-Term Effectiveness, Implementability and Net Present Cost criteria values. There is a larger difference in value between the top 4 trains as well. The first train, Train 1 = 7.474, and the fourth ranked train, Train 17 = 6.798, which results in a 0.676 difference in overall CERCLA value. In addition, notice that Train 4 receives no value for cost; its expected net present cost is approximately $32 million, the most expensive of all trains at any spill volume (Appendix B; B-35).

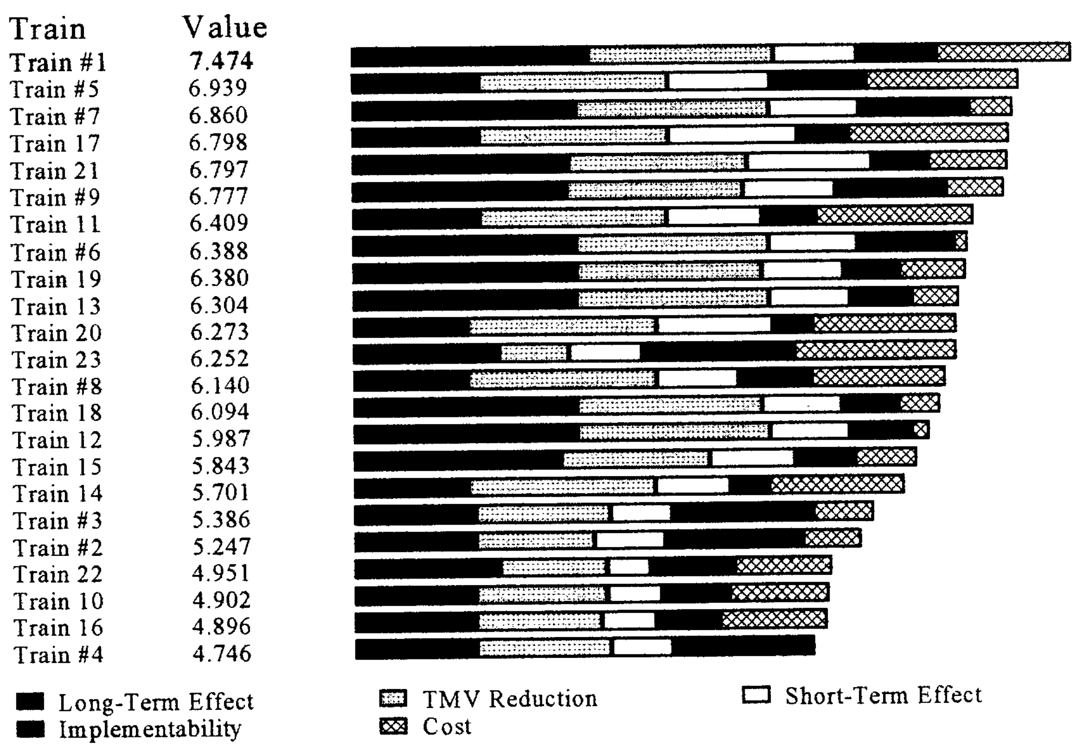


Figure 4.2 Overall CERCLA ranking for 500,000 gallon spill

At this point it becomes necessary to examine more closely each of the five balancing criteria to determine why the trains scored as they did. Since the spill volume is variable with the probability distribution discussed in Chapter 3, the expected value of that distribution is closest to a spill volume of 100,000 gallons, hence this volume is selected for further analysis. Figure 4.3 shows the overall CERCLA rankings for a 100,000 gallon TCE spill. Notice that Figure 4.3 has different overall train rankings from Figures 4.1 and 4.2, and has less variability among the top trains than Figure 4.2. There is also less of a difference in value among the top four trains compared to Figure 4.2. Train 9 = 7.596 and Train 21 = 7.49, which is only a 0.106 difference.

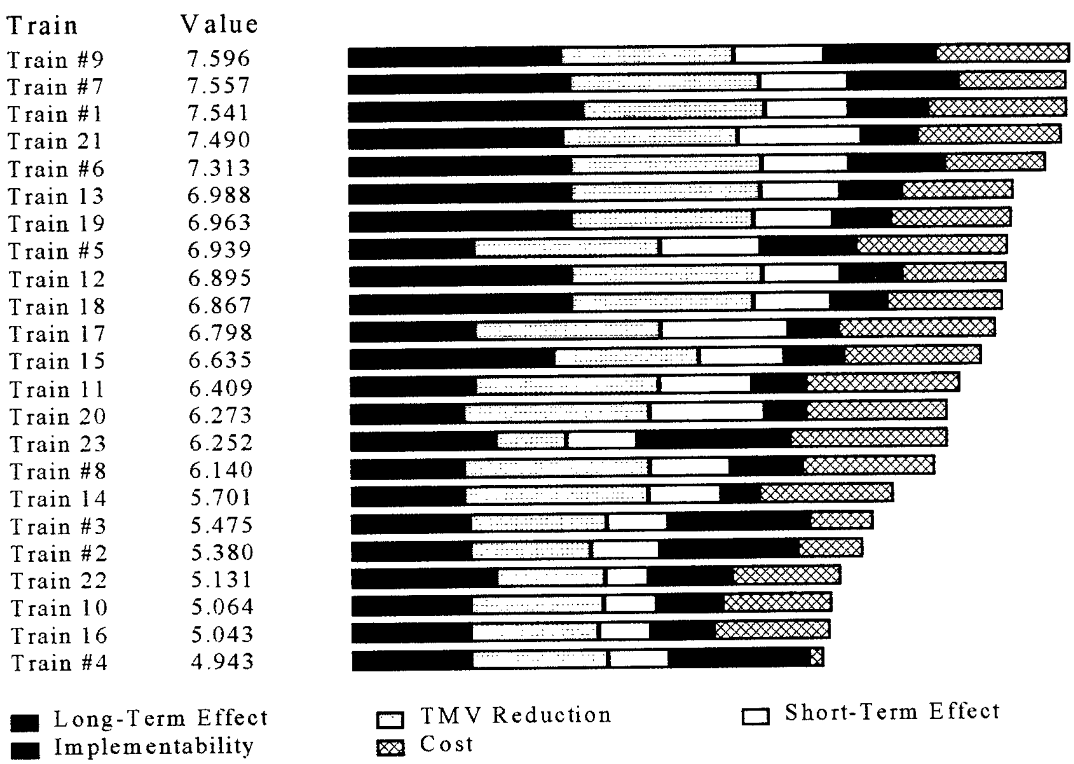


Figure 4.3 Overall CERCLA ranking for 100,000 gallon spill

It is possible to further decompose Figure 4.3 by looking at each of the balancing criteria and their related evaluation measures. Consider Figure 4.4, which demonstrates the ranking using only one evaluation measure, Net Present Cost at

100,000 gallons (the same spill volume as in Figure 4.3). Train 17 receives the maximum value for cost because its expected net present cost is approximately $1.2 million, the least expensive technology train. Although Train 23 (No Action Alternative) is assumed to have no additional cost, it is not considered a technology and therefore it cannot set the lower cost limit. Train 23 does receives a value of 10, however, which is the maximum value it could achieve. Train 4, 2 Phase and Pump & Treat, receives the lowest value because it is the most expensive train at this spill volume. Train 4 does not receive zero value, however, because it has not reached the most expensive cost, which was shown to occur at a volume of 500,000 gallons. The top four trains in Overall CERCLA value at this spill volume, that were shown in Figure 4.3, are denoted by an asterisk in Figures 4.4 and 4.5.

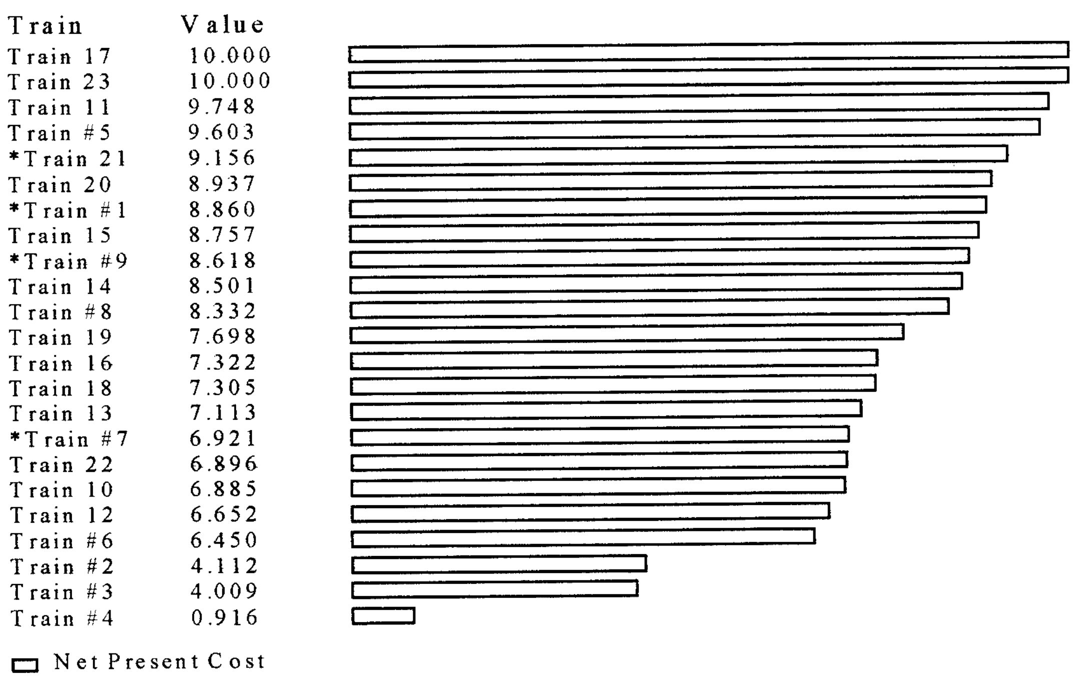


Figure 4.4 Net Present Cost Rankings Only - 100,000 gallon spill

The Short-Term Effectiveness criteria also provides a great range in value among the trains and is depicted in Figure 4.5, for a 100,000 gallon spill. Again, the train rankings do not match those for the overall CERCLA value (which are asterisked), but provide further insight into how train values for short-term effectiveness compare. Train 20, LASAGNA and Redox, receives no value for subsurface injection, because it injects reagents into the aquifer, yet it ranks third in overall short term effectiveness because it maximizes the rest of the evaluation measures.

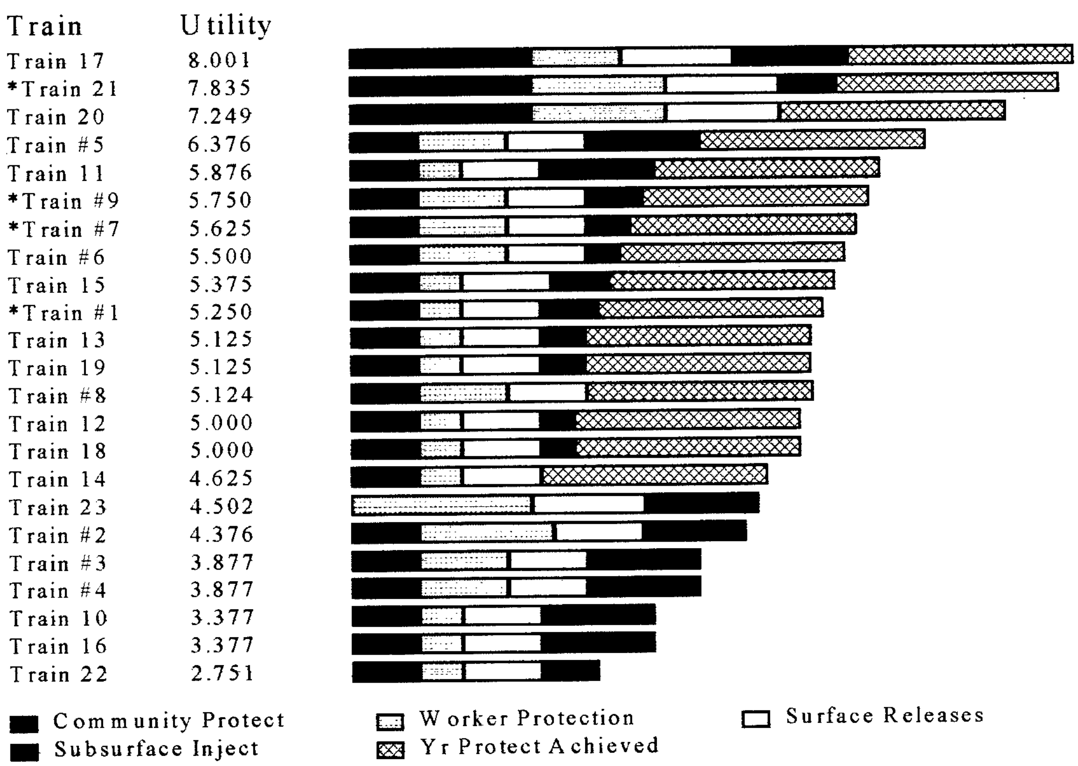


Figure 4.5 Short-Term Effectiveness Rankings Only - 100,000 gallon spill

Similarly, each of the five balancing criteria can be examined to trace the advantages of each train, against each evaluation measure, in each balancing criteria.

Appendix J contains the remaining criteria of Long-Term Effectiveness and Permanence, Reduction of Toxicity, Mobility, and Volume, and Implementability for the 100,000 gallon spill scenario.

4.3 Required CERCLA Analysis

The bar graphs just presented relate how well the trains perform overall. They are useful in comparing trains against one criterion or specific evaluation measure. To more clearly demonstrate how trains compare when they are assessed against two or more criteria, scatter plots are used. Scatter plots demonstrate a train's performance on one criteria plotted against that same train's performance on another criteria. To maintain consistency with the bar graphs, the values from the 100K gallon spill scenario will be used in this section.

CERCLA states that the remedial technology selected should be cost effective. It further defines "overall effectiveness" as the following three of the five primary balancing criteria: Long-Term Effectiveness and Permanence, Reduction of Toxicity, Mobility or Volume through Treatment, and Short-Term Effectiveness [40 CFR S300.430 (f)(ii)(D)]. Using a scatter plot, Figure 4.6 compares the Overall Effectiveness of a train, as defined by CERCLA, to the train's Net Present Cost.

Trains that are in the upper left portion of Figure 4.6 represent those trains that have the lowest cost and the highest overall effectiveness value and thus are most desirable. The train that has the highest effectiveness value is Train 21, LASAGNA and Oxidation, but it does not have as low a cost as Train 17, LASAGNA and PTZ. From Figure 4.6, it is possible for the decision makers to understand the tradeoffs between cost and overall effectiveness. As a quick check, the train that costs the least and has the lowest effectiveness value is Train 23, the No Action Alternative. There are some expected costs associated with Train 23; such as obtaining regulator approvals, monitoring, reporting, etc.

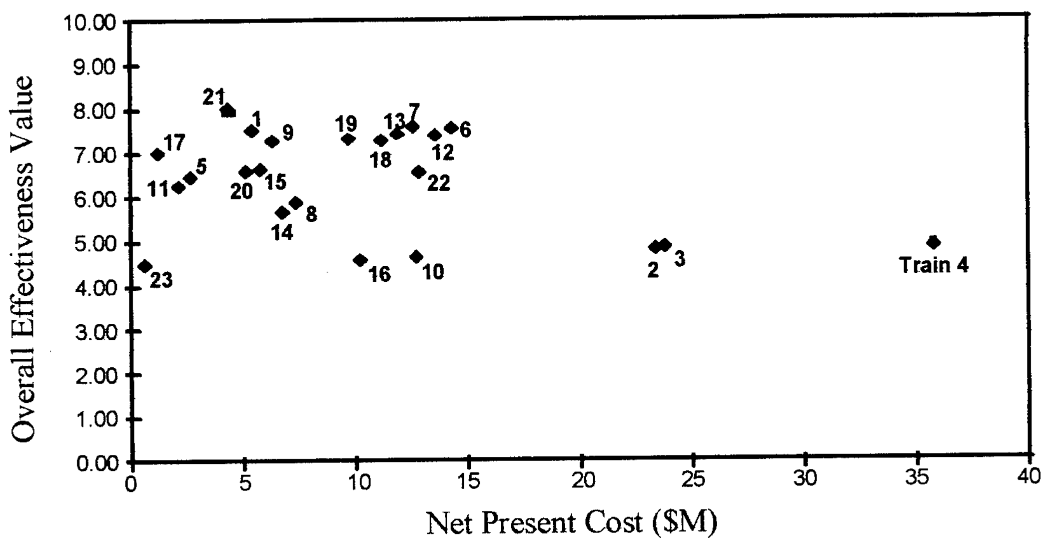


Figure 4.6 Net Present Cost vs. Overall Effectiveness Value (at 100,000 gals.)

Examining Figure 4.6 for deterministic dominance reveals that Trains 23, 17 and 21 are nondominated. That is, based on the CERCLA value-focused thinking evaluation and its assumptions, no train has both a better overall effectiveness value and a lower cost than these trains. For example, "if" all the data was completely accurate, there would be no reason to select Trains 11 or 5 because Train 17 has a higher overall effectiveness value for a lower cost. Train 17 is said to deterministically dominate Trains 11 and 5 and all other trains that are to the right and lower. Similarly, Train 21 deterministically dominates Trains 9 and 1 and all other trains below and to the right of it. Of course, such conclusions depend on the precision of the data used.

A decision maker may also find it useful to understand the tradeoffs between the overall CERCLA value determined for each train and Net Present Cost, as shown in Figure 4.7. It should be noted that the overall CERCLA value in Figure 4.7 includes values from all the balancing criteria **except** for net present cost values.

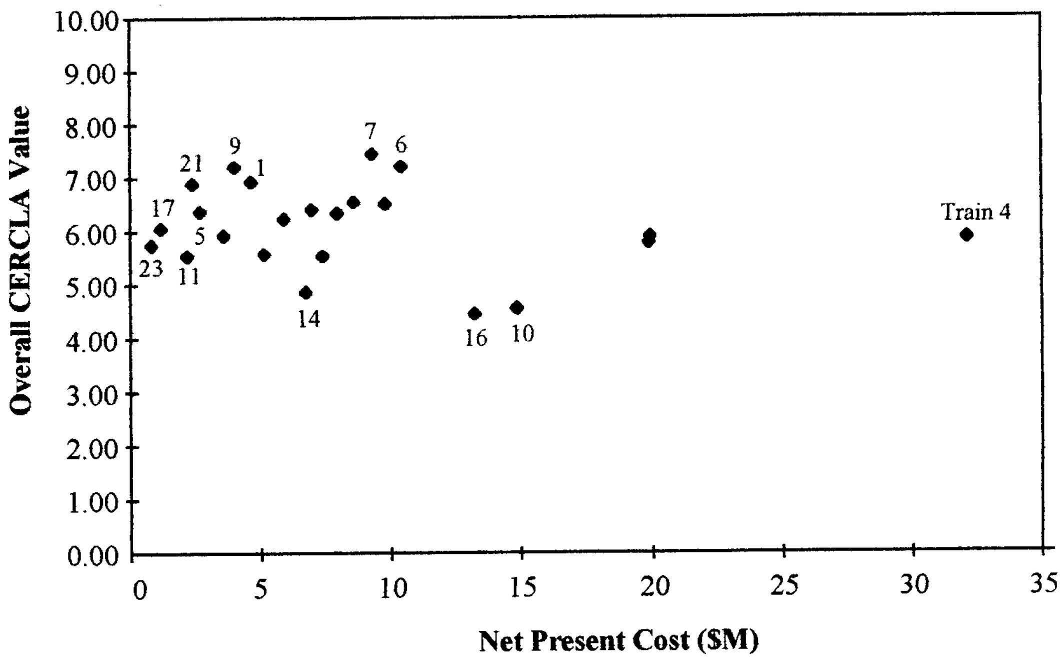


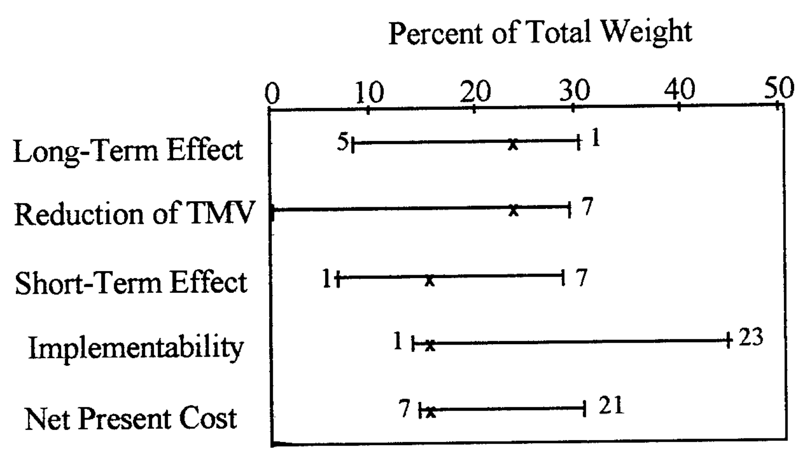
Figure 4.7 Net Present Cost vs. Overall CERCLA Value (at 100,000 gals.)

Figure 4.7 demonstrates that Trains 23, 17, 21, 9, and 7 are nondominated by the other trains when comparing cost to overall CERCLA value. No other train has both a larger overall CERCLA value and a lower cost than these trains. Train 9 has shifted over from being dominated in Figure 4.6, where overall effectiveness and net present cost were plotted, by Train 21 to being nondominated in Figure 4.7. The additional value received from the Implementability criterion within the overall CERCLA value (plotted in Figure 4.7) is enough to give Train 9 a higher overall

CERCLA value than Train 21. Deterministically, one would normally choose a nondominated train.

4.4 Criteria Weight Sensitivity Analysis

Because CERCLA fails to specifically identify weights for the five primary balancing criteria, the assignment of weights and how they affect the overall CERCLA value and ranking of trains is an area of potential concern. Chapter 3 discusses the assumptions that are made in order to arrive at the initial set of weights depicted in Figure 4.8 and Table 4.2. However, suppose a decision maker interprets CERCLA as having no preference, unless a specific criterion is explicitly stated. It is possible to examine the influence any weight may have on the top ranked train by reviewing the sensitivity analysis results presented in Figure 4.8:



x = initial weights causing Train 9 to rank the best in Overall CERCLA Value

Figure 4.8 Weight Sensitivity Analysis at 100,000 gallons

Figure 4.8 graphically demonstrates the range each weight can be varied for each criterion before changing the ranking of Train 9 to one of the other trains demonstrated at the ends of the lines. It is important to realize that as the weight for a criterion is adjusted, the other weights are changed proportionally and simultaneously for the other criteria, thus assuring that the criteria weights always total 100%.

Table 4.2 also depicts how Train 9, which is the top ranked train under the current set of weights for a 100,000 gallon spill, is sensitive to adjustments in primary balancing criteria weights. The table lists the lowest and highest percentage that the particular criterion can be adjusted, before there is a change in the ranking of the top train. The train that replaces Train 9 in rank of overall CERCLA value is indicated by the bolded number in parentheses. For example, consider the Net Present Cost (NPC) criterion, where the lowest percentage weight for which the current ranking remains valid is 14.8%. At a lower weight for NPC, Train 9 is replaced by Train 7. Likewise, a weighting of NPC higher than 30.5% will change the overall ranking resulting in Train 21 having a higher CERCLA value.

Table 4.2 Sensitivity of Train 9 to Adjustments in Criteria Weights

Criterion	Lowest Percent of Total Weight	Initial Percent of Total Weight	Highest Percent of Total Weight
Long-Term Effectiveness	8.4 **(5)**	25.0 (9)	29.5 **(1)**
Reduction of TMV	0	25.0 (9)	29.1 **(7)**
Short-Term Effectiveness	6.2 **(1)**	16.7 (9)	28.5 **(7)**
Implementability	14.0 **(1)**	16.7 (9)	45.0 **(23)**
Net Present Cost	14.8 **(7)**	16.7 (9)	30.5 **(21)**

Train 9 seems to be the most sensitive to lowering the weight for NPC criterion, allowing only a 1.9 percent decrease in weight before being usurped by Train 7 in the ranking. Decision makers may decided to increase the weight associated with

NPC, stressing the importance of a cost effective solution. If this were the case then other criteria weights would be lowered accordingly making the criterion weight for Implementability most sensitive to change. Another interesting observation that can be made from Table 4.1 is that Train 9 is replaced the same number of times by both Train 7 and 1, averaging about a 6% change in any criterion weight. Appendix K contains the sensitivity graphs that support the derivation of Figure 4.8 and Table 4.2.

4.5 Discussion of Train Rankings as Affected by Volume

After reviewing the discussion of weight sensitivity, it might be asked how do variations in volume compare? Until now, the analysis has centered around the most probable spill volume of 100,000 gallons, and a deterministic analysis has been performed. Figure 4.9 portrays the impact of volume on the overall CERCLA value rankings of the 23 trains. The extreme points of the volume distribution were used to demonstrate the range of rankings a train will experience as volume is changed. From this chart it is possible to recognize the top performers by those that consistently rank high, and have little variation in rank, regardless of the spill volume.

After examining Figure 4.9 it is clear that the top four trains are: Trains 7, 9, 1, and 21. Although Trains 5 and 17 rank above the 5^{th} place ranking line for the largest spill volume, they perform poorly at smaller spill volumes. Considering smaller spill volumes have a higher probability of existing than larger spill volumes based on the information provided in Table 3.1, further consideration of Trains 5 and 17 would suggest accepting the risk of lower overall CERCLA values. However, as more accurate estimates of the spill volume become available, this would be a critical issue to reexamine.

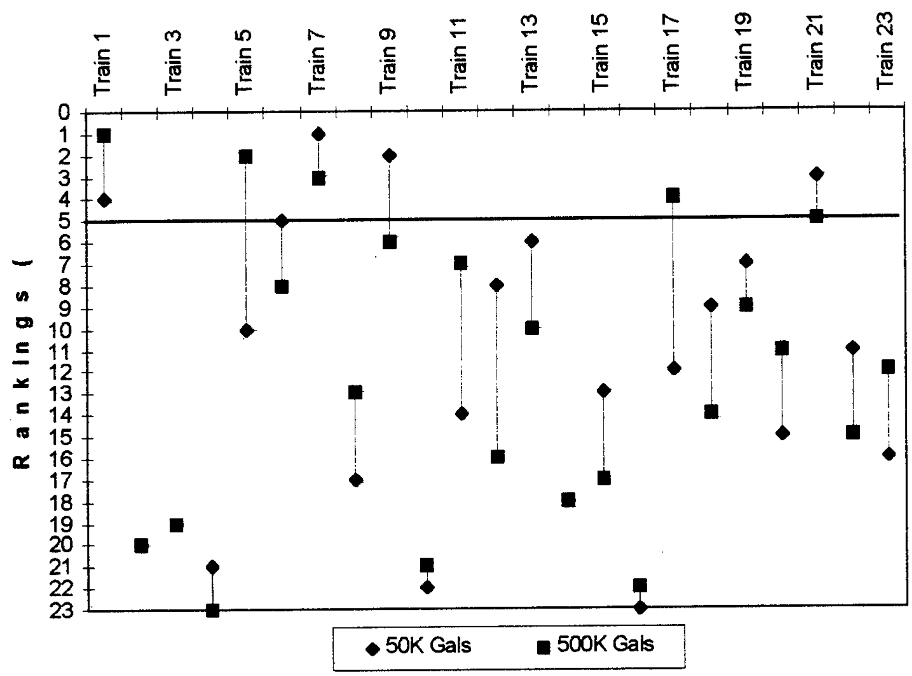


Figure 4.9 Train Rankings for Differing Spill Volumes

Appendix J contains a listing of all train rankings at all spill volumes. Interestingly, these trains are predominantly the same trains that surfaced during the deterministic criteria weight sensitivity analysis for a 100,000 gallon spill site. With these top trains identified, a probabilistic analysis was performed which better demonstrates the consequences of uncertainty in spill volume.

4.6 Probabilistic Analysis

Chapter 3 provides support for the assumption that for this decision opportunity, the expected CERCLA values can also be interpreted as expected

CERCLA utilities. Appendix E shows how the expected values/utilities for the trains are calculated. Table 4.3 shows the expected utility and ranking for each train.

Table 4.3 Expected Utility of Trains

Trains	Expected Utility	Train Ranking
7	7.61	1
9	7.60	2
1	7.56	3
21	7.49	4
6	7.36	5
13	7.04	6
19	7.00	7
12	6.94	8
5	6.94	9
18	6.91	10
22	6.81	11
17	6.80	12
15	6.61	13
11	6.41	14
20	6.27	15
23	6.25	16
8	6.14	17
14	5.70	18
3	5.63	19
2	5.49	20
16	5.13	21
4	5.06	22
10	5.01	23

The top trains identified by expected utility are 7, 9, 1 and 21. These are the same top four trains that surfaced in Figure 4.3, where the trains were ranked for a 100,000 gallon spill. There is a difference in the order of the top four. Train 7 places first in expected utility but is second to Train 9 at the 100,000 gallons scenario. This implies that while Train 9 performs well at one spill volume, it is out performed by Train 7 at the other spill volumes.

When conducting a probabilistic analysis, it is common to use risk profiles, which are plots that demonstrate the risk involved with a particular alternative or train. In this analysis, the risk is associated with differing spill volumes and quantifying its impact on train performance in the areas of overall CERCLA value, Net Present Cost and time until protection is achieved. A cumulative risk profile is nothing more than the adding up of chances or probabilities of those individual outcomes [Clemen, 1996: 123]. Consider Figure 4.10 where risk profiles of the top four trains are presented for the total CERCLA utility. These plots show the CERCLA value at different probabilities, the same probabilities that represent the spill volumes.

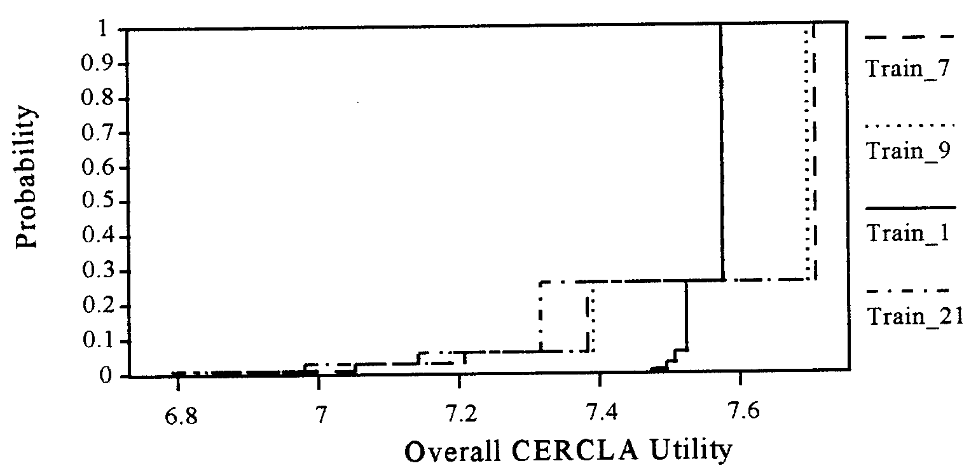


Figure 4.10 Risk Profile of Overall CERCLA Utility

The optimal train in Figure 4.10 would reach the highest CERCLA utility at the lowest possibility. Another way to interpret this figure is looking at Train 1, there is a 0.35 probability that Train 1 will have an overall CERCLA utility of 7.58 or less. Train 1 also exhibits a smaller range of utility compared to the other risk profiles, which means that uncertainty in volume changes the overall CERCLA utility very little. It is not difficult to reason then that Train 21, the line always to left of the other profiles, would never be selected. Train 21 is said to be stochastically or probabilistically dominated by the other trains, because at any point, there is always another train that has the same if not greater overall utility.

Another interesting risk profile comparison can be made with Net Present Cost. Figure 4.11 demonstrates how uncertainty in volume translates into uncertainty in cost. The interpretation of this figure is similar to Figure 4.10.

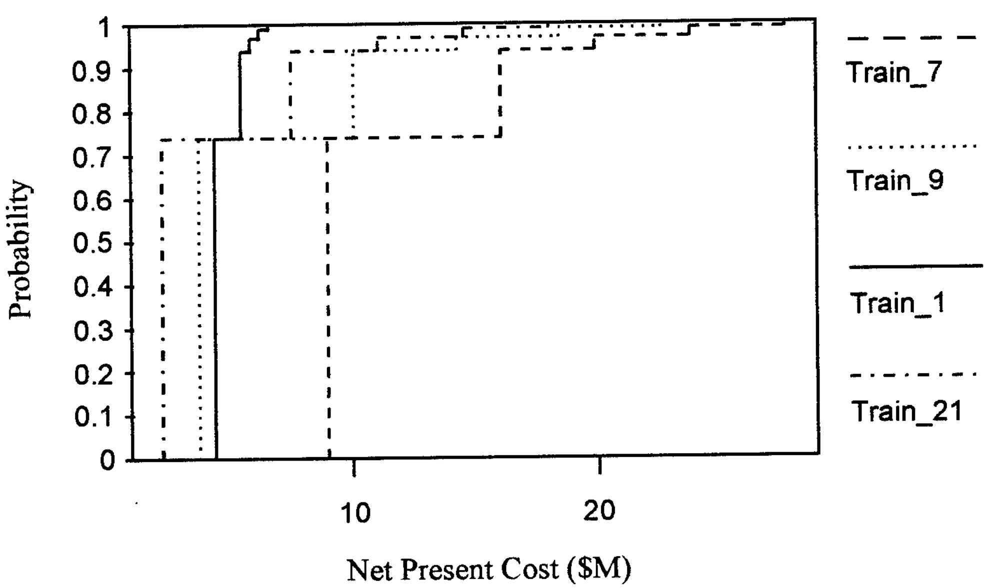


Figure 4.11 Risk Profile of Net Present Cost

Train 1 still exhibits little variance, but in this case its Net Present Cost does not seem to be affected by the uncertainty in volume. In addition, the most preferred profile will be one that has a high probability of low cost, or the profiles closest to the left, which differs from Figure 4.10. Therefore, Train 7 is the worst train in this case and is stochastically dominated by all the other trains. Additionally, Train 7 and Train 9 are stochastically dominated by Train 21.

Based on this analysis, as a decision maker considering only Net Present Cost, you would select either Train 1, 9 or 21. Train 1 seems to be the more likely choice, because there is a 74% chance of it costing $4.7 million and a 26% chance of a higher cost. The most Train 1 would ever cost is only $6.9 million, but its expected cost is $5 million. Train 9 has a 74% chance of costing $4 million and a 26 % chance of a larger cost. Train 9 has an expected cost of $6.24 million but could cost as much as $24.8 million. Train 21 has a 74% chance of costing $2.4 million with a 26% chance of a higher cost. The most Train 21 would ever cost is $19.8 million, which seems a bit risky. However, the expected cost of Train 21 is only $4.3 million. The decision maker is faced with deciding whether it is worth risking approximately $13 million (19.8-6.9) in order to save $700,000 in expected costs. Of course, this analysis is dependent upon the accuracy of the assumptions made in the decision and life cycle cost models.

Finally, the issue of time until protection is achieved is addressed with the risk profile of time, shown in Figure 4.12. The most interesting point demonstrated by this figure is that, based on the current model assumptions, uncertainty in volume has very little impact on time. Train 1 takes the least amount of time and is unaffected by uncertainty. It can be said that Train 1 deterministically dominates all other trains because its risk profile reaches completion in 1.33 years, sooner than all the other profiles begin. The next closest train is Train 7 which deterministically dominates Trains 9 and 21, as it finishes in 5.7 years, before either Train 9 or 21 begin. Finally, it can also be said that Train 21 is deterministically dominated by all other trains. It takes the longest and all other trains have finished before Train 21 even begins. It seems surprising that volume has little impact on time to remediate for these top four trains. Based on the 10-year plan and assuming construction of the train would be complete by 2002, any train taking 8 years or less would be considered extremely successful. Train 21 is the only train that does not meet that goal; it has an expected time of 8.3 years.

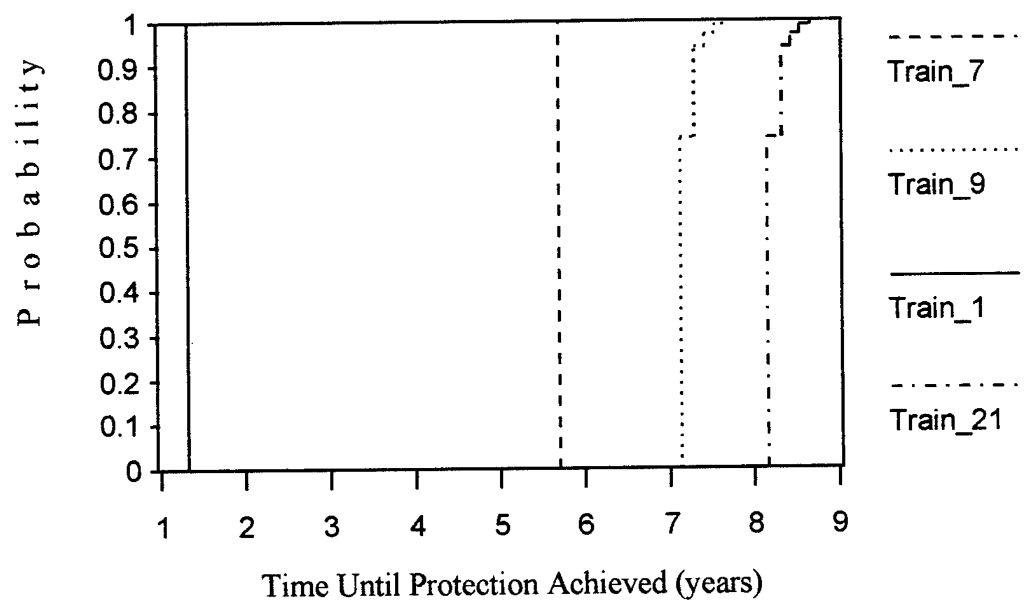


Figure 4.12 Risk Profile for Time

4.7 Conclusions

Through deterministic analysis, the 23 candidate trains were evaluated and screened by the use of bar graphs and scatter plots. The top four trains, those that best meet the CERCLA criteria at all spill volumes are:

* Train 7 - 2Phase and Surfactants
* Train 9 - 2Phase and Oxidation
* Train 1 - DUS
* Train 21 - LASAGNA and Oxidation

Further probabilistic analysis shows the impact of volume uncertainty on these trains with respect to overall CERCLA Utility, Net Present Cost and Time Until Protection is Achieved. Table 4.4 compares the top four trains against each other with respect to expected overall CERCLA Utility, expected Net Present Cost and expected Time Until Protection is Achieved by ranking the trains 1st through 4th. Appendix L provides the actual values associated with these rankings. There was no train that ranked the highest consistently across all three categories as shown in Table 4.4.

Table 4.4 Summary of Top Four Train Rankings

Trains	Expected Overall CERCLA Utility	Expected Net Present Cost	Expected Time Until Protection Achieved
Train 1	3	2	1
Train 7	1	4	2
Train 9	2	3	3
Train 21	4	1	4

A risk seeking decision maker, strictly motivated by achieving the lowest expected cost, willing to accept the risks of a longer expected time to remediate and a lower expected CERCLA utility, would select Train 21. A risk averse decision maker would select Train 1 because although the expected cost is slightly higher then Train 21, the expected variation in cost is less. In addition, Train 1 performs the quickest and has an expected CERCLA utility that is very close to Trains 9 and 7. If the decision maker is risk seeking, from the aspect that costs are of no concern, then Train 7 is the best pick as it ranks highest in expected utility and second best with respect to time.

The analysis provided in this chapter is susceptible to the accuracy of the data and assumptions made in both the decision analysis models and life cycle cost model. This information should be used in concert with expert opinion and should complement the decision making process not supersede it.

5. Findings, Conclusions, and Recommendations

5.1 Summary of Analysis and Results

Selecting a remediation technology for a CERCLA site is a very complicated process. Although guidance, such as the NCP within CERCLA and other related environmental regulations exists, it does not provide a lucid, traceable methodology for evaluating remediation technologies.

Utilizing the concepts of value-focused thinking and multiattribute preference theory and basing them in CERCLA, provides a defensible, transparent methodology to assist decision makers in structuring their analysis of remediation technologies (trains). Value-focused thinking requires decision makers to take a step back and examine their values in the decision opportunity. Identifying values assists in generating alternatives (or trains) that meet those values; trains that may not have been obvious otherwise. Multiattribute preference theory supports decision analysis modeling which quantifies the values and preferences of the decision maker; allowing trains to be ranked on their ability to meet those values. Quantification allows further sensitivity analysis on how rankings are subject to change through adjustments in model parameters; such as criteria weights and volume.

The trains selected for this analysis are limited to those that aggressively treat the PCOCs (TCE and Tc-99). There is one exception, the No Action Alternative, Train 23, which is considered as a baseline. The decision analysis model has 28 evaluation measures that evaluate the five CERCLA balancing criteria. Of these 28 measures only 8 are impacted by uncertainty in PCOC volume, the remaining evaluation measures are constant throughout the analysis.

It is important to realize the context of this analysis. This research was conducted prior to the feasibility study, while remedial investigation data was still being collected. The analysis presented serves to demonstrate the type of data that could be generated and how it could be used in the decision making process. The deterministic analysis focused on the performance of the trains and their ability to meet the CERCLA criteria at various spill volumes. This portion of the analysis showed how to screen down the initial trains to a smaller set of the most competitive trains shown in Table 5.1

Table 5.1 Description of the Top Four Trains

Train	Description
Train 1	Dynamic Underground Stripping, addresses all three hydrologic zones and includes ion exchange, working parallel in the aquifer
Train 7	2Phase in the Unsaturated and Saturated zones and Surfactants in the aquifer, working in parallel with ion exchange
Train 9	2Phase in the Unsaturated and Saturated zones and Oxidation in the aquifer, without ion exchange
Train 21	LASAGNA in the Unsaturated and Saturated zones and Oxidation in the aquifer, without ion exchange

These trains consistently placed in the top five for overall CERCLA value at all spill volumes, except for Train 9 which ranked 6^{th} at the 500,000 gallon spill volume. In addition, when expected CERCLA values/utilities are calculated, these trains again placed in the top four as shown in Table 5.2. Included in this table are the top 6 trains to demonstrate the difference in expected CERCLA value/utility. The second and third ranked trains vary by only hundredths in expected value/utility from the top train, but by the sixth ranked train, there is a 0.57 loss in expected CERCLA value/utility compared to the top train. These rankings depend upon the assumptions of the model and the precision of the scoring team in evaluating the technologies.

Table 5.2 Expected CERCLA Value/Utility of Top Trains

Train Ranking	Train	Expected CERCLA Value/Utility	Difference from Top Train
1	7	7.61	
2	9	7.60	0.01
3	1	7.56	0.05
4	21	7.49	0.12
5	6	7.36	0.25
6	13	7.04	0.57

The top four trains were then subjected to probabilistic analysis demonstrating the impact of volume uncertainty on overall CERCLA utility, Net Present Cost, and Time Until Protection is Achieved. Based on the estimated probabilities provided, in the analysis for overall CERCLA utility, Train 21 is stochastically dominated by the other top four trains. This means that at least one of the other top four trains, at the same level of probability, has equal or greater overall utility. Examining Net Present Cost for dominance revealed that Trains 1 and 21 dominate Trains 7 and 9, indicating that Trains 1 and 21 cost less than Trains 7 and 9. Concerning Time Until Protection is Achieved, Train 1 dominates the other three trains by being the train quickest to remediate the site.

5.2 Conclusions

In evaluating how well the top four trains attain overall CERCLA utility, which includes Net Present Cost and Time Until Protection is Achieved, the greatest expected utility achieved is 7.61 for Train 7. A decision maker who is risk neutral may select Train 7 because it does obtain the best overall CERCLA utility. However, a risk seeking decision maker motivated by potentially saving $700,000 in expected costs, but at the same time willing to accept the risk of incurring a $13 million cost, the loss of a little CERCLA utility and the risk of a longer expected time to remediate, may select Train 21. Conversely, if a risk averse decision maker is concerned about any variation in cost, wants the quickest Time Until Protection is Achieved, and is willing to pay an expected $700,000 more, then Train 1 is the best alternative. These are some of the tradeoffs that ultimately must be faced by the decision maker. Again, it is important that these tradeoffs are considered within the context of the modeling assumptions and data accuracy.

5.3 Recommendations

The WAG 6 team should use the decision analysis methodology presented in this effort in the actual RI/FS decision making process. The results and conclusion represented in this report support only the screening of 23 potential remediation alternatives down to four highly competitive alternatives. Although there is a temptation to base the technology selection on this analysis alone, there are serious constraints that must be realized. Quantitative models can not capture all the subtleties present in a complex decision. There is no substitute for expert judgment.

However, expert judgment can be supported through sound quantitative modeling [Deckro, 1997].

The only technical uncertainty addressed in this analysis is volume. Before implementing any of these four technologies, the decision maker should consider investigating technological risks inherent to each of these top four trains that may impact the assumed 90% source recovery/destruction rate of TCE. For example, with Train 1, DUS, the risk of hydroparalysis may limit recovery rates and lengthen time to remediate beyond what is expected. Also, consider oxidation, which is a part of Trains 9 and 21, just how much of a risk is there to unreacted material being left in the aquifer and what potential is there to produce toxic, partially degraded bi-products from this remediation process?

There are also other, potentially limiting, physical uncertainties surrounding the WAG 6 site; such as an operational building located on top of the site, which may impede some technologies' implementability as well as their performance. It may behoove the decision maker to further evaluate these limiting physical characteristics, especially once more RI data becomes available and it is possible to better characterize the geology and model the hydrologeology of the site.

Finally, assumptions made in generating the cost and performance data for the top technologies should be reviewed to determine whether any improvement to the Life Cycle Cost model can be made. In particular, as more field performance data become available to lessen the reliance on vendor performance curves, this data should be incorporated into the DA models.

Appendix A: Spill Volume Distribution

The following probability density function, Figure A.1 below, was generated by the decision makers and represents the most likely probability associated with a continuous spill volume of TCE. The graph may be interpreted such that there is zero probability of a spill volume exceeding 500,000 gallons and a zero probability of a spill volume being less than 10,000 gallons. Since this is a continuous distribution, the probability of a spill volume of 50,000 gallons or less is equal to 0.35.

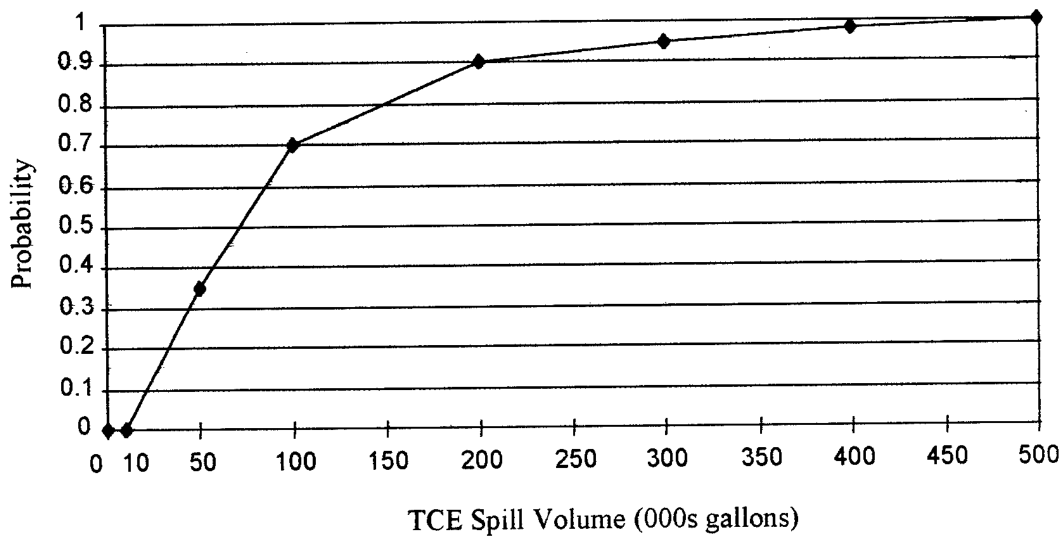


Figure A.1 Cumulative Spill Probability Distribution

Because decision makers were accustomed to relating to spill volumes in round, even numbers, and the original cost and performance data from the MSE model were run for spill volumes at 50,000, 100,000, 200,000, 300,000, 400,000 and 500,000 gallons, it was decided to discretize the above continuous, cumulative distribution. This was accomplished by first generating a probability density function, as shown in Figure A.2 which was rescaled, and then, utilizing the moment generating function and attempting to match the first five moments to derive probabilities for the spill volumes mentioned above.

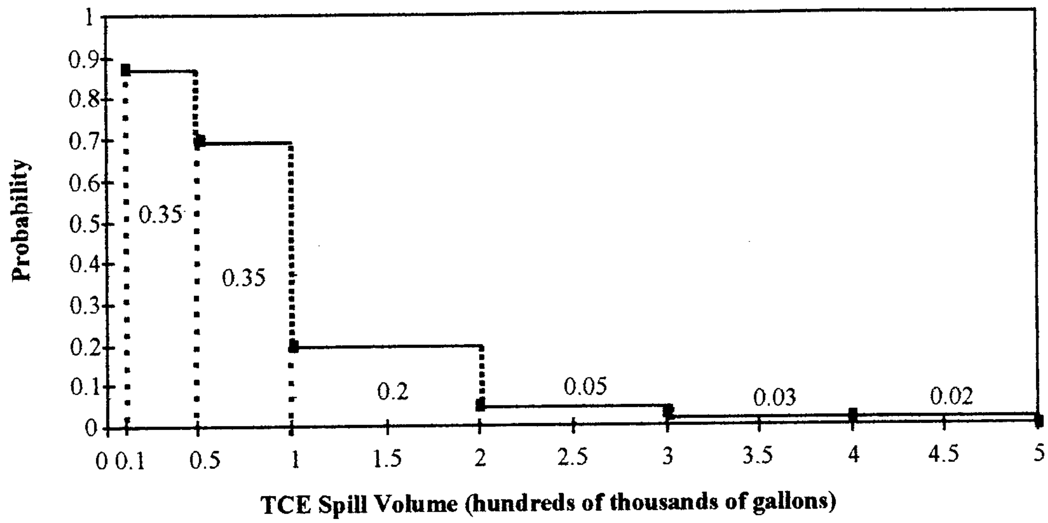


Figure A.2 Probability Density Function

From Figure A.2 it is possible to determine the piece-wise, linear functions for substitution into the following moment-generating equation, where $E(X^r)$ is the r[th] moment about the origin of the continuous random variable X [Walpole & Myers 1985: 173]:

$$M_r = E(X^r) = \int_{-\infty}^{\infty} x^r f(x)dx \tag{A.1}$$

Using Figure A.2 and Equation A.1, the first moment, also known as the expected value, can be expressed as:

$$E(X) = \int_{0.1}^{0.5} 0.875x\,dx + \int_{0.5}^{1} 0.7x\,dx + \int_{1}^{2} 0.2x\,dx + \int_{2}^{3} 0.05x\,dx + \int_{3}^{4} 0.03x\,dx + \int_{4}^{5} 0.02x\,dx$$

$E(X) = .9875$

Rescaling, the first moment, the expected spill volume is 98,750 gallons.

We can assert for any discretized probability function which has the same r^{th} moment as the continuous probability function [Kloeber, 1997]:

$$\sum_{s} P_s X_s^r = \int_{-\infty}^{\infty} x^r f(x)dx \qquad \textbf{(A.2)}$$

where P_s = the probability of the s^{th} discrete volume where s ranges from 50,000, through 500,000 gallons, and r is the r^{th} moment. In other words, if we had a discrete probability which had the same first moment then we could make the assumption that this expected value is also equal to the sum of the discrete probabilities multiplied by their corresponding spill amounts [Kloeber, 1997]:

$$E(X) = \sum_{s} (P_s X_s) = 0.9875 \qquad \textbf{(A.3)}$$

which expands to,

$$E(X^r)=P_{50K}*50K^r+P_{100K}*100K^r+P_{200K}*200K^r+P_{300K}*300K^r+P_{400K}*400K^r+P_{500K}*500K^r$$

where P_s denotes the unknown discrete probability at each corresponding spill volume, x_s, and r represents the r^{th} moment. In the expanded form, P_{50K} represents the unknown, discrete probability for a 50,000 gallon spill, which is being solved for, and x_s is replaced with the corresponding spill volume amount of 50,000. The first five moments are calculated using Equation A.1 and are set equal to the expansion of Equation A.3, as shown by Equation A.2, to establish five equations and six unknown probabilities. The final constraint needed to fully solve the equations simultaneously is that the sum of the discrete probabilities must equal one.

The LINGO© optimization program, which is designed to optimally solve a set of linear equations, was used to solve the six equations and unknown probabilities described above. The first line in the LINGO Model (see optimal LINGO model, below) represents what the model is trying to minimize. In this case, it is trying to minimize the slack variables placed into the fourth and fifth moment equations. Since it is more critical to match the fourth moment than the fifth moment, the slack variables (SO2 and SO3) in the fourth moment equation (line 6) were weighted to try to force the slack error to occur in the fifth moment equation (line 7). After numerous iterations and runs, differing positions of the slack variables, and adjusting the weights on the slacks, the best solution was arrived at using the model presented below:

Optimal LINGO MODEL:

```
1]MIN=SO+SO1+100*SO2+100*SO3;
2]1=A+B+C+D+E+F;
3]0.9875=.5*A+B+2*C+3*D+4*E+5*F;
4]1.8002575=.25*A+B+4*C+9*D+16*E+25*F;
5]4.8975215=.125*A+B+8*C+27*D+64*E+125*F;
6]16.5798474=.0625*A+B+16*C+81*D+256*E+625*F-SO2+SO3;
7]63.0180239=.03125*A+B+32*C+243*D+1024*E+3125*F-SO+SO1;
END
```

MODEL OUTPUT:

ROWS= 7 VARS= 10 NO. INTEGER VARS= 0 (ALL ARE LINEAR)

NONZEROES= 50 CONSTRAINT NONZ= 40(15 ARE +- 1) DENSITY=0.649

SMALLEST AND LARGEST ELEMENTS IN ABSOLUTE VALUE= 0.312500E-01

3125.00NO. < : 0 NO. =: 6 NO. > : 0. OBJ=MIN. GUBS <= 1SINGLE COLS= 0

OPTIMUM FOUND AT STEP 9 SOLUTION OBJECTIVE VALUE = 0.1375

VARIABLE	VALUE	REDUCED COST
SO	0.0000000E+00	0.9310345
SO1	0.0000000E+00	1.068966
SO2	0.0000000E+00	2.000000
SO3	0.1375445E-02	0.0000000E+00
A	**0.7385445**	0.0000000E+00
B	**0.0000000E+00**	0.8275853
C	**0.2021462**	0.0000000E+00
D	**0.3390179E-01**	0.0000000E+00
E	**0.1480730E-01**	0.0000000E+00
F	**0.1060014E-01**	0.0000000E+00

where p_{50K} = A = 0.74, p_{100K} = B = 0, p_{200K} = C = 0.20, p_{300K} = D = 0.03, p_{400K} = E = 0.02, p_{500K} = F = 0.01.

This optimal solution matches the first three moments and moment five, as no value is assigned to them in the output. Moment four contains the only error and it is less than 1%. These probabilities are used for representing the discrete probabilities of the spill volumes, and allow for uncertainty in the spill volume to be incorporated into the decision analysis model.

Appendix B: WAG 6 CERCLA Hierarchy, Evaluation Measures, and Weights

This appendix is based upon the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) of 1980. The primary guidance document for CERCLA response actions is the National Contingency Plan (or NCP). The NCP (40 CFR S300) establishes criteria, for determining the appropriate environmental response by outlining the procedures to be followed in performing cleanups, remedial actions or removals.

The purpose of this appendix is to provide rationale for the development of a value hierarchy developed specifically for WAG 6 based upon the original CERCLA criteria as stated in the NCP. This value hierarchy will be used to rank remedial technologies or trains. According to CERCLA and the NCP, there are nine specified criteria; they are depicted on the following page (40 CFR S300.430(e)(9)(iii)):

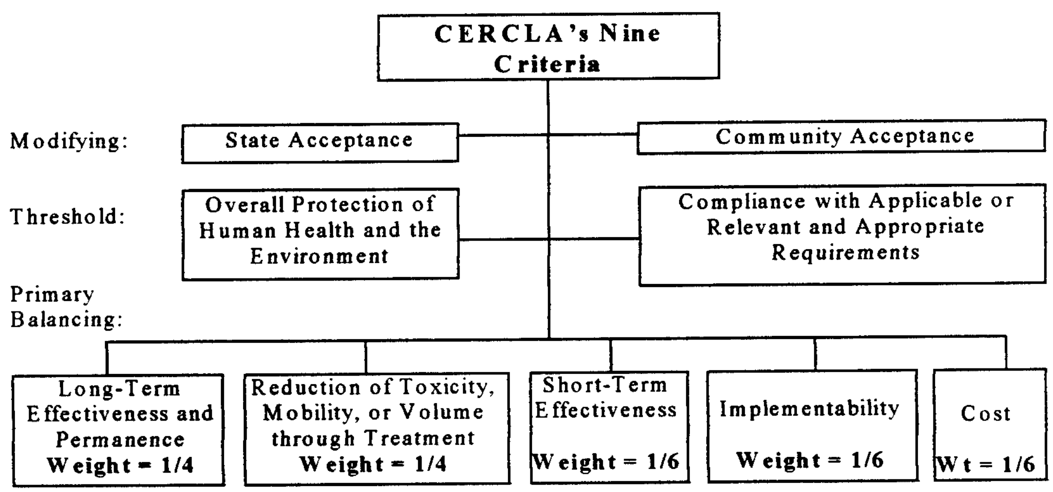


Figure B.1 - CERCLA Value Hierarchy and Associated Weights

Modifying and Threshold Criteria:

The CERCLA criteria are divided into the following three distinct groups: Modifying Criteria, Threshold Criteria, and Primary Balancing Criteria (40 CFR S300.430(f)(1)). The Modifying Criteria, State and Community Acceptance, are not included in this analysis. The Modifying Criteria should be considered after the Record of Decision (ROD) has been released to the public for review. The Threshold Criteria, consisting of the Overall Protection of Human Health and the Environment and Compliance with Applicable or Relevant and Appropriate Requirements (ARARs) are threshold objectives that all evaluated remediation trains must meet in order to be eligible for selection. Therefore, in order for a remediation train to be considered and used in this analysis, it will have already been examined to ensure it has met the Threshold Criteria.

CERCLA Value Hierarchy and Weights:

In the following sections are the WAG 6 CERCLA Balancing Criteria (capitalized and bolded-the first box in the hierarchy) and subcriteria (subsequent solid lined boxes with Roman numerals) with their associated evaluation measures (dashed boxes) and weights. Immediately following this hierarchy is a brief discussion on the assignment of weights, along with each evaluation measure's single dimensional value (or scoring) function. Note that for each evaluation measure, a value of ten indicates the best possible outcome for that measure while a value of zero indicates the worst possible outcome. These measures will later be used, in combination with the weights shown, to compare each remediation train and determine which train provides the greatest value under the CERCLA based measures.

Balancing Criteria 1: LONG-TERM EFFECTIVENESS AND PERMANENCE (40 CFR S300.430(e)(9)(iii)(C)): CERCLA states that "alternatives shall be assessed for the long-term effectiveness and permanence they afford, along with the degree of certainty that the alternative will prove successful."

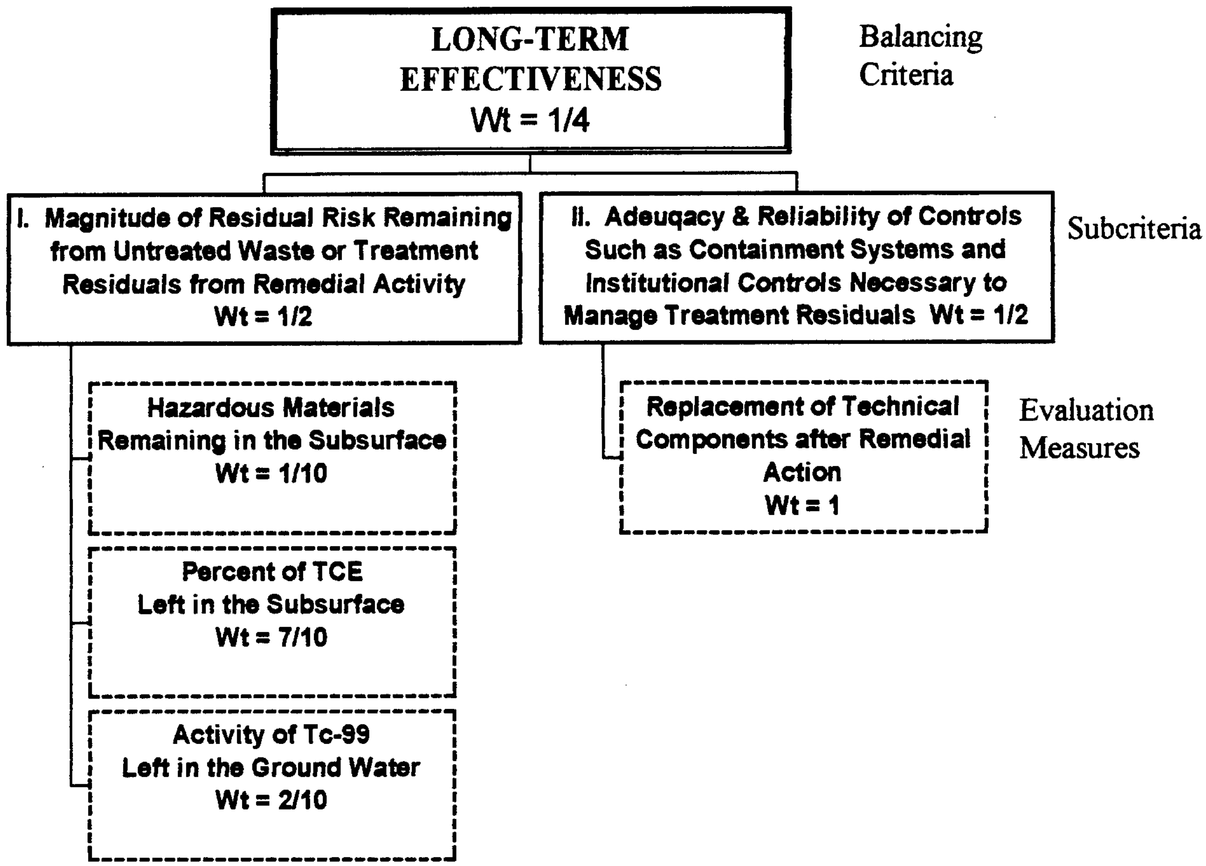


Figure B.2 - Long-Term Effectiveness and Permanence Hierarchy

EPA guidance suggests that long-term effectiveness and permanence "...addresses the results of a remedial action in terms of the risk remaining at the site after response objectives have been met." The weight for Long-Term Effectiveness and Permanence was derived directly from CERCLA (40 CFR S300.430(f)(1)(ii)(E)), as stated earlier in Chapter 3. Unfortunately, CERCLA does not go on to distinguish or provide additional guidance for balancing/weighting the subcriteria. The WAG 6 team members applied the following decision rules, noting the restriction that weights at each level of the hierarchy must sum to one: all weights are equally divided among the subcriteria, and all evaluation measure weights were also equally divided, except when there were separate measures for TCE and Tc-99, then the TCE weight would be three times as large as the Tc-99 weight.

Referencing CERCLA (40 CFR S300.430(f)(1)(ii)(E)), it states, "The balancing shall also consider the preference for treatment as a principal element and the bias against off-site land disposal of untreated waste." The WAG 6 team members interpreted this to mean that treating a waste was three times more valuable then disposing of it. Hence, TCE, which can be treated or destroyed, and does not need to be disposed of off-site in a landfill weighs 7/10 (about 3 times the weight for Tc-99). Tc-99 cannot be readily destroyed, however, and in high concentrations it must be landfilled so it receives a weight of 2/10. The remaining weight of 1/10 was then assigned to the evaluation measure for hazardous materials remaining in the subsurface.

The overall weight for any evaluation measure is the weight assigned to that evaluation measure, multiplied by all the criterion weights above it in the CERCLA hierarchy. For example, to calculate the overall weight for the evaluation measure of the Percent of Tc-99 Left in the Subsurface, simply multiply 2/10 * 1/2 * 1/4 = 1/40.

I. Magnitude of Residual Risk Remaining from Untreated Waste or Treatment Residuals Remaining at the Conclusion of the Remedial Activities (40 CFR S300.430(e)(9)(iii)(C)(1)): The WAG 6 team assumed that there would be no long term, on-site storage of Potential Contaminants Of Concern (PCOCs); all waste will be treated or sent off-site for disposal. However, treatment residuals may be left within the subsurface. The first measure, applicable to both TCE and Tc-99, evaluates the effect of hazardous materials (HM) remaining in the subsurface of the site. These HM may include treatment residuals, degradation products, or unreacted materials. HM are also those materials brought to the site to be used as part of the treatment but are defined hazardous under Department of Transportation definitions. As stated earlier, the best outcome has a value of 10 (or an answer of "no" in this case), when there are no HM remaining in the subsurface of the site, and the worst outcome has a value of zero (or "yes"), when there are HM remaining in the subsurface at the site. There is no continuous relationship between these two points (no straight line) because there are only two, discrete possibilities, either there are HM remaining in the subsurface or there are not.

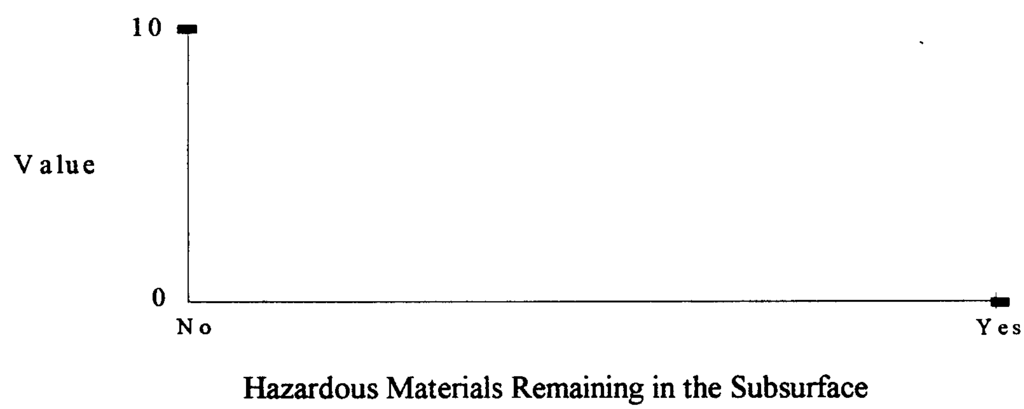


Figure B.3 Evaluation Measure for Residual Risk from Hazardous Materials

The long-term magnitude of residual risk for TCE can best be described by the Percent of TCE left in the ground. The preliminary goal of this project is to remove/destroy at least 95% of the TCE contamination. A technology that removes 95% or greater (therefore, leaving less than 5% in-situ) receives a score of 10. Because it is uncertain whether a 95% performance standard can be achieved in a cost effective manner, remediation trains will receive a positive score if more than 30% of the contaminant is removed (70% is remaining). This standard was chosen from examining other remedial action sites which have shown that, at a minimum, 30% removal/destruction of Non-Aqueous Phase Liquids (NAPLs) is achievable.

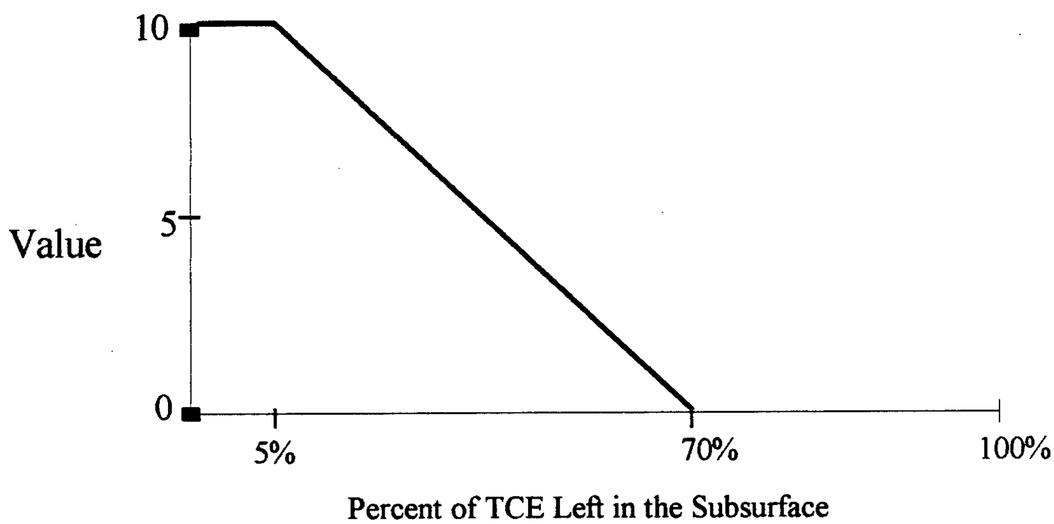


Figure B.4 Evaluation Measure for Residual Risk from TCE

The long-term magnitude of residual risk for Tc-99 can best be measured by the Percent Removal of Tc-99. Since Tc-99 will never be completely destroyed, the more that is removed the better. Therefore, a linear scoring function is used. The upper limit of this scale is the highest known concentration of Tc-99 found to date at the site (43,922 piC/L).

Any train that accomplishes a reduction from this initial amount will have value. The lower limit of this scale represents the current, regulatory limit (900 piC/L). Any train that can reduce the concentration of Tc-99 to the regulatory limit, or less, would receive a value of 10.

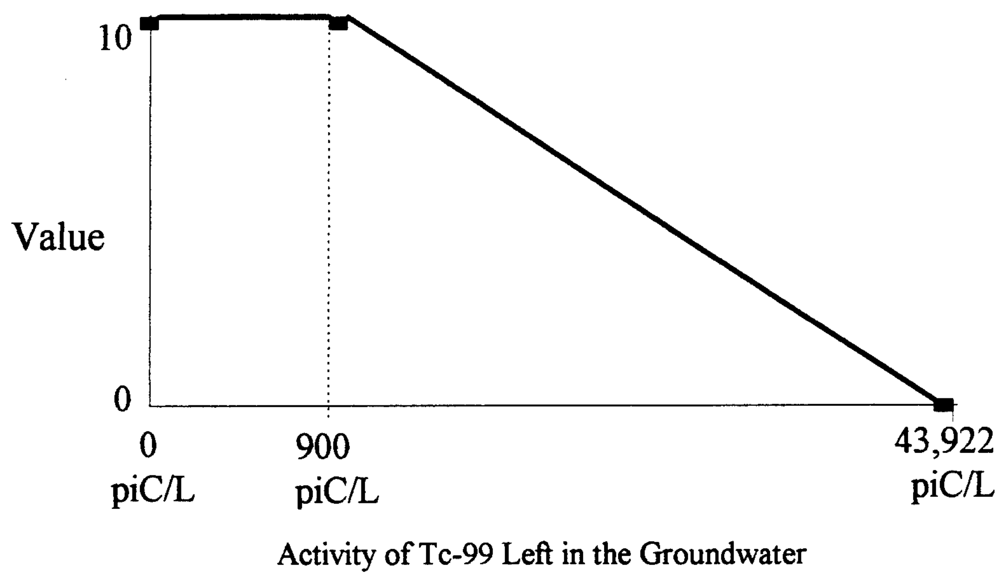


Figure B.5 Evaluation Measure for Residual Risk from Tc-99

II. Adequacy and Reliability of Controls Such as Containment Systems and Institutional Controls that are Necessary to Manage Treatment Residuals and Untreated Waste (40 CFR S300.430(e)(9)(iii)(C)(2)): CERCLA lists three subcriteria under this criteria:

1. Uncertainties associated with land disposal for providing long-term protection from residuals were not evaluated because there are no significant differences between the trains in this area.

2. The assessment of potential need to replace technical components of the alternative, such as a cap, a slurry wall, or a treatment system was combined with the third subcriteria:

3. The potential exposure pathways and risk posed should the remedial action need replacement.

The second and third criteria can be succinctly measured by the need for technical component replacement and whether there will be any threat of exposure or release when the replacement is occurring. This measure considers both TCE and Tc-99 and combines both frequency and risk of exposure during replacement. Note that the most value can be obtained from this measure when there is no replacement required (10). Replacement without risk of release follows rather closely at 7. However, any replacement that could occur with a risk of release is considered to have a very low value at 1.

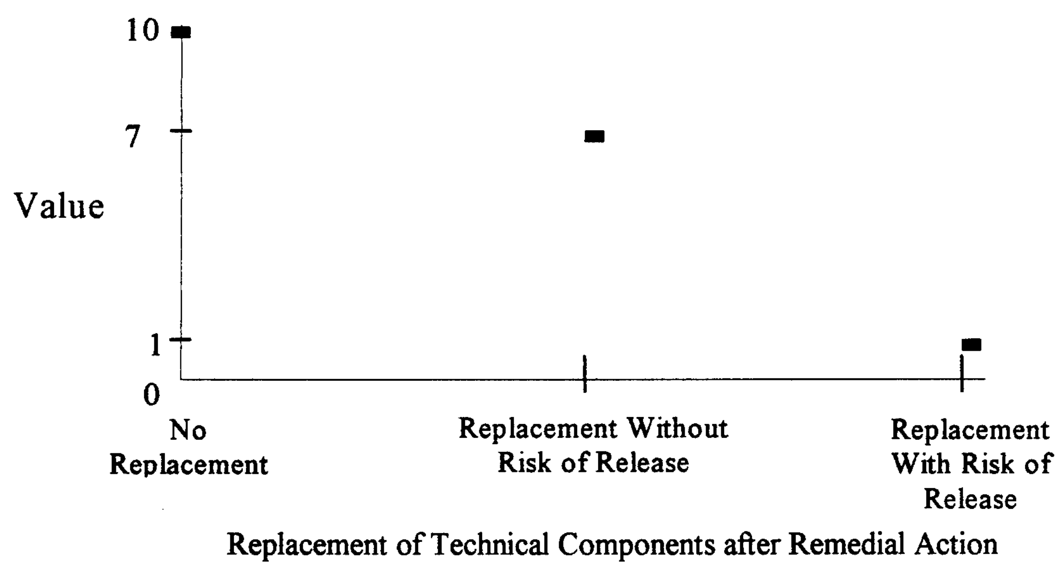


Figure B.6 Evaluation Measure for Adequacy and Reliability of Controls

Balancing Criteria 2: REDUCTION OF TOXICITY, MOBILITY, OR VOLUME THROUGH TREATMENT (40 CFR S300.430(e)(9)(iii)(D)): CERCLA states that "the degree to which alternatives employ recycling or treatment that reduces toxicity, mobility, or volume (TMV) shall be assessed, including how treatment is used to address the principal threats posed by the site. Factors that shall be considered, as appropriate, include the following ..." CERCLA then lists six subcriteria.

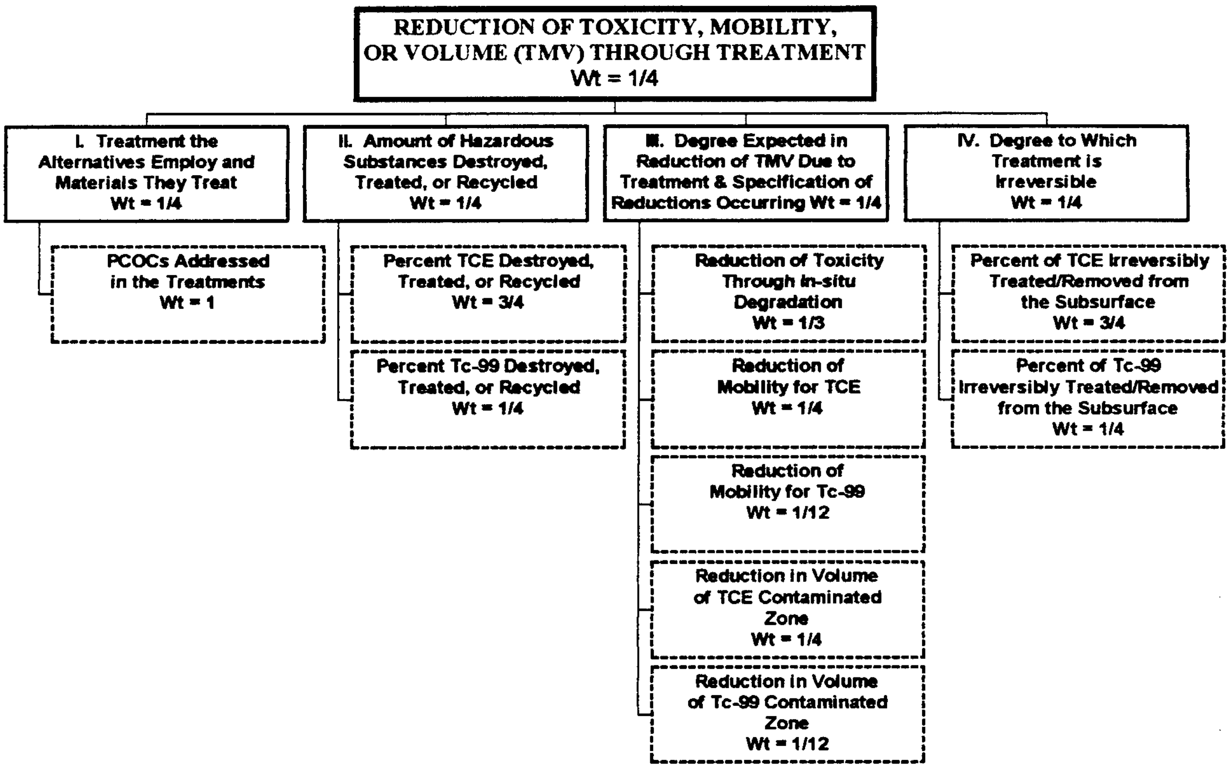


Figure B.7 - Reduction of Toxicity, Mobility, or Volume Hierarchy

The first four subcriteria CERCLA lists directly correspond to the four subcriteria shown in the hierarchy that the WAG 6 team developed (Figure B.7). However, the evaluation measure that would quantify subcriteria five, which is "the type and quantity of residuals that will remain following treatment, considering the persistence, toxicity, mobility, and propensity to bioaccumulate of such hazardous substances and their constituents", was seen as redundant with the measures developed for subcriteria 1 under Long-Term Effectiveness. The evaluation measure that would best characterize subcriteria six, which is "the degree to which treatment reduces the inherent hazards posed by principal threats at the site," was seen as redundant with the evaluation measure developed for subcriteria III.

EPA Guidance suggests that Reduction of Toxicity, Mobility, or Volume Through Treatment "...address the statutory preference for selecting remedial actions that employ treatment technologies that permanently and significantly reduce toxicity, mobility, or volume of the hazardous substances as their principal element. This preference is satisfied when treatment is used to reduce the principal threats at a site through destruction of toxic contaminants, reduction of the total mass of toxic contaminants, irreversible reduction in contaminant mobility, or reduction of total volume of contaminant media." The guidance also suggested incorporating treatment residuals, but the issue of residual risk has already been addressed under Long-Term Effectiveness and Permanence.

The weight for Reduction of Toxicity, Mobility, or Volume Through Treatment was derived directly from CERCLA (40 CFR S300.430(f)(1)(ii)(E)), as stated earlier. The weights for the subcriteria level of the hierarchy are equally weighted at 1/4 each (meeting the requirement that they sum to one), as explained previously. The next level of weights are those assigned to the evaluation measures. The same "rule of thumb" developed earlier continues to apply, with the TCE measure outweighing the Tc-99 measure by a factor of three. Under subcriteria III, the degree expected in reduction of TMV, the evaluation measures for the reduction of toxicity, mobility, and volume are each weighted 1/3. In the cases of mobility and volume, where there are separate measures for TCE and Tc-99, then the weight of 1/3 is divided such that the TCE measure holds three times more weight then Tc-99 measure, hence the weight of 1/4 for TCE measures and 1/12 for Tc-99 measures.

I. Treatment or Recycling Processes the Alternatives Employ and Materials They Will Treat (40 CFR S300.430(e)(9)(iii)(D)(1)): This measure indicates that treating both potential contaminants of concern (PCOCs), TCE and Tc-99, is preferable to treating only one. It also reflects the increased importance of addressing TCE compared to Tc-99, by giving three times the value to technologies that treat only TCE.

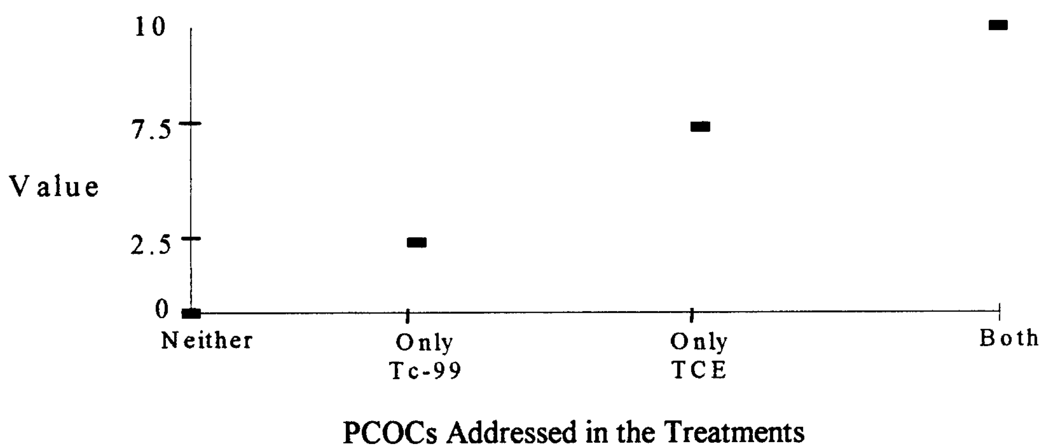


Figure B.8 Evaluation Measure for Treatment Employed and Materials Treated

II. Amount of Hazardous Substances, Pollutants, or Contaminants that will be Destroyed, Treated, or Recycled (40 CFR S300.430(e)(9)(iii)(D)(2)): Note that TCE and Tc-99 are evaluated separately and the evaluation measures developed only apply to technologies/treatments that address the PCOCs. The team agreed that Amount could be interpreted to mean Volume of hazardous substances, pollutants, or contaminants that will be destroyed, treated or recycled.

Amount (or Volume) of Principal Threat Treated for TCE: 30% was considered to be a standard recovery factor for TCE (as explained previously under Long-Term Effectiveness, subcriteria I).

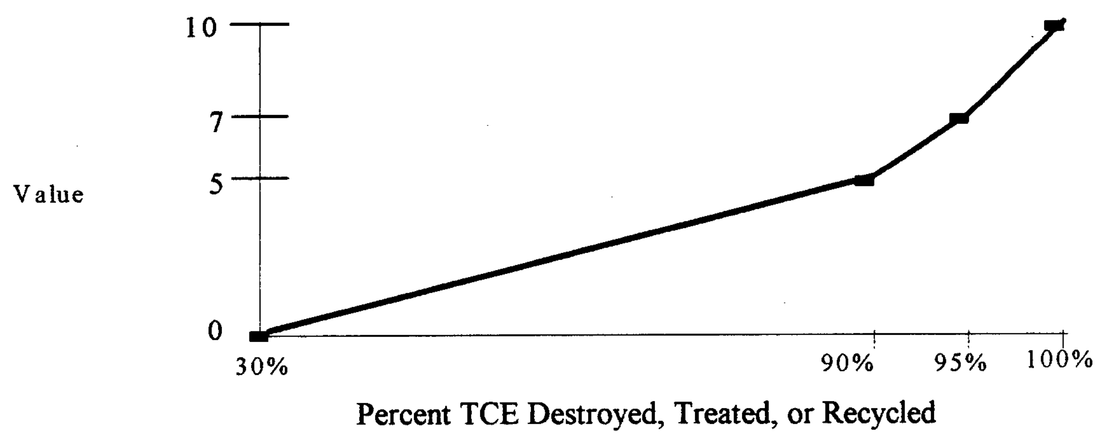


Figure B.9 Evaluation Measure for Amount of TCE Destroyed, Treated or Recycled

Amount (or Volume) of Principal Threat Treated for Tc-99 : Removing Tc-99 from the subsurface is considered treatment because the substance changes status from uncontrolled to controlled because of the removal. The WAG 6 team agreed that 95% of the value would be obtained when 91.1% of the Tc-99 was destroyed, treated, or recycled. The 91.1% removal is based on the draft regulatory limit of 3,900 pico Curies per liter (pCi/L) and the Tc-99 activity observed at C-400 (43,922 pCi/L). Note to reach the current regulatory limit of 900 pCi/L, 98% would need to be destroyed, treated or recycled.

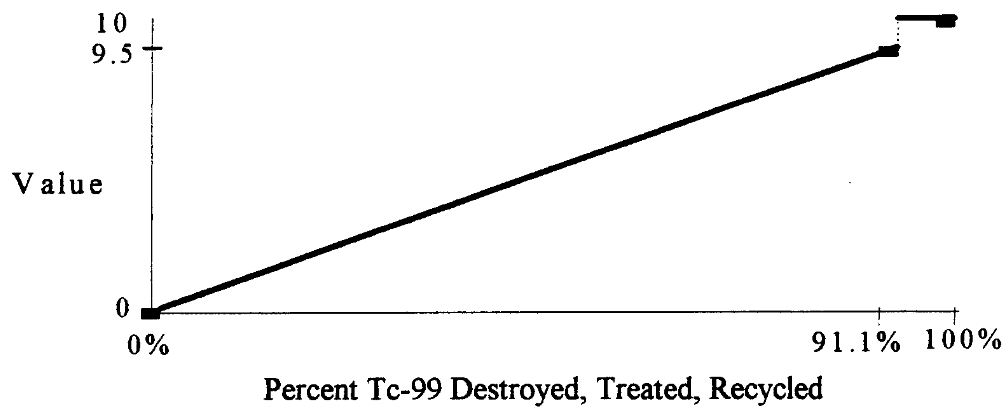
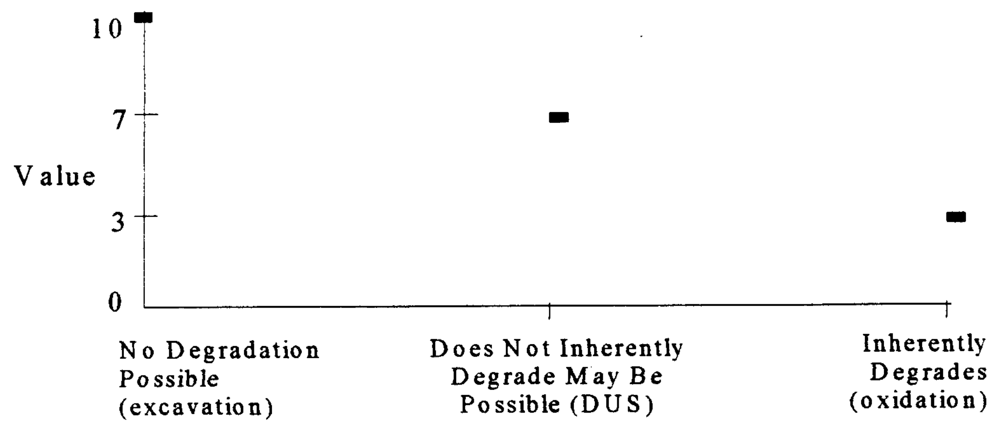


Figure B.10 Evaluation Measure for Amount of Tc-99 Destroyed, Treated or Recycled

III. The Degree of Expected Reduction in Toxicity, Mobility, and Volume of the Waste Due to Treatment or Recycling and the Specification of Which Reduction(s) are Occurring (40 CFR S300.430(e)(9)(iii)(D)(3)):

Measure for the Reduction of Toxicity: There is no measure for the reduction of toxicity for Tc-99 because Tc-99 cannot be destroyed. However, the reduction of total mass of contaminant (as stated in Table 6-2 in EPA Guidance) can be applied to TCE. The evaluation measure developed considers whether a treatment relies totally on the degradation of TCE to reduce toxicity. The concern being if degradation is not complete and there are some residuals, those residuals may be more toxic than TCE. Hence, the three distinct categories; where if degradation is not possible with a technology, (like excavation) the score for that technology would be a 10. If degradation may occur, but is not the inherent focus of the technology (like surfactants) then it would score a 7. If the primary focus of the technology is degradation (like oxidation) then it would score a 3.



Reduction of Toxicity Through In-situ Degradation

Figure B.11 Evaluation Measure for Reduction of Toxicity

Measures for the Reduction of Mobility: The team quantified this evaluation measure assuming successful treatment, because an unsuccessful treatment may increase mobility with some technologies. Separate evaluation measures were created to evaluate the mobility of TCE and Tc-99. The best situation would be to reduce the mobility of TCE and keep it from migrating off site, and so it was given the highest value of 10. Conversely, increasing the mobility of TCE may increase the risk of off site migration and hence escape treatment. However, increased mobility could also facilitate the extraction of TCE, which would mean that increasing mobility may not necessarily be all that negative. For these reasons, stated above, increasing the mobility of TCE gets a value of 7. Not changing the mobility, but allowing it to remain the same, yields a value of 9. This measure is less sensitive to the extremes in mobility because these extremes do not necessarily warrant extremes in scores.

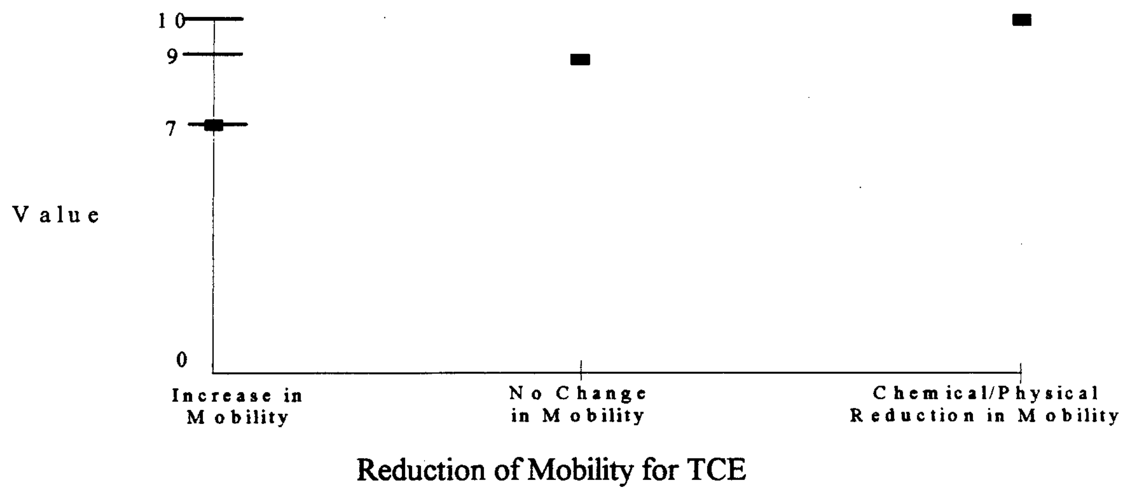


Figure B.12 Evaluation Measure for Reduction of Mobility of TCE

A similar measure was created for Tc-99. The most effective means for reducing the mobility of Tc-99 is to cause it to chemically change (precipitate) and this is given a value of 10. Since Tc-99 is already soluble, there is not much difference in value from increasing its mobility (7) then allowing no change in mobility (8) .

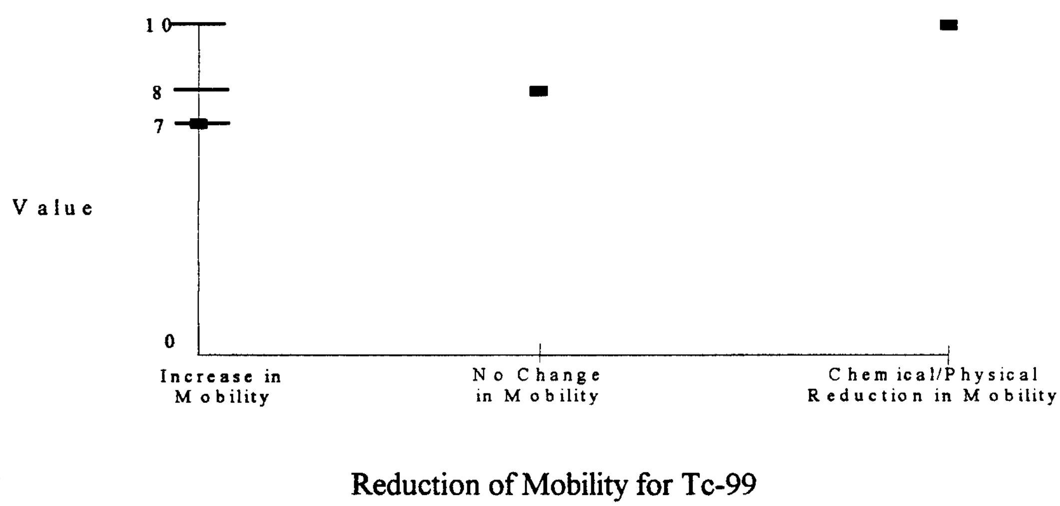


Figure B.13 Evaluation Measure for Reduction of Mobility of Tc-99

Measures for the Reduction in Volume: The focus of the remedial action is the source not the plume; emphasis is on reduction of mass/volume (EPA Guidance Table 6-2). However, a technology that increases the volume of the source zone, such as a steam flood, is less desirable in this criteria than one that decreases the volume. The source is the media contaminated with DNAPL/TCE. Note: TCE and Tc-99 each have their own evaluation measure for this subcriteria.

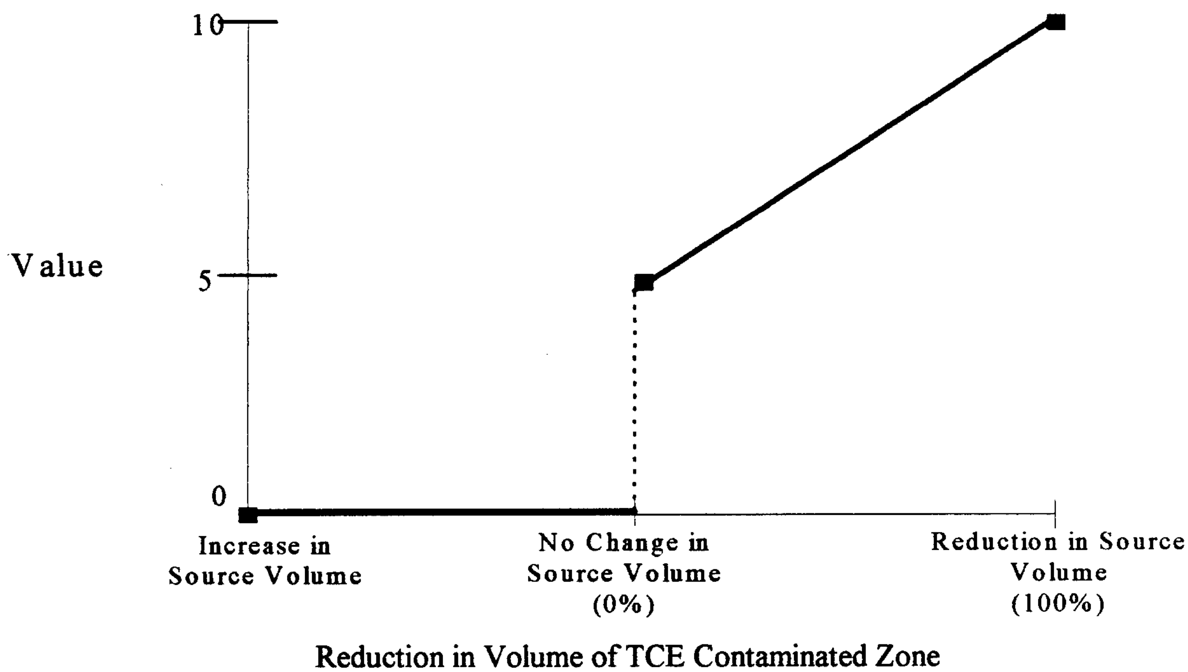
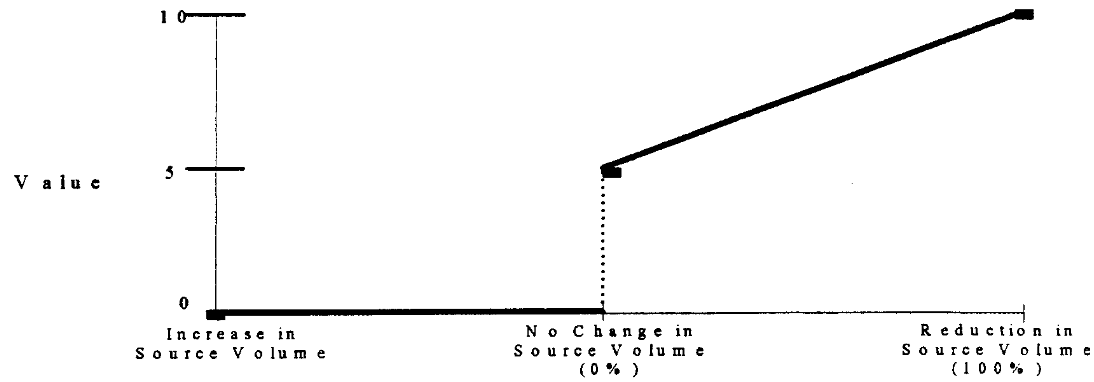


Figure B.14 Evaluation Measure for the Reduction of Volume of TCE Zone

A similar measure was created for Tc-99, where the emphasis is on the reduction of mass and volume (EPA Guidance Table 6-2). Once again, a technology that increases the volume of the source zone; such as a steam flood, will be considered worse in this criteria than one that decreases the overall volume. The source, in this case, is the media contaminated with Tc-99.



Reduction in Volume of Tc-99 Contaminated Zone

Figure B.15 Evaluation Measure for the Reduction of Volume of Tc-99 Zone

IV. The Degree to Which the Treatment is Irreversible (40 CFR S300.430(e)(9)(iii)(D)(4)): Note distinct evaluation measures for TCE and Tc-99. The WAG 6 team assumed that once TCE was removed or treated, it would not be reinjected into the subsurface and, therefore, it would have been treated irreversibly. Treatment could also include in-situ treatment where the TCE has been irreversibly altered or destroyed. The more TCE removed the better.

Percent of TCE Irreversibly Treated/Removed from the Subsurface

Figure B.16 Evaluation Measure For Irreversible Treatment of TCE

A similar evaluation measure was developed for Tc-99. Again, the team assumed that once the Tc-99 was removed, it would not be reinjected into the subsurface and so it could be considered to have been treated irreversibly. It is important to note that Tc-99 cannot be treated irreversibly other than to be removed from the subsurface for this evaluation measure. The more Tc-99 removed the better.

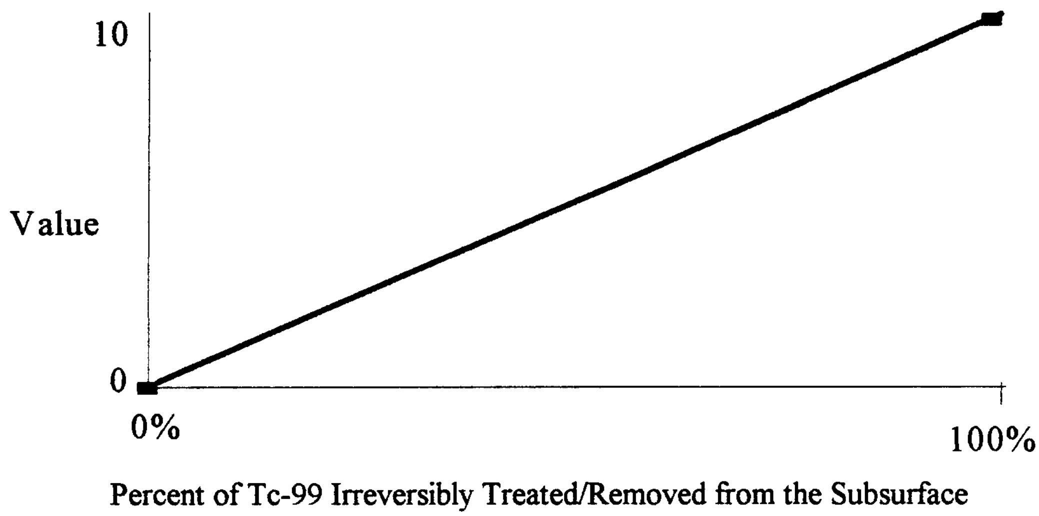


Figure B.17 Evaluation Measure For Irreversible Treatment of Tc-99

Balancing Criteria 3 SHORT-TERM EFFECTIVENESS (40 CFR S300.430(e)(9)(iii)(E)): CERCLA states that "the short-term impacts of alternatives shall be assessed by considering the following subcriteria..." and then lists the four subcriteria depicted below:

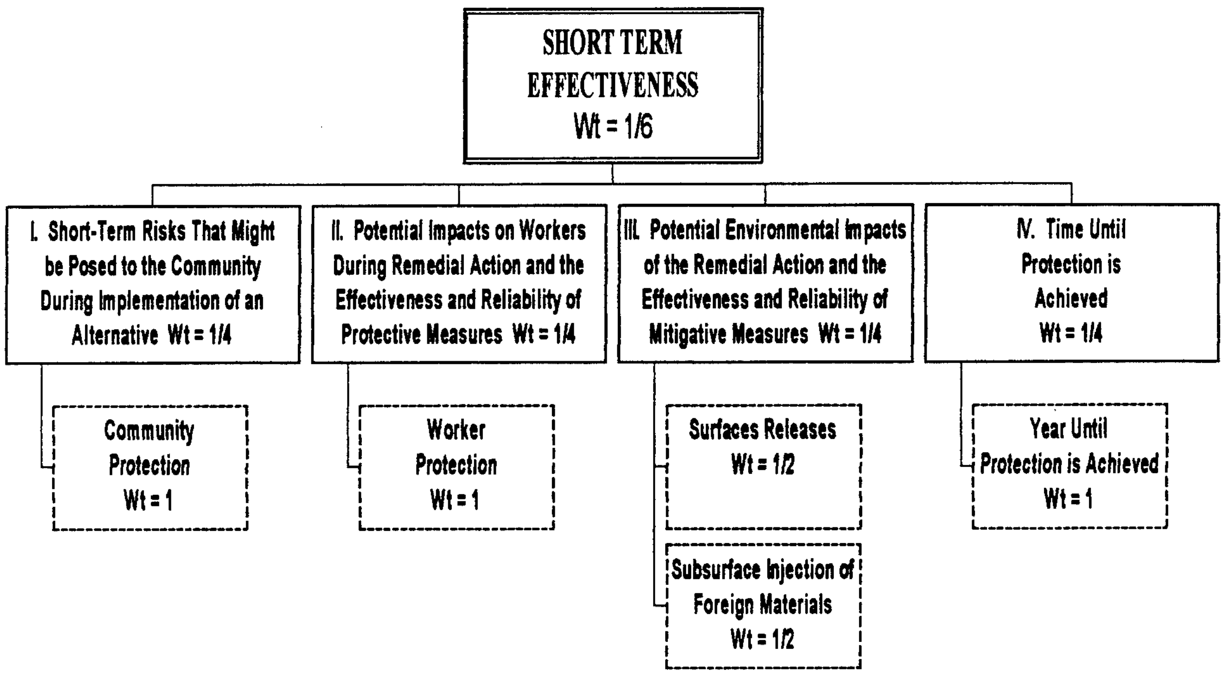


Figure B.18 - Short-Term Effectiveness Hierarchy

EPA guidance suggests that "short-term effectiveness addresses the effects of the alternative during the construction and implementation phase until remedial response objectives are met."

The weights were derived as explained previously, where the subcriteria are equally weighted and the evaluation measures are also evenly weighted (as there is no distinction between TCE and Tc-99 in the evaluation measures for Short-Term Effectiveness).

I. Short-Term Risks that Might be Posed to the Community During Implementation of an Alternative (40 CFR S300.430(e)(9)(iii)(E)(1)): The evaluation measure of Community Protection is a constructed measure, developed because there was no standard way of evaluating Community Protection. This evaluation measure uses the requirements of air emission monitoring and hazardous waste (HW) and hazardous material (HM) shipment both on and off site. HM has previously been defined, and HW is considered any waste generated at the site that meets the RCRA definition of a HW. The "community" is defined to be both those individuals who are employed at the site and the local community in the vicinity of the site. The team believed that the occurrences shown represent the entire range of possible events during any remedial action. The best score is achieved when there are no emissions and no transportation of HW/HM. The worst score is when there are untreated radiological emissions to the air/water. As the figure below depicts, the largest gain in value is obtained when there are no emissions from the technology.

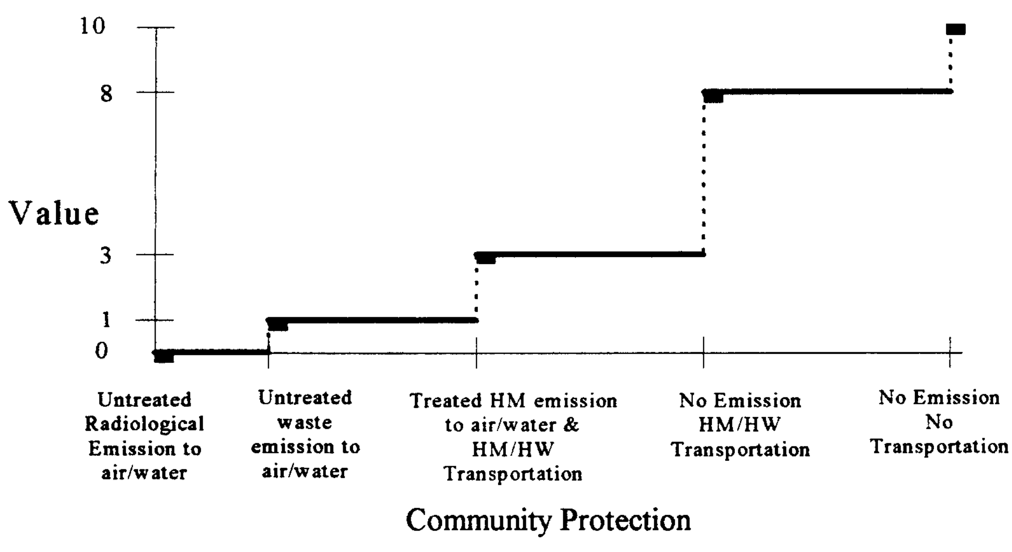


Figure B.19 Evaluation Measure for Risks Posed to the Community

II. Potential Impacts on Workers During Remedial Action and the Effectiveness and Reliability of Protective Measures (40 CFR S300.430(e)(9)(iii)(E)(2)):

The evaluation measure of Worker Protection is a constructed measure which uses radiation, mechanical, chemical, heat, and electrical risks to cover the range of hazards workers may face. The best value is no exposure to hazards for the remediation workers on site (those workers specifically performing tasks related to the remedial action). The worst value (not expected for any of the trains) is zero, when all five hazards cannot be readily controlled.

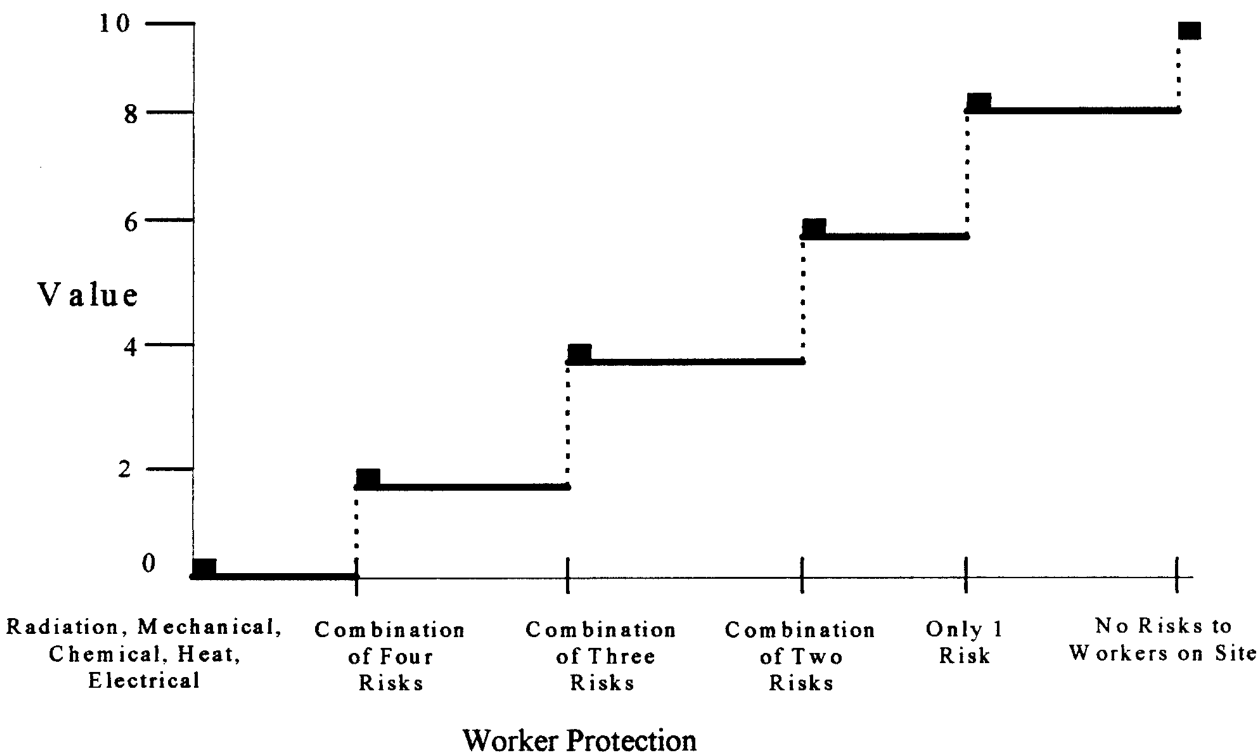


Figure B.20 Evaluation Measure for Potential Impact on Workers

III. Potential Environmental Impacts of the Remedial Action and the Effectiveness and Reliability of Mitigating Measures During Implementation (40 CFR S300.430(e)(9)(iii)(E)(3)): The team decomposed this evaluation measure to produce two measures - surface release and subsurface injection of foreign materials.

Surface Release: At the surface, no release is considered best and receives a value of 10. An uncontrolled air and uncontrolled water release is considered the worst case and receives no value (0). Water releases are considered less dangerous and pose less risk than air releases. The largest increase in value is between uncontrolled and controlled releases as shown below:

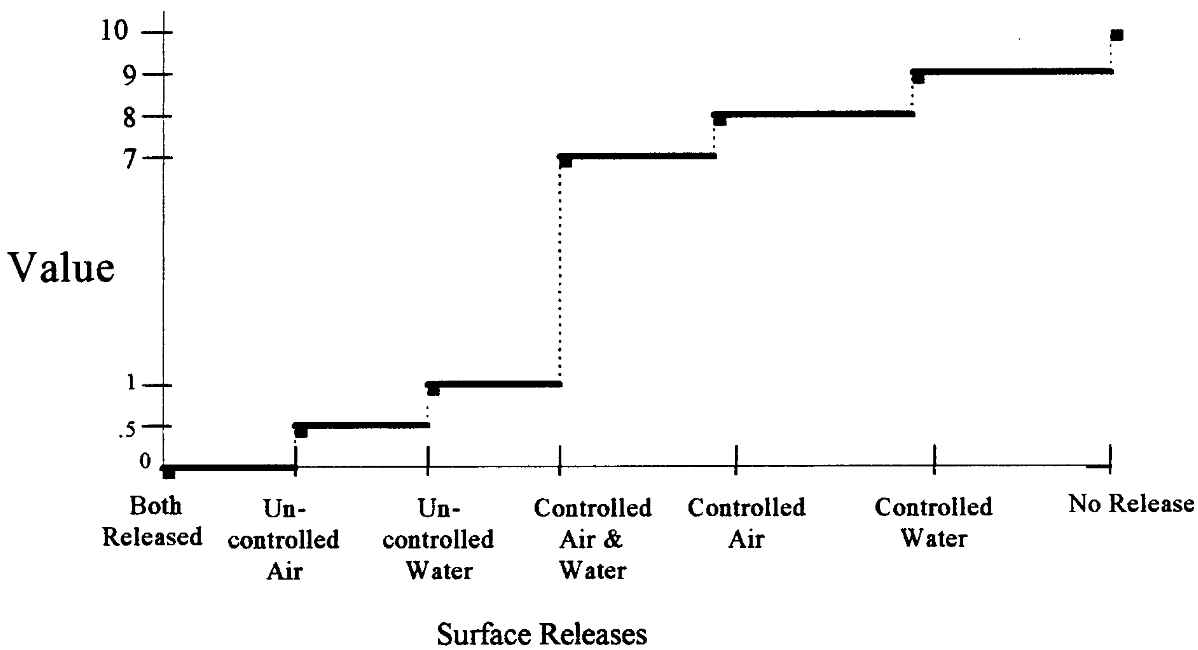


Figure B.21 Evaluation Measure for Potential Surface Releases

Subsurface Injection of Foreign Materials: The step function for this evaluation measure assumes that the risk due to injection increases as the material injected changes from air, to water, to steam, to surfactants, to solvents, and, finally, to toxic materials which rate the worst value (0). The best value is assigned to the alternative that does not inject anything into the subsurface.

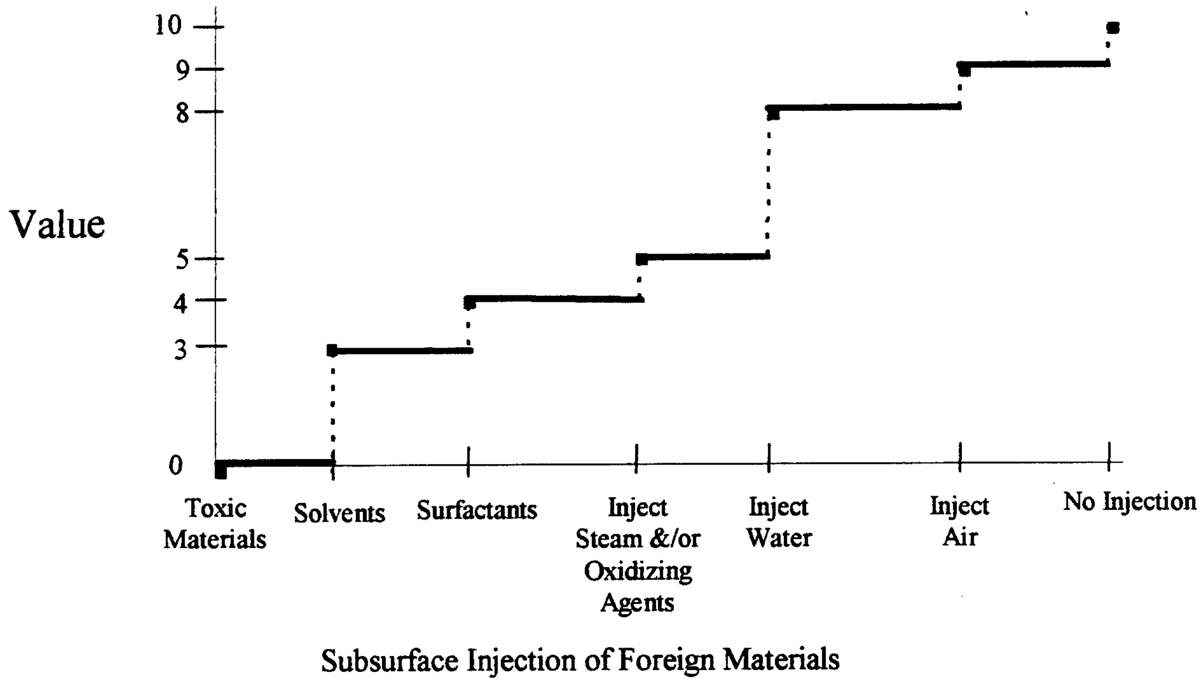


Figure B.22 Evaluation Measure for Potential Subsurface Injection of Materials

IV. Time Until Protection is Achieved (40 CFR S300.430(e)(9)(iii)(E)(4)): The 10-year plan, beginning in 1996, provides the rationale for the evaluation measure assigning a train a value of 10 at the 2006 milestone. Assuming construction would finish by 2002, if the Remedial Action (RA) was completed in eight years (i.e. 2010) it would be considered an extremely successful project with respect to time. Any remedial actions that require more than thirty years past construction completion would have little or no added value with respect to time. Therefore, any project that takes longer to complete than 2032 scores a 0.

The value is considered to reduce linearly with each year beginning in 2010 until 2032 is reached.

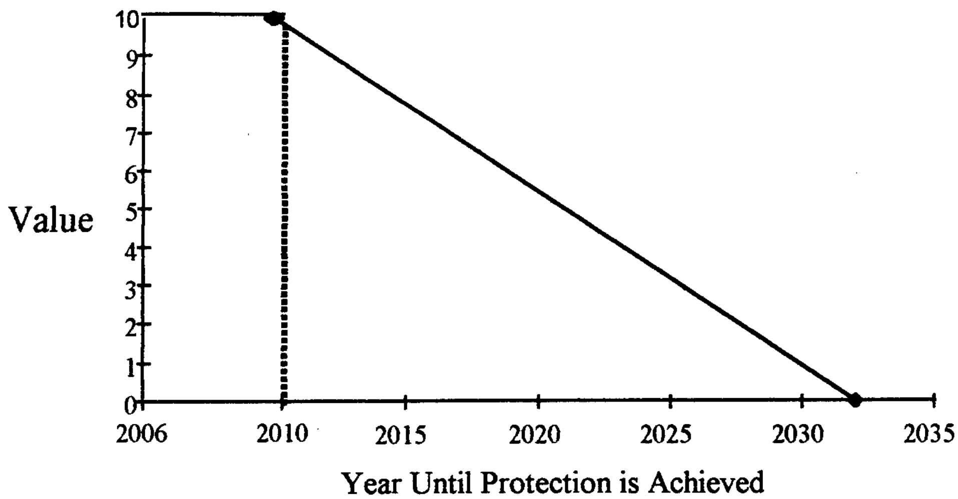


Figure B.23 Evaluation Measure for Time Until Protection is Achieved

Balancing Criteria 4: IMPLEMENTABILITY (40 CFR S300.430(e)(9)(iii)(F)):

CERCLA states that "the ease or difficulty of implementing the alternatives shall be assessed by considering the following types of factors as appropriate" and then lists the three subcriteria expressed below:

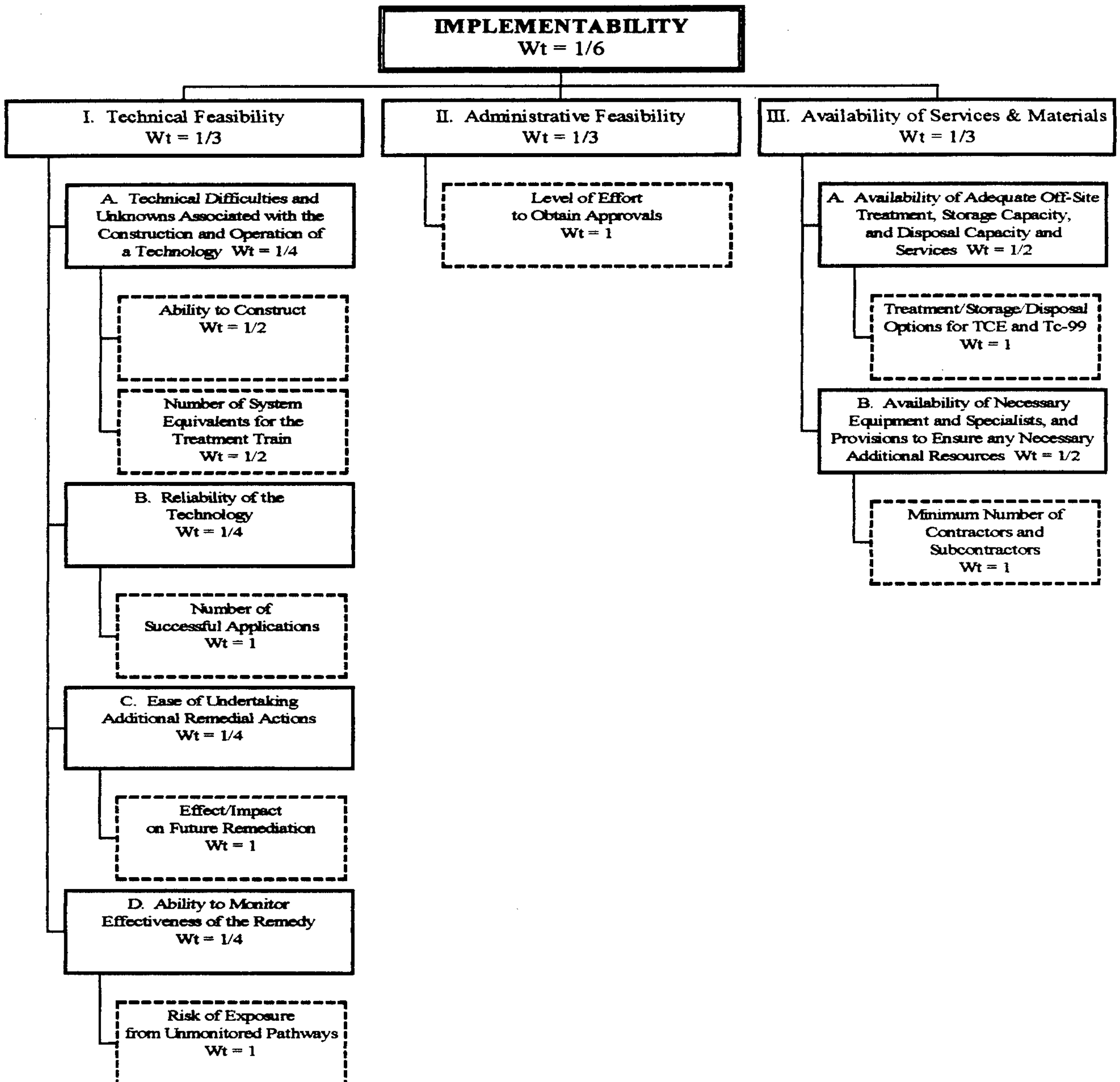


Figure B.24 Implementability Hierarchy

The weights were derived as before; the subcriteria are equally weighted and the evaluation measures are also evenly weighted (as there is no distinction between TCE and Tc-99 in the Implementability criteria, each evaluation measure considers both PCOCs).

I. Technical Feasibility (40 CFR S300.430(e)(9)(iii)(F)(1)): CERCLA further subdivides Technical Feasibility into the subcriteria presented in the preceding hierarchy (A, B, C, and D - solid lined boxes).

IA. Technical Difficulties and Unknowns Associated with the Construction and Operation of a Technology. This section is evaluated using two measures. The first measure addresses the difficulty of construction and is scored by giving one point for each "yes" to the following questions:

1. Is the technology sensitive to obstructions? (yes = 1, no = 0)
2. Does the technology require unconventional techniques/equipment? (y=1, n=0)
3. Does the technology have unconventional operational requirements? (y=1, n=0)

Unconventional is defined to mean that which is not readily available or previously applied in the field of environmental restoration. The scores for these three questions are then added and their total is used to enter into the x-axis of the figure below to calculate the corresponding value. For example, to score the DUS technology, the answer to question 1 would be yes (score = 1) because DUS requires well emplacement which could be sensitive to obstructions (like the C-400 building located at the site). The answers to questions 2 and 3 would both be no (score = 1 + 0 + 0 = 1), because the emplacement of the DUS technology does not require any unconventional/extraordinary techniques or operational requirements above and beyond standard construction/operation procedures. The total score for DUS of 1 corresponds to a value of 6.67.

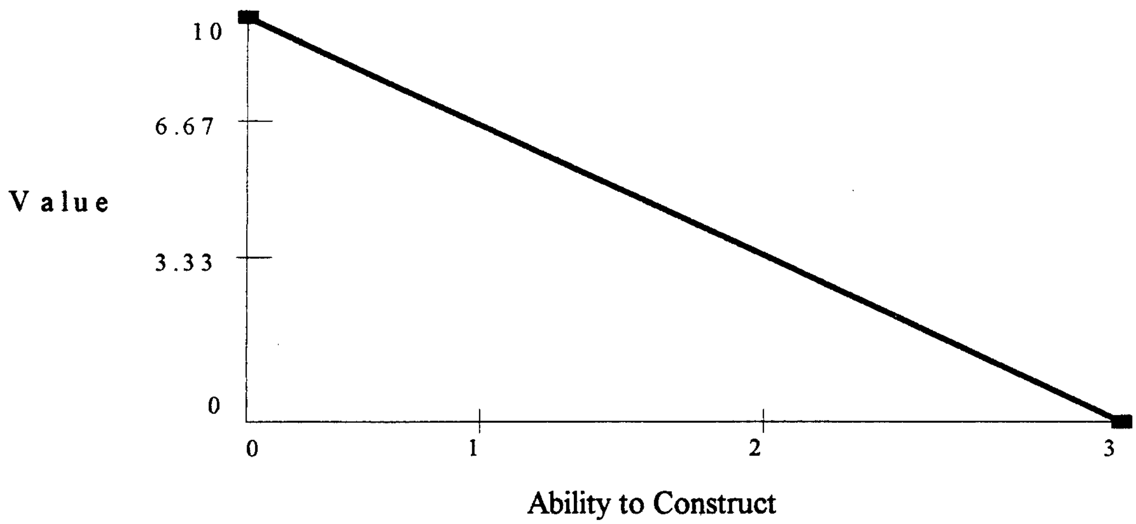


Figure B.25 Evaluation Measure for Unknowns Associated with Construction and Operation

The second measure used to evaluate this criteria is the complexity of the treatment trains being considered. The complexity of a system can be estimated by the number of systems components, which vary greatly for each alternative. A method was designed to count the number of system components by using system equivalents where an estimated 1 system equivalent is viewed as the simplest technology and receives a value of 10, and the most complicated technology is estimated at 20 system equivalents and receives a value of 0. The following system equivalents guide was proposed for scoring alternatives:

3 system equivalents SVE

1	system equivalent	air movement
1	system equivalent	treatment
1	system equivalent	wells

4	system equivalents	Pump & Treat
1	system equivalent	pump
1	system equivalent	well
1	system equivalent	water treatment
1	system equivalent	vapor treatment

10	system equivalents	DUS
2	system equivalents	pump (liquid and vacuum)
1	system equivalents	injection wells
1	system equivalents	extraction wells
1	system equivalent	injection system
2	system equivalents	controlling monitoring system
2	system equivalents	remove vapor extraction treatment (steam & water)
1	system equivalent	steam generation package

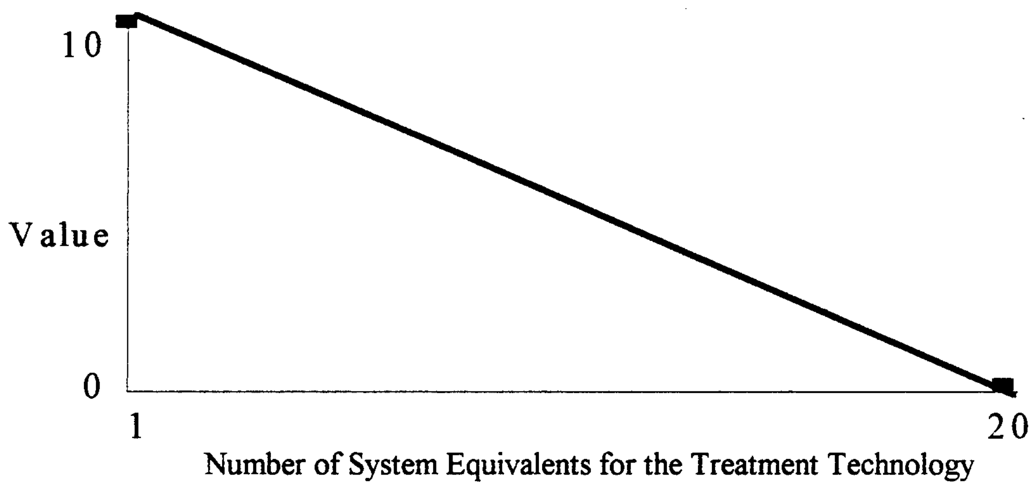


Figure B.26 Evaluation Measure for Technical Difficulties Associated With Construction and Operation

IB. The Reliability of the Technology: This evaluation measure focuses on the likelihood that technical problems associated with implementation will lead to schedule delays (EPA Guidance, Table 6-4). The number of times the technology being considered has been successfully used in a similar medium is a good proxy measure. A conservative measure of reliability of a treatment train is the reliability of the component technology that has been successfully implemented the least number of times. After a technology has been successfully implemented 10 times, there is little additional perceived increase in reliability and therefore no increase in value for this measure. The lowest value case would be for a treatment train that includes a technology that has never been successfully implemented.

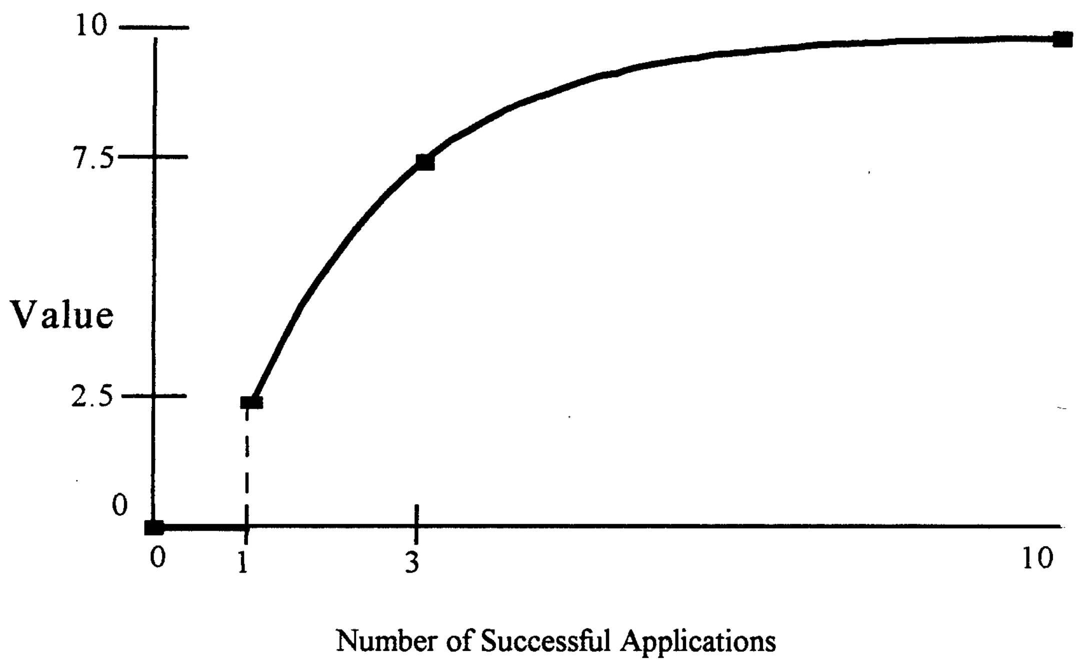


Figure B.27 Evaluation Measure for the Reliability of the Technology

IC. Ease of Undertaking Additional Remedial Actions: This evaluation measure estimates the impact on potential future additional remediation activities either for other principal threats or for other overlapping or nearby operable units. We developed a constructed scale ranging from no impact on additional remedial activities to alternatives that have a major impact on additional remedial activities. For example, injecting a chemical into the aquifer which precipitates the Tc-99 may actually increase the mobility of TCE and therefore hinder the TCE remediation activities which would result in a minor negative impact. A major negative impact would be the plugging of the aquifer; a major positive impact would be leaving an operational system in place that could be used for future remediation activities; and a minor positive impact would be putting in wells which could be used for future remediation activities.

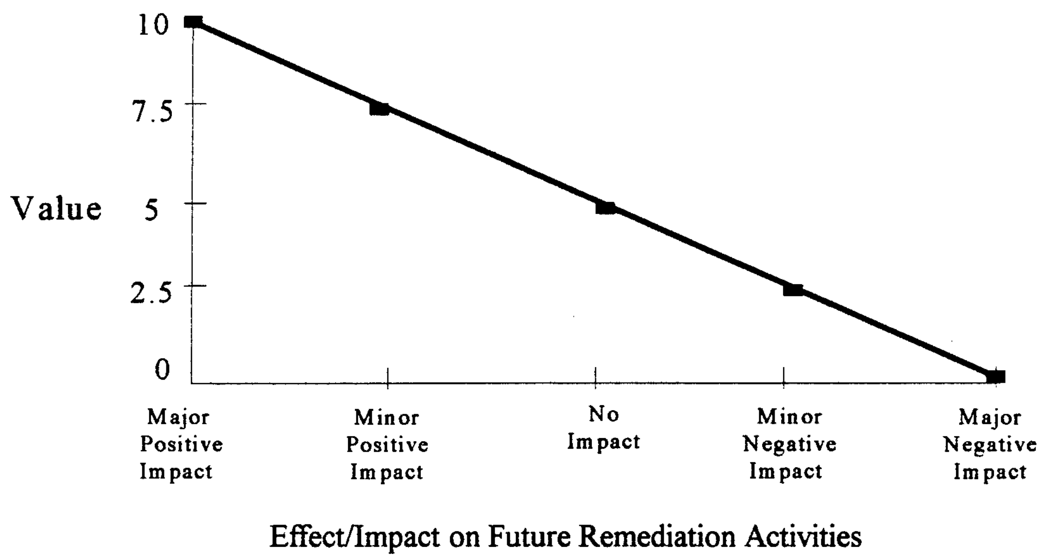


Figure B.28 Evaluation Measure for the Ease of Undertaking Future Remediation

ID. Ability to Monitor the Effectiveness of the Remedy: The ability to monitor a pathway combined with the risk associated with that pathway is important. The ability to monitor the effectiveness of a remedial action varies with each hydrogeological zone and with each train. The proposed evaluation measure is a subjective assessment over all three zones for a given treatment train. The largest potential risk is not being able to completely monitor all pathways to the aquifer. For example, a surfactant that is inserted into one zone breaks into another geological zone that is not monitored. The three categories created were: low probability of exposure and low health and safety risk which receives a value of 10, low probability of exposure and high health and safety risk which receives a value of 5, and high probability of exposure with a high health and safety risk which receives a value of 0.

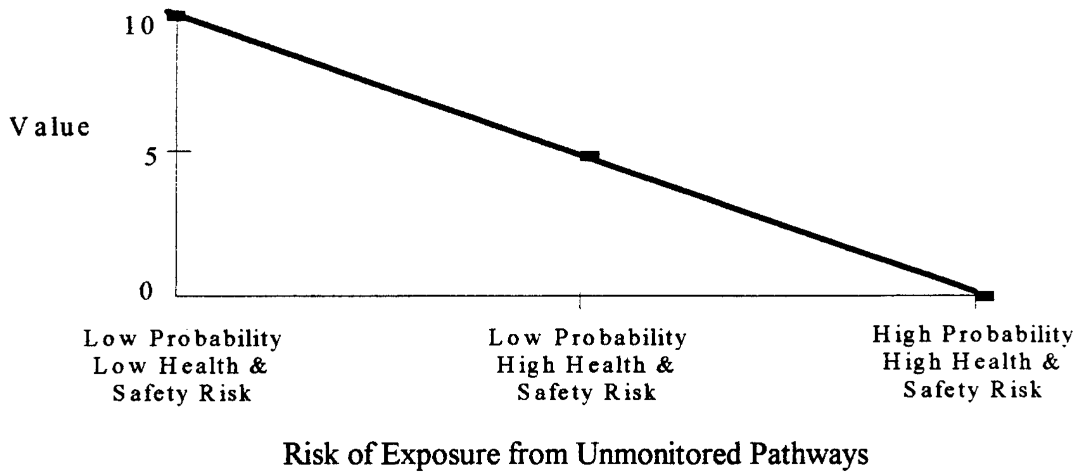


Figure B.29 Evaluation Measure for the Ability to Monitor Effectiveness of Remedy

II. Administrative Feasibility (40 CFR S300.430(e)(9)(iii)(F)(2)): CERCLA further subdivides Administrative Feasibility into two subcriteria: "activities needed to coordinate with other offices and agencies and the ability and time required to obtain any necessary approvals and permits from other agencies (for off-site actions)". The team decided that one evaluation measure, Level of Effort to Obtain Approvals, could adequately cover this subcriteria.

It was decided that the Level of Effort to Obtain Critical Approvals the pump and treat remediation train would serve as the ideal base case (receives a value of 10), from which all other treatments would be compared. If any one of the following five approvals are needed in addition to the approvals needed for the pump and treat base case, the remediation train would receive a score of one with a corresponding value of 8. Likewise, if three out of the five approvals were needed above the base case, then the train would score a three with a corresponding value of 4. The following list of approvals is not comprehensive, approvals may exist that are not on the list below, but will be counted against the technology when it is scored.

Additional Approvals That May be Needed in Addition to Pump and Treat Approvals:

1) Requires Underground Injection
2) Requires Electrodes
3) Interferes With Building
4) Interferes With Existing Utilities
5) Requires New Utilities

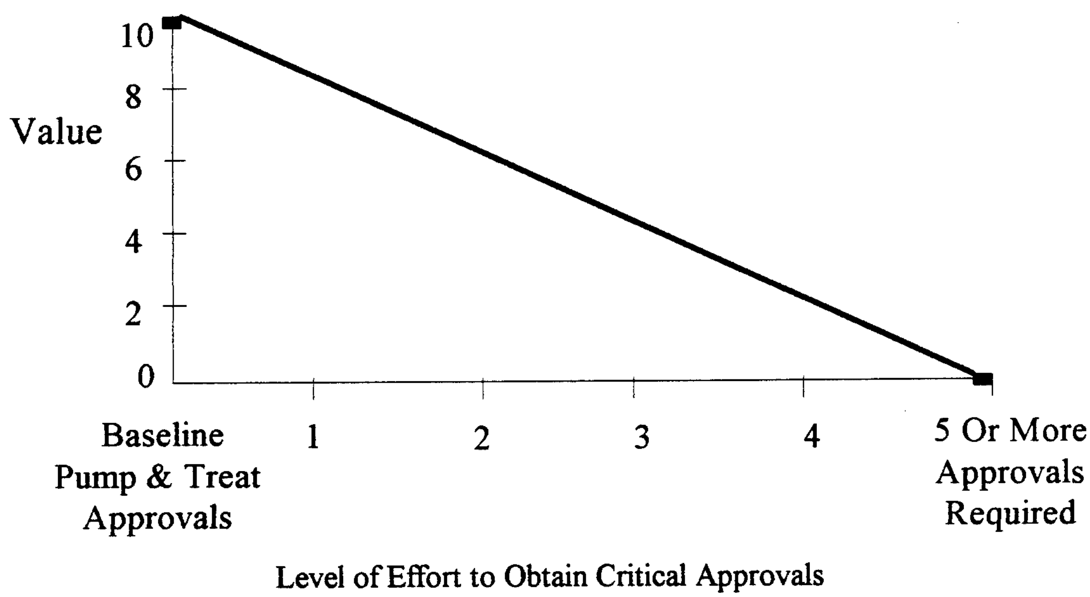


Figure B.30 Evaluation Measure for Administrative Feasibility

III. Availability of Services and Materials (40 CFR S300.430(e)(9)(iii)(F)(3)):

CERCLA further subdivides Availability of Services and Materials into four subcriteria, the first two were presented in the preceding hierarchy (A and B - solid lined boxes above).

The remaining two subcriteria: availability of services and materials and availability of prospective technologies were considered redundant by the team. The team felt these last two criteria were adequately addressed by the evaluation measures developed for A, B, C, and D under the Technical Feasibility subcriteria branch.

III A. Availability of Adequate Off-Site Treatment, Storage Capacity and Disposal Capacity and Services: The team agreed that if there was adequate off-site treatment, storage capacity, or disposal capacity, then this criteria would be considered satisfied. For example, the score of zero would be given if there was no adequate off-site treatment, storage, or disposal and a score of one would be given if any one of the three were available. Currently, all trains score a ten on this evaluation measure.

The team noted that the off-site treatment for Tc-99 was limited to low level waste and that the TSCA incinerator requires mostly pure TCE. Furthermore, the team expected there to be a preference from some Treatment, Storage, and Disposal (TSD) facilities for waste with higher TCE concentration and lower Tc-99 activity.

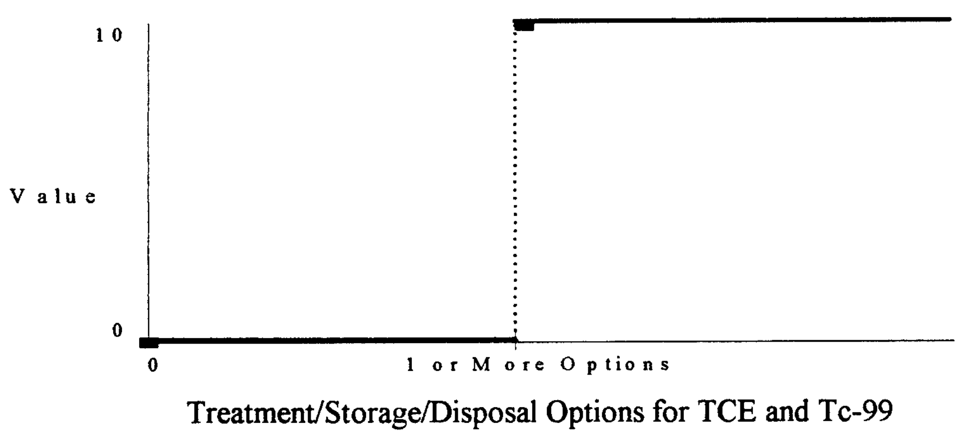


Figure B.31 Evaluation Measure for Availability of Off-Site Treatment, etc.

IIIB. Availability of Necessary Equipment and Specialists and Provisions to Ensure Any Necessary Additional Resources: The team agreed upon the evaluation measure of the number of contractors/subcontractors/specialists available for the limiting treatment/technology within a given train. Each train would be examined, and the train would score based on the treatment/technology, within that train, that had the minimum number of contractors, subcontractors or specialists.

The team agreed that if space were a limiting factor in implementing a particular technology, the technology would have already been screened out of the acceptable alternatives, prior to this evaluation. A score of zero indicates that DOE is developing the technology and there are no commercial contractors available.

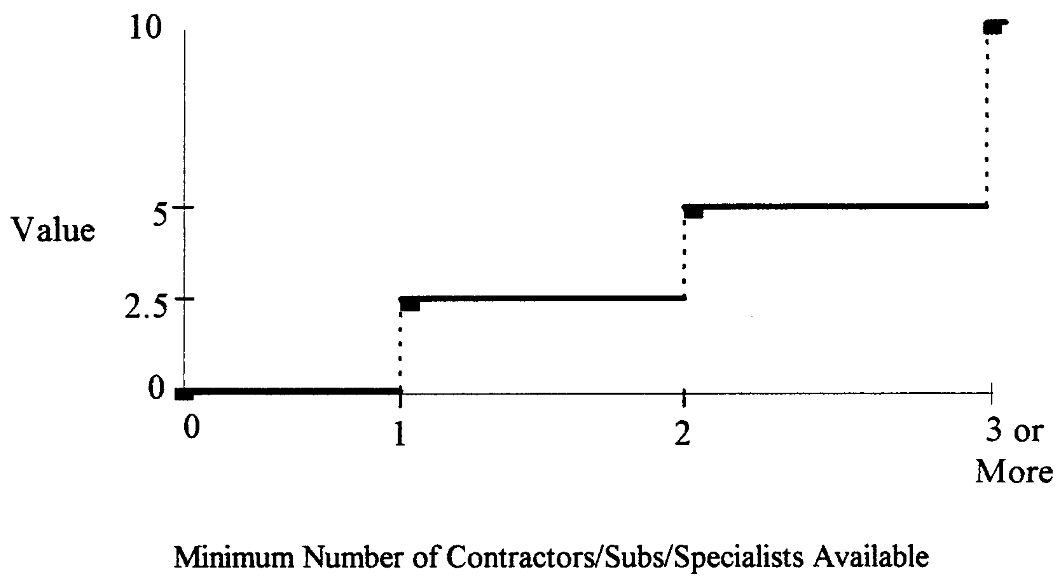


Figure B.32 Evaluation Measure for Availability of Necessary Equipment and Specialists

Balancing Criteria 5 COST (40 CFR S300.430(e)(9)(iii)(G)): CERCLA states "the following types of costs shall be assessed: capital costs, including both direct and indirect costs; annual operation and maintenance costs: and net present value of capital and O&M costs." The team agreed that the best way to develop and evaluation measure for cost was to consider Net Present Cost, which is the discounted sum of Capital Costs and the Annual O&M Costs.

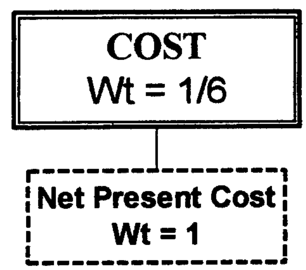


Figure B.33 - Cost Hierarchy

Since there is only one evaluation measure with no distinction between TCE and Tc-99, the measure is assigned the weight of one. The most expensive alternative would receive the lowest (0) value and the least expensive alternative would receive the highest (10) value. MSE cost data provided the thresholds demonstrated below:

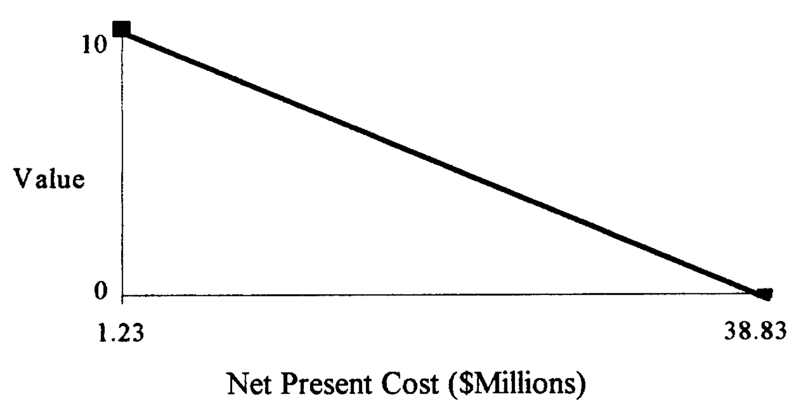


Figure B.34 Evaluation Measure for Net Present Cost

Appendix C: Technology Descriptions

The purpose of this appendix is to provide a brief description of the technologies that are being considered for implementation at WAG 6. A large portion of this Appendix is credited to the work performed by Papatyi [Papatyi, 1997: D-1]. His original work was reviewed and revised for this effort by the technology experts at WAG 6 in a scoring meeting on 7 Sep 97.

6 Phase Heating

This technology uses a six-pointed star configuration of electrodes placed in the ground to enhance the mobility of contaminants. When power is applied to the electrodes in the unsaturated zone the resistive heat volatizes the contaminants and in the saturated zone the resistive heat produces steam that in-turn strips the pollutant from the formation. The volatized contaminants are then removed via soil vapor extraction (SVE).

The six pointed star configuration allows for the uniform heating of the soil, although other patterns have been used. Multiple configurations may be necessary to get around buildings. The patented process breaks the conventional 3 phase electricity into a six phase system. This reduces the amount of soil heating needed, which is estimated to cost approximately 100 kWh per cubic meter of soil [DOE/EM-0248, 1995: 206]. Some Tc-99 removal occurs, though minimal.

Cosolvent Enhanced Treatment

Cosolvents, like surfactants, are used to enhance conventional pump and treat systems. Cosolvents are substances that, when mixed with water, can enhance the solubility of the contaminant. Typical cosolvents are methanol, and acetone alcohols. The idea behind this technology is similar to that of surfactant flooding. The cosolvent agent is injected into the ground and the area is flooded. The cosolvent then acts to strip contaminant from the soil. Then the pump and treat systems pump the liberated contaminant and the cosolvent to the surface for treatment. The cosolvent acts to increase the solubility of the contaminant as well as decrease the contaminant sorption, and is especially effective for DNAPLs [National Research Council, 1995: 148 - 149]. This technology will also address Tc-99. The volume of Hazardous Waste (HW) generated in the short term may be greater than other technologies that do not inject chemicals to flush contaminants.

Dynamic Underground Stripping

This technology is actually a combination of three separate technologies:

1. Steam injection - Steam is injected around a contaminated site to heat the subsurface, vaporize contaminants, and strip contaminants from the soil. The steam and contaminants are extracted from an extraction well located in the center of the injection zone.

2. Electrical Heating - Electrical probes are used in areas that contain the highest concentration of contaminants or areas with relatively low permeability. The

energized probes heat the soil, volatilizing contaminants so they can be extracted along with the steam.

3. Underground Imaging - Electrical Resistance Tomography is used as an imaging technique to regulate the steam application to the heated areas. Underground imaging is essential for control feedback.

This technology can be used above and below the water table, and is especially well suited for subsurfaces where clay and sand are interlaced together [Mather, 1995: WWWeb]. May not need electrical heating in the application at WAG 6.

LASAGNA™ or Electro-Osmosis

Electro-osmosis is a process that uses electrodes placed into the soil to mobilize DNAPL contaminants. Once power is applied to the electrodes, the DNAPL contaminant will migrate in the direction of current flow. The induced contaminant movement may be used with other extraction technologies or contaminants may be destroyed in situ. Typically, the contaminant is removed via adsorption or destroyed in situ. The technology appears to be most beneficial when contaminants are located in the saturated zone and where the soil has a low permeability. Tc-99 will be adsorbed as a precipitate within a permeable treatment zone, so the technology can address Tc-99.

The term LASAGNA™ was derived by a consortium of private companies that were researching methods to speed VOC contaminant cleanup. The researchers determined that a *layered* application of Electro-osmotic probes would speed the migration of the contaminants to the destructive zones and thus increase the speed at which cleanup could occur. The biggest uncertainty with LASAGNA is the vertical layering. Monsanto (one of the consortium members) patented and trademarked the process [Falta et al. 1996: 24]. The layering effect may be horizontally or vertically oriented.

Oxidation

Chemical Oxidation is an in-situ remediation technology that uses a chemical oxidant solution such as hydrogen Peroxide (H_2O_2) or Potassium Permanganate ($KMnO_4$) to degrade organic contaminants (like DNAPLs) into less harmful substances. The oxidant solution (i.e. H_2O_2 or $KMnO_4$) either is injected into the ground or is mixed with the soil through a soil mixing apparatus. In either case, the oxidant encounters the organic DNAPL contaminant, and destroys it [West, 1996]. Greater effectiveness may be achieved with soil mixing, though this not an option at WAG 6.

Pump and Treat

Conventional pump and treat systems operate by pumping ground water to the surface, for treatment and returning the water to the ground or discharging it to a permitted outfall. Because organic contaminants have low solubility and sorb to the soil, this technology requires large volumes of water to be pumped out of the ground. The residual contaminants that adhere to subsurface particles may require extremely long periods of operation to completely clean up a site. Therefore, pump and treat is often used for plume containment [National Research Council, 1995: 29]. This technology will also address Tc-99.

Permeable Treatment Zones

This technology makes use of a permeable "wall" that is excavated into the subsurface. The wall allows ground water to flow through it. As the groundwater flows through, reactive media in the "wall" chemically treats the contaminant. The most common type of PTZ media is iron filings. The iron filings cause chlorinated hydrocarbons to degrade to less harmful substances [Clayton, 1997]. Depending on the reactive media used, this technology will also address Tc-99. While this technology provides in situ treatment, it is generally considered a containment strategy.

Radio Frequency (RF) Heating

Radio Frequency (RF) heating uses the heat energy induced by the application of RF energy into the soil to enhance conventional vapor extraction methods. The heat applied to the soil through RF causes a liberation of the contaminants, especially Volatile Organic Compounds (VOCs) like TCE. This technology is most applicable to remediation of the vadose zone (unsaturated) [DOE/EM-0248, 1995: 215 - 217]. It is not a stand alone technology and must be coupled with another technology, such as SVE, to extract the liberated contaminants. Overheating of the formation can occur if the soil becomes sufficiently desiccated. This technology does not treat Tc-99.

Surfactant Enhanced Treatment

Surfactants (surface active agents) are used to enhance conventional pump and treat systems. They are used to enhance soil flushing techniques. The idea behind this technology is to inject a surfactant into the ground and flood the area with a surfactant agent. Once the flood is complete, conventional pump and treat systems are used to recover both the contaminant and the surfactant. The surfactant acts as a loosening agent to separate the contaminant from the water saturated soil [Falta et al., 1996:26 - 29 and National Research Council, 1995: 148 - 149]. This technology will also address Tc-99.

Two Phase

This technology makes use of a powerful vacuum system that extracts soil vapor and liquids. It is typically used in low to moderate permeability soils. As the vacuum is applied through a screened well, soil vapors are extracted and groundwater is entrained in the extracted vapors. Therefore, no pumps are required in the well. It can accelerate remediation by dewatering the site and removing contaminants in the vapor phase. Once the vapors and groundwater are above ground, they are separated and treated individually. It is more effective than using SVE singularly since it treats soil above and below the water table and extracts contaminated groundwater. This is a patented technology, requiring licensed contractors and royalty fees per wellhead. [EPA/542/B-94/013, 1994: 4.145 - 4.147].

Dual Phase

Very similar to Two Phase with regard to effectiveness, but is not a patented technology. A pump is required in the well to convey ground water to the surface.

UVB (Unterdruck-Verdampfer-Brunnen)

This technology is similar to pump and treat except that it treats captured ground water inside the well and reintroduces it to the formation after the treatment.

The technology treats the groundwater inside the well using air stripping and then injects it back into the surface. Typically, this technology is used to affect an area no larger than 50' in diameter per well. Typically effective for formations with high to moderate hydraulic conductivity. [Gelb 1997, Clayton, 1997].

Redox

This technology reduces an aquifer's redox potential, which allows a variety of redox sensitive contaminants to be treated. The goal is to create a permeable treatment zone downstream of the contaminant plume by injecting appropriate reagents and buffers to chemically reduce the structural iron in the sediments; or by injection of microbial nutrients to stimulate microbial reduction of the sediments. The reducing zone can also be created by the injection of colloidal iron or chemically reduced colloidal clays. The reducing zone created can either immobilize contaminants or degrade them to less harmful substances. Once inorganic contaminants are immobilized they can be destroyed through reduction. [Fruchter,1996] This technology is generally used for containment. This technology is primary used to extract Tc-99 although it may extract minimum amounts of TCE.

Appendix References

Clayton, Bryan. Technical Expert, Lockheed Martin Energy Systems, Paducah, Kentucky. Scoring Meeting. 9 Sep 97.

Department of Energy. Contaminant Plumes Containment and Remediation Focus Area Technology Summary. June 1995. DOE/EM-0248.

Environmental Protection Agency. Remediation Technologies Screening Matrix. EPA/542/B-94/013. October, 1994.

Falta, R.W. and T.R. Jarosch and Kueper B.H. and Looney B.B. and Sabitini D.A. and Siegrist R.L. and K. S. Udell. Technical Evaluation of DNAPL Enhanced Removal Technologies. June 1996.

Mather, John. "Technology Summary", September 1995 WWWeb http://www.em.doe.gov/plumesfa/intech/dus/sum.hmtl.

Morti, Eric, Technical Expert, Lockheed Martin Energy Systems, Paducah, Kentucky. Scoring Meeting. 9 Sep 97.

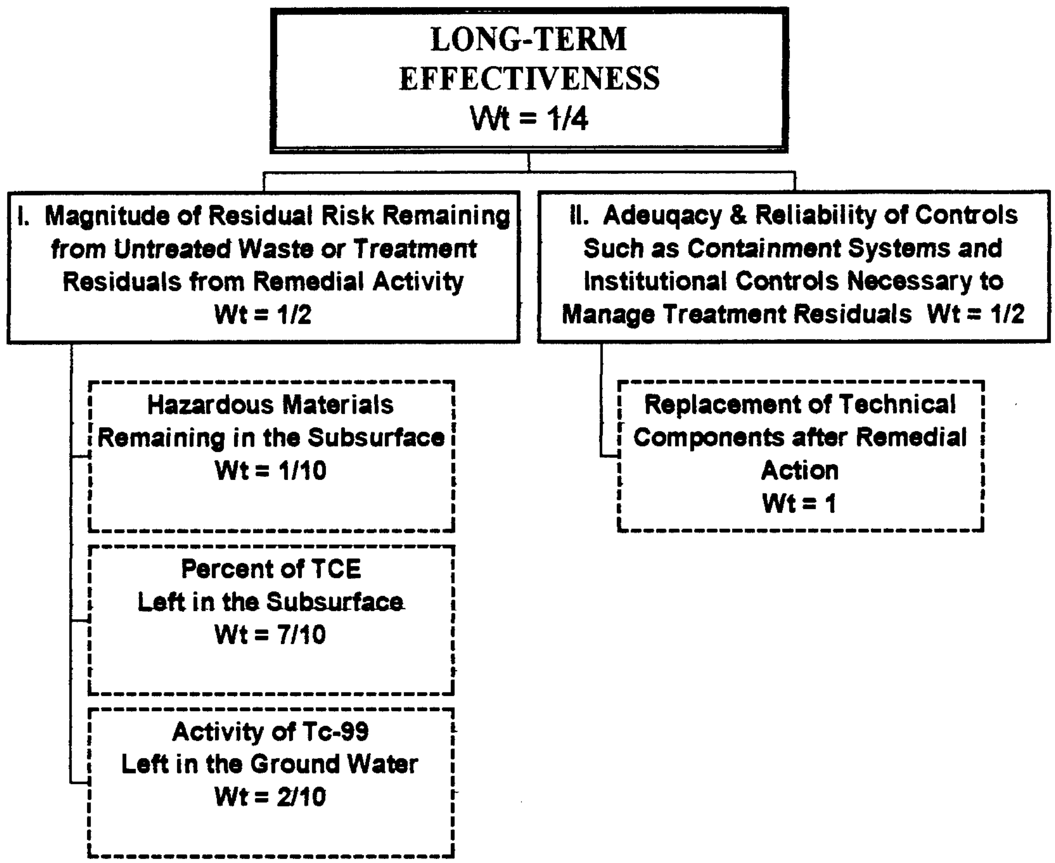
National Research Council. Alternatives for Groundwater Cleanup. National Academy Press, Washington D. C. 1995

Gelb, Dan, Technical Expert, Jacobs Engineering Company, Paducah, Kentucky. Scoring Meeting. 9 Sep 97.

Fruchter, John, "In-Situ Redox Manipulation" , Fact Sheet, PNNL-11372, VC-602, 1996

Appendix D: Scoring Packet

Balancing Criteria #1: Long-Term Effectiveness (LTE) and Permanence
Hierarchy: EPA guidance suggests that long-term effectiveness and permanence "…addresses the results of a remedial action in terms of the risk remaining at the site after response objectives have been met."

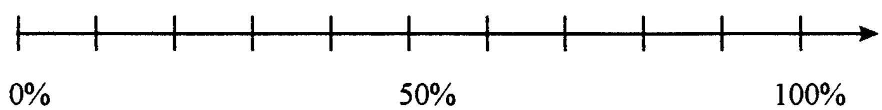


I. Magnitude of Residual Risk Remaining from Untreated Waste or Treatment Residuals Remaining at the Conclusion of the Remedial Activities

Hazardous Materials Remaining in the Subsurface: The WAG 6 team assumed that there would be no long term, on-site storage of Potential Contaminants Of Concern (PCOCs); all waste will be treated or sent off-site for disposal. However, treatment residuals may be left within the subsurface. The first measure, applicable to both TCE and Tc-99, evaluates the effect of hazardous materials (HM) remaining in the subsurface of the site. These HM may include treatment residuals, degradation products, or unreacted treatment materials. HM are also those materials brought to the site to be used as part of the treatment but are defined hazardous under Department of Transportation definitions.

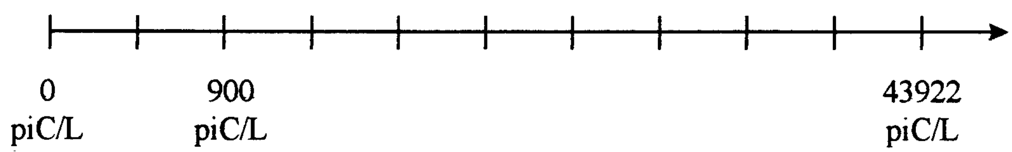
Are there Hazardous Materials Remaining in the Subsurface? Yes or No

LTE : Percent of TCE Left in Subsurface: The long-term magnitude of residual risk for TCE can best be described by the Percent of TCE left in the ground. The preliminary goal of this project is to remove/destroy 95% of the TCE contamination. Because it is uncertain whether a 95% performance standard can be achieved in a cost effective manner, remediation trains will receive a positive score if more than 30% of the contaminant is removed (or 70% is remaining). This standard was chosen from examining other remedial action sites which have shown that at least, 30% removal/destruction of Non-Aqueous Phase Liquids (NAPLs) is achievable.



Percent of TCE Left in Subsurface

Activity of Tc-99 Left in Ground Water: The long-term magnitude of residual risk for Tc-99 can best be measured by the Activity of Tc-99 Left in Ground Water. Since Tc-99 will never be completely destroyed, the more that is removed the better. The upper limit of this scale is the highest known concentration of Tc-99 found to date at the site (43,922 piC/L). Any train that accomplishes a reduction from this initial amount will have value. The lower limit of this scale represents the current, regulatory limit (900 piC/L).



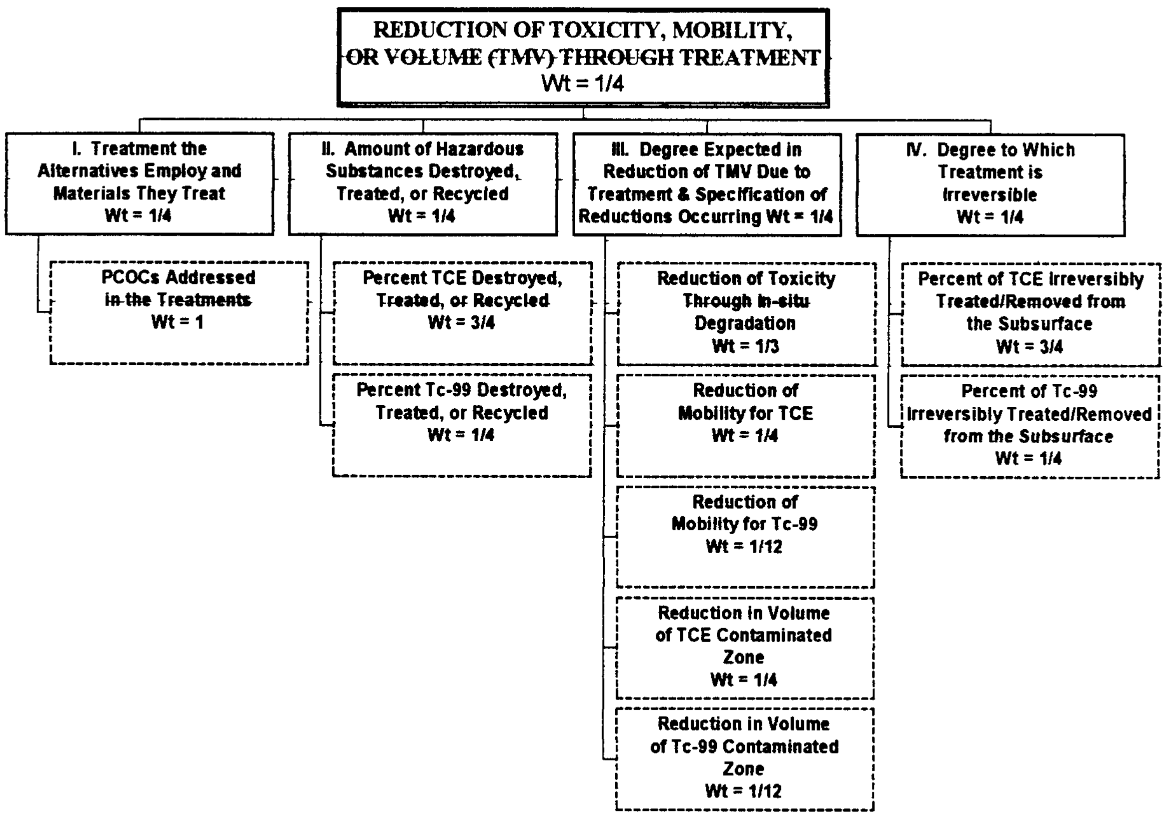
Activity of Tc-99 Left in Ground Water

II. Adequacy and Reliability of Controls Such as Containment Systems and Institutional Controls that are Necessary to Manage Treatment Residuals and Untreated Waste

Replacement of Technical Components After Remedial Action: This measure addresses whether there will be any threat of exposure or release when the replacement is occurring. This measure considers both TCE and Tc-99 and combines both frequency and risk of exposure during replacement and has three distinct options. Choose the option that best describes the remediation chain:

1. No Replacement Required
2. Replacement Without Risk of Release
3. Replacement With Risk of Release

Balancing Criteria #2: Reduction of Toxicity, Mobility, or Volume (TMV) Through Treatment Hierarchy: EPA Guidance suggests that Reduction of Toxicity, Mobility, or Volume Through Treatment "…address the statutory preference for selecting remedial actions that employ treatment technologies that permanently and significantly reduce toxicity, mobility, or volume of the hazardous substances as their principal element. This preference is satisfied when treatment is used to reduce the principal threats at a site through destruction of toxic contaminants, reduction of the total mass of toxic contaminants, irreversible reduction in contaminant mobility, or reduction of total volume of contaminant media." The guidance also suggested incorporating treatment residuals, but the issue of residual risk has already been addressed under Long-Term Effectiveness and Permanence.



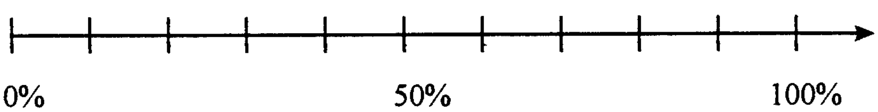
TMV I. Treatment or Recycling Processes the Alternatives Employ and Materials They Will Treat

PCOCs Addressed in the Treatments: This measure assesses which potential contaminants of concern are being treated in the remediation train. There are four distinct categories, choose the one that best describes the remediation train.

0. Neither Addressed
1. Only Tc-99 Addressed
2. Only TCE Addressed
3. Both Addressed

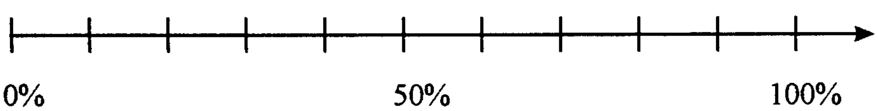
II. Amount of Hazardous Substances, Pollutants, or Contaminants that will be Destroyed, Treated or Recycled

Percent TCE Destroyed, Treated, or Recycled: Estimate of how much (amount/volume) TCE the remediation train is expected to destroy.



Percent TCE Destroyed, Treated, or Recycled

Percent Tc-99 Destroyed, Treated, or Recycled: Estimate of how much (amount/volume) Tc-99 the remediation train is expected to remove. Removing Tc-99 from the subsurface is considered treatment because the substance changes status from uncontrolled to controlled because of the removal.



Percent Tc-99 Destroyed, Treated, or Recycled

TMV III. The Degree of Expected Reduction in Toxicity, Mobility, and Volume of the Waste Due to Treatment or Recycling and the Specification of Which Reduction(s) are Occurring

Reduction of Toxicity Through In-situ Degradation: There is no measure for the reduction of toxicity for Tc-99 because Tc-99 cannot be destroyed. However, the reduction of total mass of contaminant (as stated in Table 6-2 in EPA Guidance) can be applied to TCE. The evaluation measure developed considers whether a treatment relies on degradation to reduce toxicity. The concern being if degradation is not complete and there are some residuals, those residuals may be more toxic than TCE. Hence, the three distinct categories listed below. Choose the category that best describes the remediation train being considered.

1. No Degradation Possible	2. Does Not Inherently Degrade but it May Be Possible	3. Inherently Degrades

Reduction of Mobility for TCE: The team quantified this evaluation measure assuming successful treatment, because an unsuccessful treatment may increase mobility with some technologies. The team noted that the treatment trains currently being assessed do not reduce the mobility of TCE, however future alternatives/treatment trains may. Further definition will be required to determine the mobility continuum, hence two measuring scales: Pick one of the categories below to describe the remediation train:

Increase in Mobility	No Change in Mobility	Chemical/Physical Reduction in Mobility

Reduction of Mobility for Tc-99: A similar measure was created for Tc-99. Since Tc-99 is soluble, the most effective means for reducing its mobility is to cause it to chemically change (precipitate). A study is planned next fiscal year to determine how to reduce the mobility of Tc-99 by examining various treatment processes. Further definition will be required to determine the mobility continuum, hence two measuring scales: Pick one of the categories below to describe the remediation train:

Increase in Mobility	No Change in Mobility	Chemical/Physical Reduction in Mobility

TMV: Reduction in Volume of TCE Contaminated Zone: The focus of the remedial action is the source not the plume; emphasis is on reduction of mass/volume (EPA Guidance Table 6-2). However, a technology that increases the volume of the source zone, such as a steam flood, is worse in this criteria than one that decreases the volume. The source is the media contaminated with DNAPL/ TCE. All have been scoring 0%.

0% or Increase | 50% | 100% Reduction

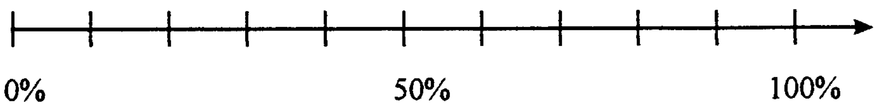
% Reduction in Volume of TCE Contaminated Zone

Reduction in Volume of Tc-99 Contaminated Zone: A similar measure was created for Tc-99, where the emphasis is on the reduction of mass and volume (EPA Guidance Table 6-2). Once again, a technology that increases the volume of the source zone, such as a steam flood, is considered worse in this criteria than one that decreases the volume. The source is the media contaminated with Tc-99. All technologies have been scoring 0%.

0% or Increase | 50% | 100% Reduction

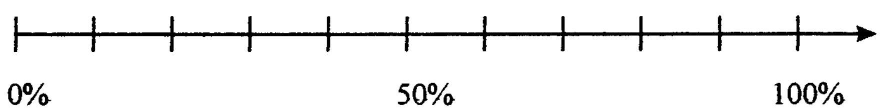
% Reduction in Volume of Tc-99 Contaminated Zone

Percent of TCE Irreversibly Treated/Removed from the Subsurface: The WAG 6 team assumed that once TCE was removed or treated, it would not be reinjected into the subsurface and, therefore, it would have been treated irreversibly. Treatment could also include in-situ treatment where the TCE has been irreversibly altered or destroyed. Measure will be completed as detailed below, once MSE data is obtained.



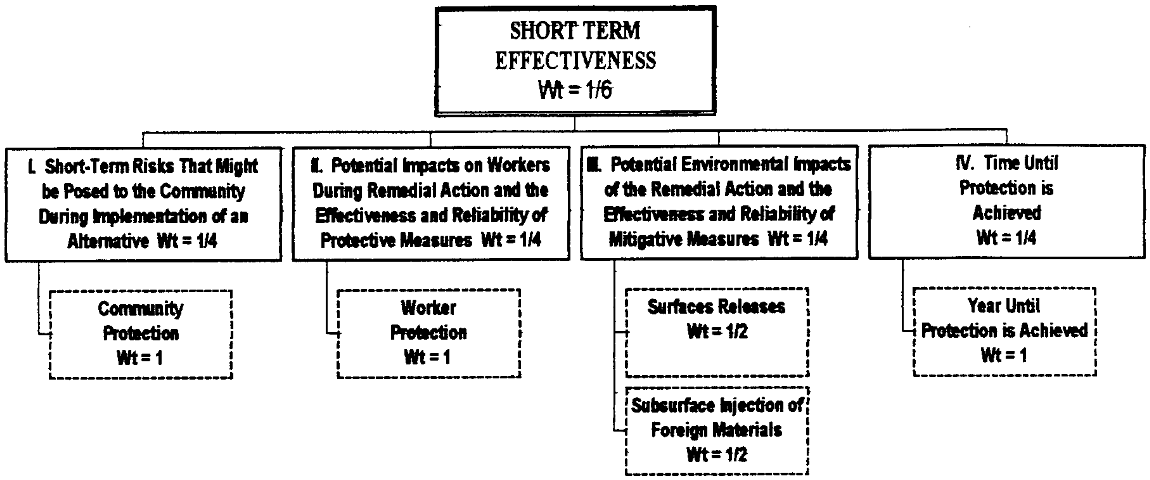
Percent of TCE Irreversibly Treated/Removed from the Subsurface

Percent of Tc-99 Irreversibly Treated/Removed from the Subsurface: A similar evaluation measure was developed for Tc-99. Again, the team assumed that once the Tc-99 was removed, it would not be reinjected into the subsurface and so it could be considered to have been treated irreversibly. It is important to note that Tc-99 cannot be treated irreversibly other than to be removed from the subsurface for this evaluation measure.



Percent of Tc-99 Irreversibly Treated/Removed from the Subsurface

Balancing Criteria #3: Short Term Effectiveness (STE) Hierarchy: EPA guidance suggests that "short-term effectiveness addresses the effects of the alternative during the construction and implementation phase until remedial response objectives are met."



I. Short-Term Risks that Might be Posed to the Community During Implementation of an Alternative

Community Protection: This is a constructed measure which uses the requirements of air emission monitoring and hazardous waste (HW) and hazardous material (HM) shipment both on and off site. HM has previously been defined, and HW is considered any waste generated at the site that meets the RCRA definition of a HW. The "community" is defined to be those individuals who are employed at the site and the local community near the site. Specifically excluded from this group are the remediation workers themselves, because they have their own evaluation measure that follows. The team believed that the occurrences shown represent the entire range of possible events during any remedial action. The best situation is when there are no emissions and no transportation of HW/HM. The worst situation is when there are untreated radiological emissions to the air/water. Pick the best category below that describes the influence the remediation train will have on community protection.

1. Untreated Radiological Emission to air/water
2. Untreated Waste Emission to air/water
3. Treated HM Emission to air/water & HM/HW Transportation
4. No Emission but HM/HW Transportation
5. No Emission and No Transportation

STE: II. Potential Impacts on Workers During Remedial Action and the Effectiveness and Reliability of Protective Measures

Worker Protection: This is a constructed measure which uses radiation, mechanical, chemical, heat, and electrical risks to cover the range of hazards workers may face. The best situation is when there is no exposure to hazards for the remediation workers on site (those workers specifically performing tasks related to the remedial action). The worst situation (not expected for any of the trains) is when all five hazards cannot be readily controlled. Pick the category that best describes the remediation train's affect on Worker Protection:

1. Radiation, Mechanical, Chemical, Heat, and Electrical Risks
2. A combination of any four of the above risks
3. A combination of any three of the above risks
4. A combination of any two of the above risks
5. Only one of the above risks
6. No risks to Workers on Site

III. Potential Environmental Impacts of the Remedial Action and the Effectiveness and Reliability of Mitigating Measures During Implementation: The team decomposed this evaluation measure to produce two measures - surface release and subsurface injection of foreign materials.

Surface Release: At the surface, no release is considered best. An uncontrolled air and uncontrolled water release is considered the worst case. Water releases are considered less dangerous and pose less risk than air releases. Select the category that best describes the remediation train's impact on surface releases:

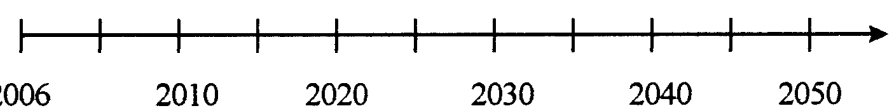
1. Both Air and Water Released
2. Uncontrolled Air
3. Uncontrolled Water
4. Controlled Air and Water
5. Controlled Air
6. Controlled Water
7. No Release to the Surface

STE: Subsurface Injection of Foreign Materials: This evaluation measure assumes that the risk due to injection increases as the material injected changes from air, to water, to biological organisms, to steam, and, finally, to RCRA toxic chemicals which rate the worst case. Select the category below that best identifies the affect the remediation train will have on subsurface injection of foreign materials.

1. Inject RCRA Class 2-4 Materials
2. Inject Steam
3. Inject biological treatments
4. Inject water
5. Inject Air
6. No injection

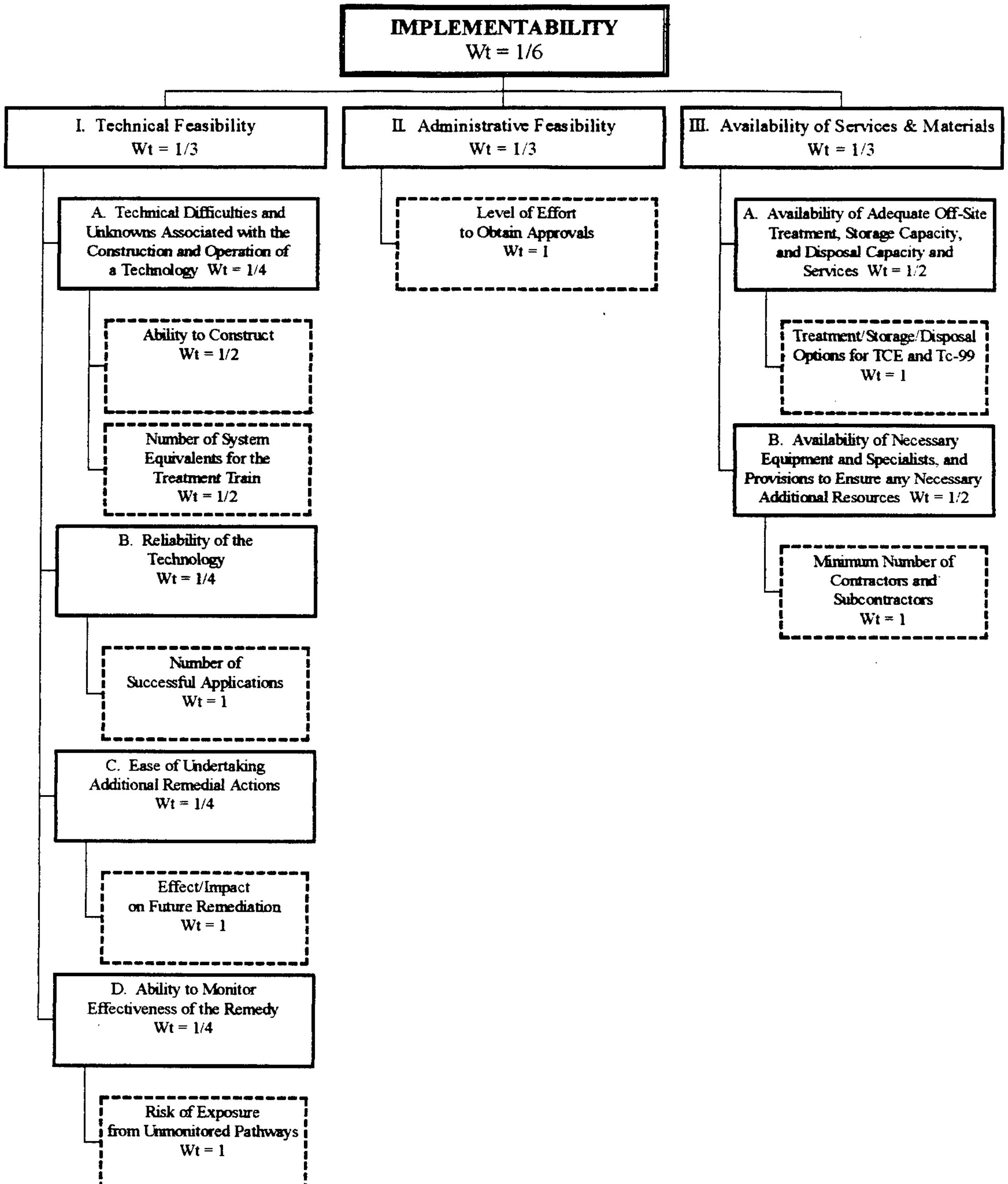
IV. Time Until Protection is Achieved

Year Until Protection is Achieved: The 10-year plan, starting from 1996, provides the rationale for the evaluation measure. Assuming construction would finish by 2002, if the Remedial Action (RA) was completed in eight years (i.e. 2010) it would be considered an extremely successful project with respect to time. Any remedial actions that require more than thirty years past construction completion would have little or no added value with respect to time.



Year Until Protection is Achieved

Balancing Criteria #4: Implementability (IP) Hierarchy:



IA. Technical Difficulties and Unknowns Associated with the Construction and Operation of a Technology. This section is evaluated using two measures; Ability to construct and Number of System Equivalents for the Treatment Technology.

IP: Ability to Construct: This measure addresses the difficulty of construction and is scored by giving one point for each "yes" answer to the following questions. The scores for these three questions are then added and their total is used to score the remediation train.

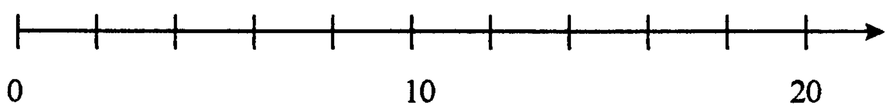
1. Is the technology sensitive to obstructions? (yes = 1, no = 0)
2. Does the technology require unconventional techniques/equipment? (y = 1, n = 0)
3. Does the technology have unconventional operational requirements? (y = 1, n = 0)

Total Score for Ability to Construct:

Number of System Equivalents for the Treatment Technology: The complexity of a system can be estimated by the number of systems components, which vary greatly for each alternative. The following system equivalents guide was proposed for scoring:

3 system equivalents	SVE	
1 system equivalent		air movement
1 system equivalent		treatment
1 system equivalent		wells
4 system equivalents	Pump & Treat	
1 system equivalent		pump
1 system equivalent		well
1 system equivalent		water treatment
1 system equivalent		vapor treatment

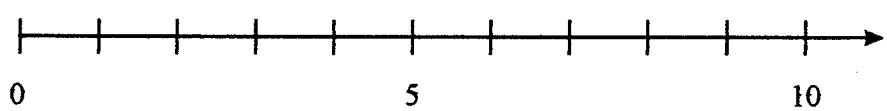
10	system equivalents	DUS
2	system equivalents	pump (liquid and vacuum)
1	system equivalents	injection wells
1	system equivalents	extraction wells
1	system equivalent	injection system
2	system equivalents	controlling monitoring system
2	system equivalents	remove vapor extraction (steam & water)
1	system equivalent	steam generation package



Number of System Equivalents for the Treatment Technology

IB. The Reliability of the Technology: This evaluation measure focuses on the likelihood that technical problems associated with implementation will lead to schedule delays (EPA Guidance, Table 6-4).

Number of Successful Applications: The number of times the technology being considered has been successfully used in a similar medium is a good proxy measure. A conservative measure of reliability of a treatment train is the reliability of the component technology that has been successfully implemented the least number of times.



Number of Successful Applications

IC. Ease of Undertaking Additional Remedial Actions: This evaluation measure estimates the impact on potential future additional remediation activities either for other principal threats or for other overlapping or nearby operable units.

Effect/Impact on Future Remediation Activities: We developed a constructed scale ranging from no impact on additional remedial activities to alternatives that have a major impact on additional remedial activities. For example, injecting a chemical into the aquifer which precipitates the Tc-99 may actually increase the mobility of TCE and therefore hinder the TCE remediation activities which would result in a minor negative impact. A major negative impact would be the plugging of the aquifer; a major positive impact would be leaving an operational system in place that could be used for future remediation activities; and a minor positive impact would be putting in wells which also could be used for future remediation activities. Further definition will be required to determine x-axis. Select the category that best describes the remediation train's impact on future remediation activities:

Major Positive Impact	Minor Positive Impact	No Impact	Minor Negative Impact	Major Negative Impact

ID. Ability to Monitor the Effectiveness of the Remedy: The ability to monitor a pathway combined with the risk associated with that pathway is important. The ability to monitor the effectiveness of a remedial action varies with each hydrogeological zone and with each train.

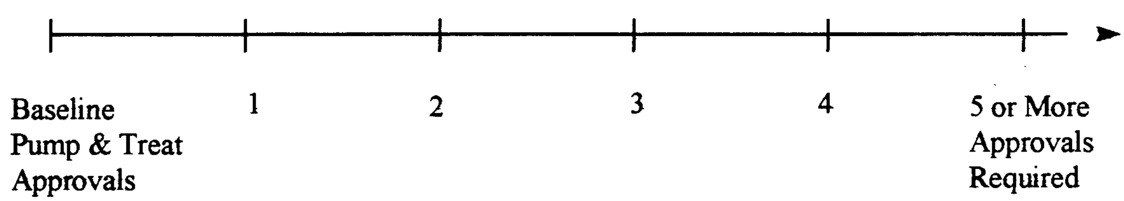
Risk of Exposure from Unmonitored Pathways: This proposed evaluation measure is a subjective assessment over all three zones for a given treatment train. The largest potential risk is not being able to completely monitor all pathways to the aquifer. For example, a surfactant that is inserted into one zone breaks into another geological zone that is not monitored. The three categories created were: low probability of exposure and low health and safety risk, low probability of exposure and high health and safety risk, and high probability of exposure with a high health and safety risk. Further definition will be required to determine high and low probability and high and low safety risk.

Low Probability Low Health & Safety Risk	Low Probability High Health & Safety Risk	High Probability High Health & Safety Risk

II. Administrative Feasibility:

Level of Effort to Obtain Approvals: It was decided that the pump and treat remediation train would serve as the ideal base case, from which all other treatments would be compared. If any one of the following five approvals are needed in addition to the base case, the remediation train would score a one. Likewise, if two of the five are needed, the train would score a two. Additional approvals that may be needed in addition to pump and treat approvals:

1) Requires Underground Injection
2) Requires Electrodes
3) Interferes With Building
4) Interferes With Existing Utilities
5) Requires New Utilities



III. Availability of Services and Materials

III A. Availability of Adequate Off-Site Treatment, Storage Capacity and Disposal Capacity and Services

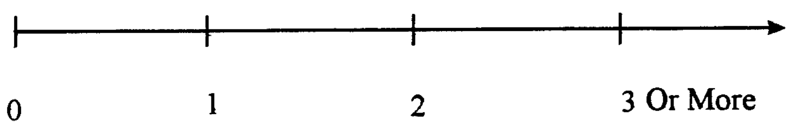
Treatment/Storage/Disposal Options for TCE and Tc-99: The team agreed that if there was adequate off-site treatment, storage capacity, or disposal capacity, then this criteria would be considered satisfied. For example, the score of zero would be given if there was no adequate off-site treatment, storage, or disposal and a score of one would be given if any one of the three were available. Therefore, the remediation train can be scored by answering the following:

Is there adequate off-site treatment, storage capacity, or disposal capacity and services?

Yes or No

IIIB. Availability of Necessary Equipment and Specialists and Provisions to Ensure Any Necessary Additional Resources

Minimum Number of Contractors/Subs/Specialists Available: The team agreed upon the evaluation measure of the number of contractors/subcontractors/specialists available for the limiting treatment/technology within a given train. Each train would be examined, and the train would score based on the treatment/technology, within that train, that had the minimum number of contractors, subcontractors or specialists. A score of zero indicates that DOE is developing the technology and there are no commercial contractors available.



Minimum Number of Contractors/Subs/Specialists Available

Appendix E: Expected CERCLA Values/Utilities for All Trains at All Spill Volumes

Spill Volume Probabilities: Sum check: 1

50K	0.74	100K	0	200K	0.2	300K	0.03	400K	0.02	500K	0.01

Value Scores at Differing Spill Volumes

Trains	50K	100K	200K	300K	400K	500K	Total Value	Trains	
1	7.58	7.54	7.52	7.51	7.50	7.47	7.56	7	7.61
2	5.56	5.38	5.31	5.29	5.28	5.25	5.49	9	7.60
3	5.70	5.48	5.42	5.41	5.41	5.39	5.63	1	7.56
4	5.12	4.94	4.90	4.88	4.78	4.75	5.06	21	7.49
5	6.94	6.94	6.94	6.94	6.94	6.94	6.94	6	7.36
6	7.49	7.31	7.09	6.85	6.64	6.39	7.36	13	7.04
7	7.71	7.56	7.38	7.21	7.05	6.86	7.61	19	7.00
8	6.14	6.14	6.14	6.14	6.14	6.14	6.14	12	6.94
9	7.70	7.60	7.39	7.19	7.00	6.78	7.60	5	6.94
10	5.00	5.06	5.05	5.04	4.92	4.90	5.01	18	6.91
11	6.41	6.41	6.41	6.41	6.41	6.41	6.41	22	6.81
12	7.07	6.90	6.67	6.44	6.24	5.99	6.94	17	6.80
13	7.14	6.99	6.82	6.65	6.49	6.30	7.04	15	6.61
14	5.70	5.70	5.70	5.70	5.71	5.70	5.70	11	6.41
15	6.70	6.64	6.44	6.24	6.05	5.84	6.61	20	6.27
16	5.17	5.04	5.03	5.02	4.91	4.90	5.13	23	6.25
17	6.80	6.80	6.80	6.80	6.80	6.80	6.80	8	6.14
18	7.02	6.87	6.68	6.48	6.31	6.09	6.91	14	5.70
19	7.09	6.96	6.82	6.67	6.54	6.38	7.00	3	5.63
20	6.27	6.27	6.27	6.27	6.28	6.27	6.27	2	5.49
21	7.58	7.49	7.32	7.14	6.98	6.80	7.49	16	5.13
22	6.90	6.83	6.63	6.43	6.24	6.03	6.81	4	5.06
23	6.25	6.25	6.25	6.25	6.25	6.25	6.25	10	5.01

Appendix F: Sensitivity Analysis of the Multiattribute Risk Tolerance Factor

Figure F.1 demonstrates the various shapes associated with varying values of the multiattribute risk tolerance factor, ρ_m. As ρ_m approaches infinity, the shape of the exponential curve becomes linear. Similarly, the smaller ρ_m gets, the larger the curve.

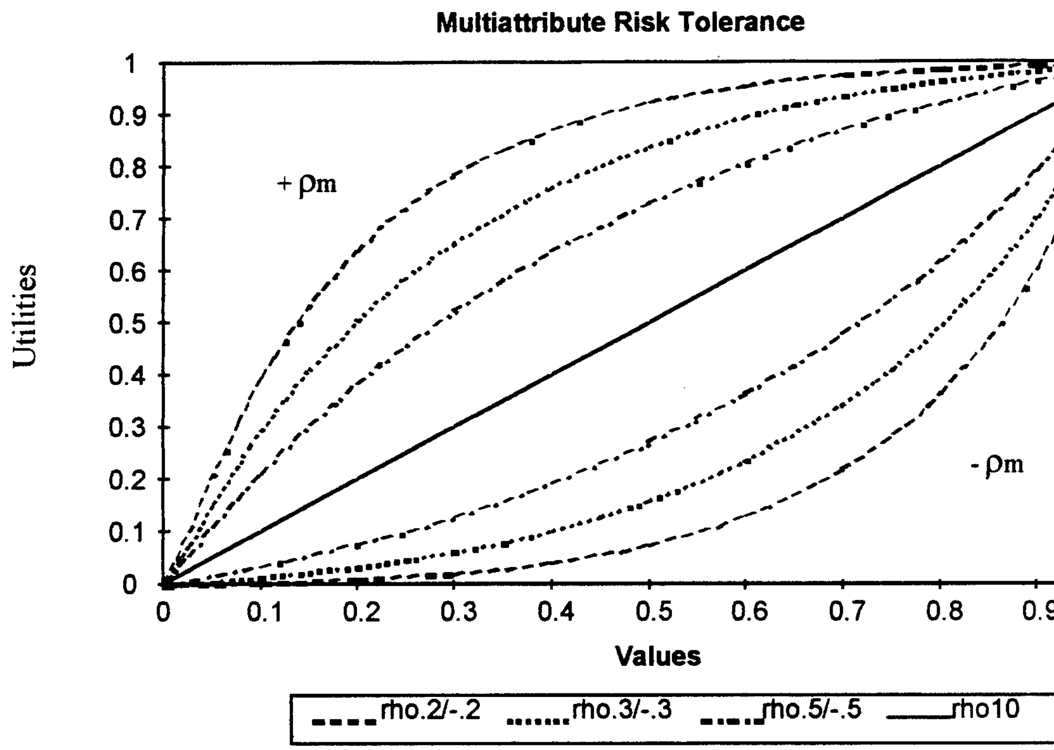


Figure F.1 Varying shapes of the Multiattribute Risk Tolerance Factor

Half of the single dimensional value functions derived in this research are linear [Appendix B]. It is also interesting to note that the single dimensional value function with the largest associated weight, net present cost, is also linear. Although an argument could be made that risk neutrality exists on these two points alone, a sensitivity analysis was performed where ρ_m, was varied between 0.2 and infinity (or 1E8). At 30 significant figures, there was no difference in values among the trains so assignment of rank is questionable. When ρ_m reaches .22 a difference in value is noticeable and the ranking established is the same ranking that follows through the rest of the tested values of ρ_m (out to ρ_m =1E8). Table F.1 below demonstrates a portion of the data table that was used in the spreadsheet analysis.

Table F.1 Sensitivity of Trains to Variance in ρ_m

	Total		Rho =	0.3				
Trains	Value	Utility			0.2	0.5	1	5
1	7.56089	1.037		1.036993707	1.00678	1.15652	1.5812	4.301
2	5.49026	1.037		1.036993695	1.00678	1.1565	1.5754	3.677
3	5.62625	1.037		1.036993699	1.00678	1.1565	1.5763	3.726
4	5.0588	1.037		1.036993657	1.00678	1.15647	1.5719	3.511
5	6.93902	1.037		1.036993706	1.00678	1.15652	1.5804	4.14
6	7.36255	1.037		1.036993707	1.00678	1.15652	1.581	4.251
7	7.60714	1.037		1.036993707	1.00678	1.15652	1.5812	4.312
8	6.14008	1.037		1.036993705	1.00678	1.15651	1.5786	3.901
9	7.59799	1.037		1.036993707	1.00678	1.15652	1.5812	4.31
10	5.00905	1.037		1.036993648	1.00678	1.15647	1.5714	3.491
11	6.40902	1.037		1.036993706	1.00678	1.15651	1.5794	3.986
12	6.94381	1.037		1.036993706	1.00678	1.15652	1.5805	4.141
13	7.03704	1.037		1.036993707	1.00678	1.15652	1.5806	4.166
14	5.7011	1.037		1.036993701	1.00678	1.1565	1.5767	3.753
15	6.6143	1.037		1.036993706	1.00678	1.15652	1.5799	4.047
16	5.12559	1.037		1.036993667	1.00678	1.15648	1.5726	3.538
17	6.798	1.037		1.036993706	1.00678	1.15652	1.5802	4.1
18	6.90845	1.037		1.036993706	1.00678	1.15652	1.5804	4.131
19	7.00397	1.037		1.036993707	1.00678	1.15652	1.5805	4.157
20	6.27306	1.037		1.036993706	1.00678	1.15651	1.579	3.943
21	7.49201	1.037		1.036993707	1.00678	1.15652	1.5811	4.284
22	6.15495	1.037		1.036993705	1.00678	1.15651	1.5786	3.906
23	6.252	1.037		1.036993706	1.00678	1.15651	1.5789	3.937

From this analysis it can be conclude that the value of ρ_m has no affect on the ranking of trains and therefore it can assumed that train values convert directly to utilities.

Appendix G: Technology Performance for Tc-99

The following assumptions were provided by the WAG 6 technical experts when assessing technology performance on reducing the concentration of Tc-99.

1. Tc-99 removal efficiency is assessed by the aquifer technology, because the majority of Tc-99 is assumed to be in the aquifer.

2. For DUS and Redox technologies, the removal efficiency is assumed to be 100% for all spill volumes.

3. Dual Phase, Pump and Treat, and PTZ, are technologies that rely on the natural solubility of the DNAPL in water to remove TCE. It is assumed that these technologies are allowed to continue until TCE is reduced to acceptable levels. Since Tc-99 is far more soluble then TCE, then the TC-99 should be completely removed by the time the TCE is reduced to acceptable levels.

4. Cosolvents and Sufactants increase the solubility and decrease the retardation factors of DNAPLs. It is unclear what their impact would be on Tc-99, however it is assumed that cosolvents or surfactants would not inhibit the solubility of Tc-99. Based upon removal efficiencies from another plume on site, it was determined that 100% removal of Tc-99 would occur prior to the acceptable reduction of TCE.

5. UVB and Oxidation essentially provide no additional removal of Tc-99 beyond that provided by the flushing of ground water through the contaminant zone under the existing hydraulic gradient. So based upon 12.783%, the current rate of annual reduction for Tc-99, and an initial concentration of 43,922 pCi/L, the concentrations

of Tc-99 can be calculated for different remediation times and spill volumes. The spreadsheet that follows (Table G.1) employs the standard decay equation:

$$C_o / e^{r*t} = C_t$$

where C_o is the initial concentration amount of 43,922 pCi/L, r is the decay rate of .12783/yr and t is the number of years, which produces the concentration at time t, C_t.

Table G.1: Tc-99 Concentrations for UVB, Oxidation and the No Action Alternative Trains

Assuming: 0.12783 /Yr
43922 pCi/L Inital Concentration

Spill @ 50K

Trains	Time	Concentration	%Remain	%Destroyed
2	30	948.87	2.16	97.84
9	7.25	17385.70	39.58	60.42
15	2.26	32901.54	74.91	25.09
21	8.28	15240.91	34.70	65.30
22	1.83	34760.67	79.14	20.86
23	30	948.87	2.16	97.84

Spill @ 100K

Trains	Time	Concentration	%Remain	%Destroyed
2	30	948.87	2.16	97.84
9	7.33	17208.81	39.18	60.82
15	2.33	32608.45	74.24	25.76
21	8.35	15105.14	34.39	65.61
22	1.9	34451.01	78.44	21.56
23	30	948.87	2.16	97.84

Spill @ 200K

Trains	Time	Concentration	%Remain	%Destroyed
2	30	948.87	2.16	97.84
9	7.45	16946.85	38.58	61.42
15	2.45	32112.07	73.11	26.89
21	8.47	14875.20	33.87	66.13
22	2.02	33926.58	77.24	22.76
23	30	948.87	2.16	97.84

Spill @ 300K

Trains	Time	Concentration	%Remain	%Destroyed
2	30	948.87	2.16	97.84
9	7.56	16710.22	38.05	61.95
15	2.57	31623.24	72.00	28.00
21	8.58	14667.50	33.39	66.61
22	2.14	33410.13	76.07	23.93
23	30	948.87	2.16	97.84

Spill @ 400K

Trains	Time	Concentration	%Remain	%Destroyed
2	30	948.87	2.16	97.84
9	7.67	16476.90	37.51	62.49
15	2.68	31181.69	70.99	29.01
21	8.69	14462.70	32.93	67.07
22	2.25	32943.63	75.00	25.00
23	30	948.87	2.16	97.84

Spill @ 500K

Trains	Time	Concentration	%Remain	%Destroyed
2	30	948.87	2.16	97.84
9	7.78	16246.83	36.99	63.01
15	2.79	30746.30	70.00	30.00
21	8.81	14242.54	32.43	67.57
22	2.36	32483.64	73.96	26.04
23	30	948.87	2.16	97.84

The time data that it takes for each train to reach 90% removal efficiency of TCE was supplied by MSE and used as the time data above. Thirty years was considered to be the longest allowed time of operation for a technology. If a technology exceeded 30 years, then a lower level of efficiency for TCE removal was linearly extrapolated from the MSE data and incorporated into the LDW model.

Appendix H: Deterministic Models

The deterministic models were created in Logical Decisions (LDW), which is a commercial software package that utilizes decision analysis techniques to lend insight into the desirability of alternatives [Logical Decisions, 1995; 23]. LDW is used in this analysis because it assesses alternatives using the same value focused thinking and multiattribute preference theory approach as outlined in Chapter 3.

Figures H.1 through H.5 represent the WAG 6 Hierarchy as inputted into LDW. The figures have been broken into readable pieces, but should be viewed as one continuous hierarchy. This hierarchy is the same for all spill volumes and thus the same for all the LDW models. The criteria and subcriteria are denoted by boxes and the evaluation measures are contained within the ellipses. The weights are displayed within each level of the hierarchy and the weights remain constant throughout the LDW models.

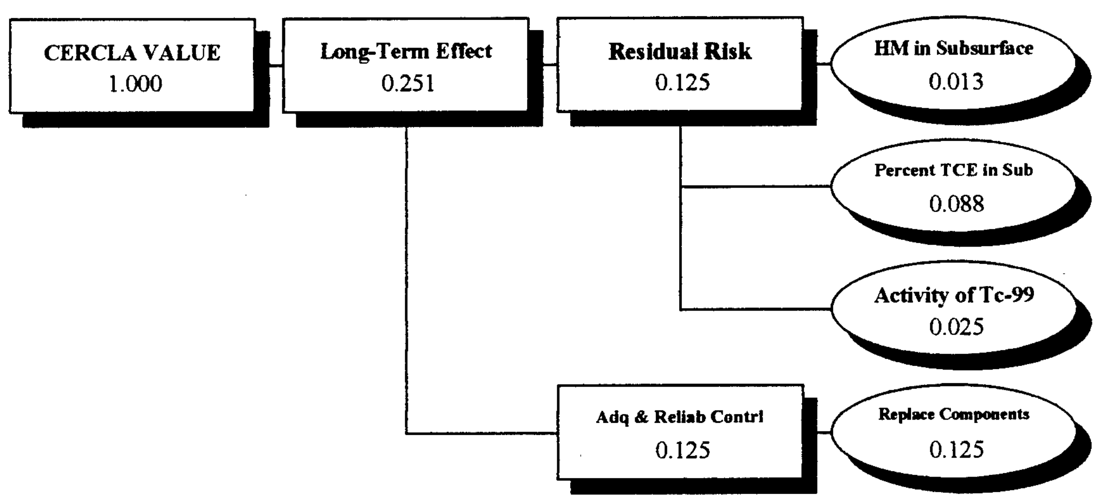


Figure H.1 Long-Term Effectiveness and Permanence Hierarchy

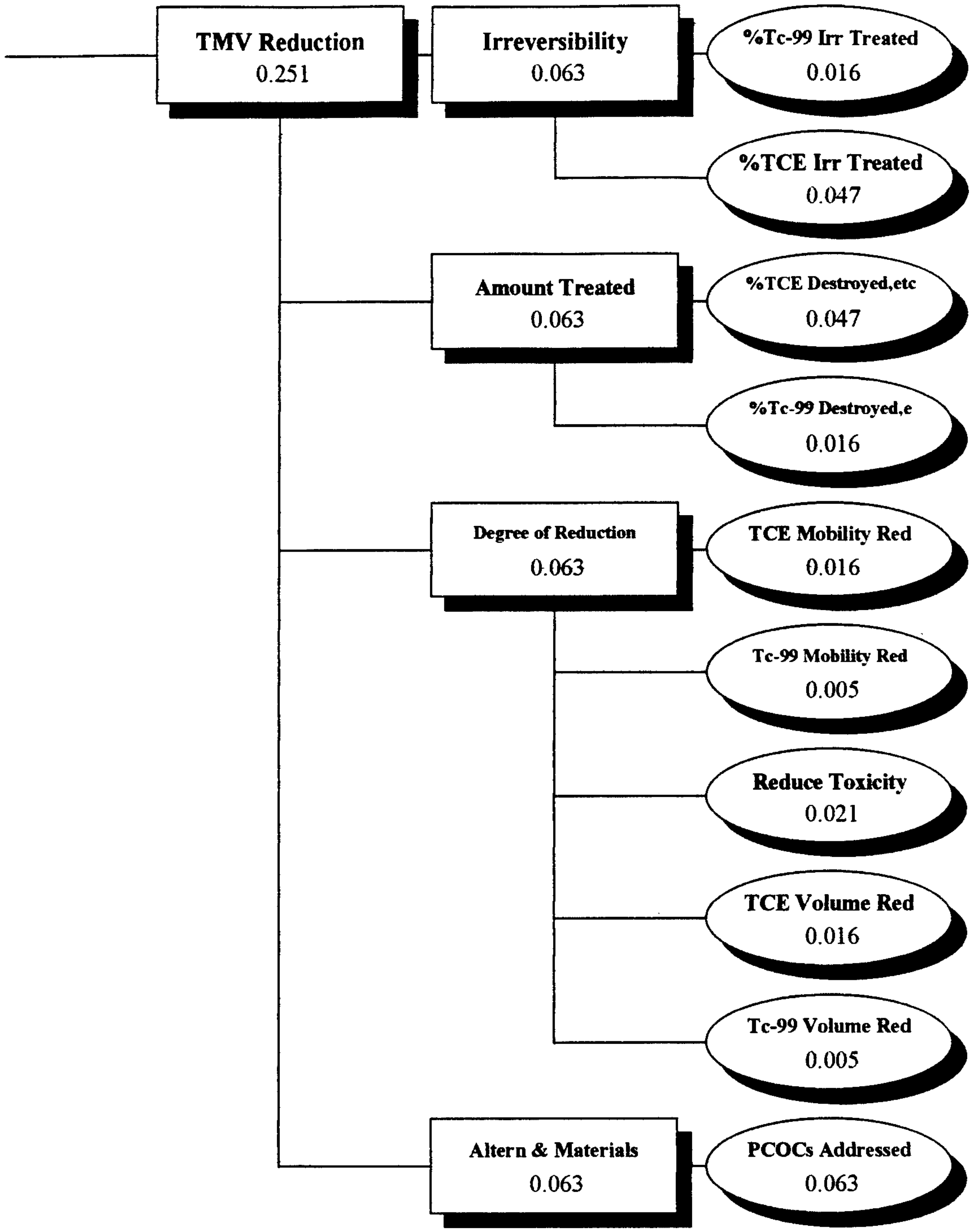


Figure H.2 Reduction of Toxicity, Mobility or Volume Hierarchy

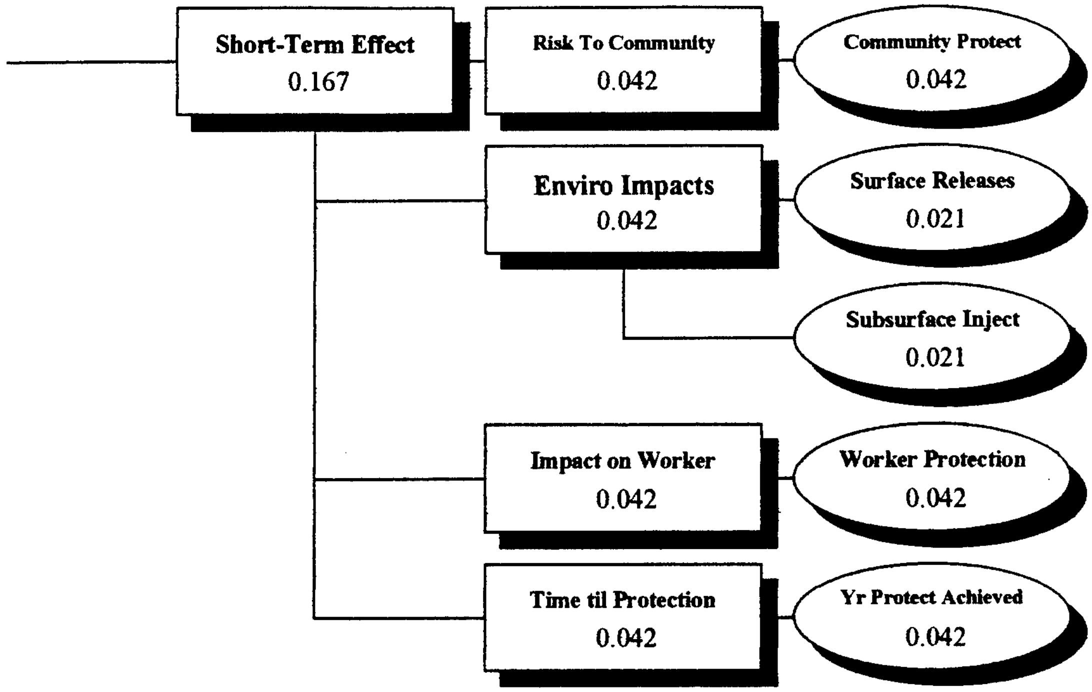


Figure H.3 Short-Term Effectiveness Hierarchy

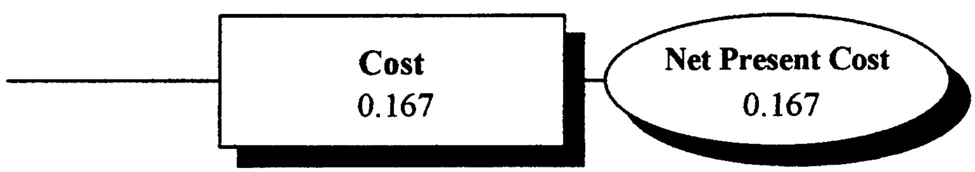


Figure H.4 Cost Hierarchy

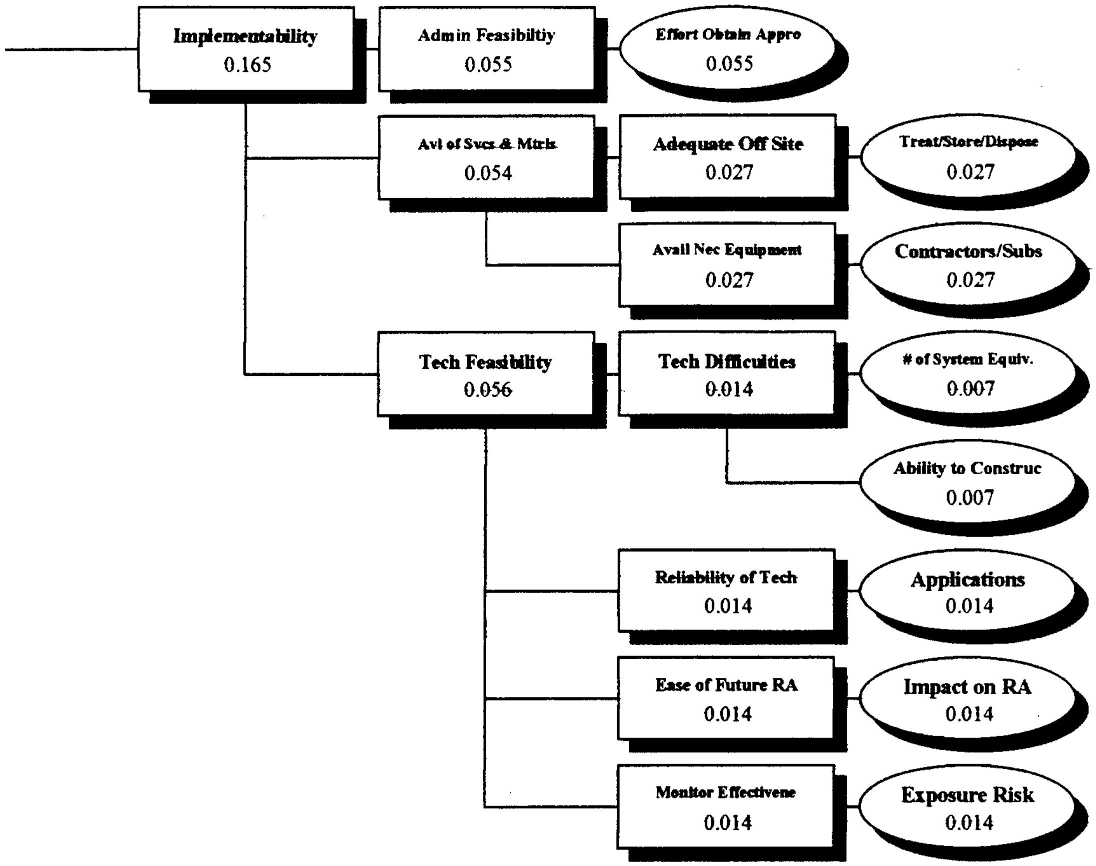


Figure H.5 Implementability Hierarchy

The evaluation measures and value functions also remain the same, regardless of spill volume. Table H.1 presents all 28 evaluation measures and value functions, lists their range, midpoint, and parameters for the single dimensional value functions. Although the names may vary slightly from Appendix B, where they were originally presented, by examining the range and parameters, it is relatively easy to discern which measure represents which criterion

Table 4.1 Evaluation Measures and Single Dimensional Value Function Parameters

Range		Midpoint		SVF Parameters		
Minimum	Maximum	Level	Utility	a	b	c
HM in Subsurface						
1	2	1.5	0.5	-10	10	0
%Tc-99 Irr Treated						
0	100	50	0.5	0	0.1	0
# of System Equiv.						
1	20	10.5	0.5	10.53	-0.5263	0
%TCE Destroyed,etc						
90	100	95	0.7	1	0.002707	-0.08109
30	90	60	0.25	-2.5	0.08333	0
%Tc-99 Destroyed,e						
91.1	100	95.55	1	10	0	0
91.1	91.1	91.1	0.975	10	0	0
0	91.1	45.55	0.475	0	0.1043	0
TCE Mobility Red						
1	2	1.5	0.95	11	-1	0
2	3	2.5	0.8	13	-2	0
Tc-99 Mobility Red						
1	2	1.5	0.75	6	1	0
2	3	2.5	0.9	4	2	0
Reduce Toxicity						
1	2	1.5	0.5	-1	4	0
2	3	2.5	0.85	1	3	0
%TCE Irr Treated						
0	100	50	0.5	0	0.1	0

Range		Midpoint		SUF Parameters		
Minimum	Maximum	Level	Utility	a	b	c
Community Protect						
1	2	1.5	0.05	-1	1	0
2	3	2.5	0.2	-3	2	0
3	4	3.5	0.55	-12	5	0
4	5	4.5	0.9	0	2	0
Worker Protection						
1	2	1.5	0.9	12	-2	0
2	3	2.5	0.7	12	-2	0
3	4	3.5	0.5	12	-2	0
4	5	4.5	0.3	12	-2	0
5	6	5.5	0.1	12	-2	0
Surface Releases						
1	2	1.5	0.025	-0.5	0.5	0
2	3	2.5	0.075	-0.5	0.5	0
3	4	3.5	0.4	-17	6	0
4	5	4.5	0.75	3	1	0
5	6	5.5	0.85	3	1	0
6	7	6.5	0.95	3	1	0
Subsurface Inject						
1	2	1.5	0.15	-3	3	0
2	3	2.5	0.35	1	1	0
3	4	3.5	0.45	1	1	0
4	5	4.5	0.65	-7	3	0
5	6	5.5	0.85	3	1	0
6	7	6.5	0.95	3	1	0
Yr Protect Achieved						
2006	2010	2008	1	10	-2.831e-14	0
2010	2032	2021	0.5	923.6	-0.4545	0
Percent TCE in Sub						
0	5	2.5	1	10	-2e-07	0
5	70	37.5	0.5	10.77	-0.1538	0

Range		Midpoint		SUF Parameters		
Minimum	Maximum	Level	Utility	a	b	c
Ability to Construc						
0	3	1.5	0.5	10	-3.333	0
Applications						
1	10	3	0.75	10.06	-12.99	0.5417
1	1	1	0.1281	2.5	0	0
0	1	0.5	0.003077	0	0.06154	0
Impact on RA						
0	10	5	0.5	10	-1	0
Exposure Risk						
0	10	5	0.5	10	-1	0
Effort Obtain Appro						
0	5	2.5	0.5	10	-2	0
Treat/Store/Dispose						
1	2	1.5	0.5	20	-10	0
Contractors/Subs						
1	2	1.5	0.75	15	-5	0
2	3	2.5	0.375	10	-2.5	0
3	4	3.5	0.125	10	-2.5	0
Net Present Cost						
1.229e+06	3.819e+07	1.971e+07	0.5	10.33	-2.706e-07	0
Activity of Tc-99						
0	900	450	1	10	0	0
900	4.392e+04	2.241e+04	0.5	10.21	-0.0002324	0
Replace Components						
1	2	1.5	0.85	13	-3	0
2	3	2.5	0.4	19	-6	0
PCOCs Addressed						
1	2	1.5	0.85	13	-3	0
2	3	2.5	0.5	15	-4	0
3	4	3.5	0.15	12	-3	0
TCE Volume Red						
0	100	50	0.75	5	0.05	0
0	0	0	0.5054	5	0	0
-100	0	-50	0.003077	0.06154	0.0006154	0
Tc-99 Volume Red						
0	100	50	0.75	5	0.05	0
0	0	0	0.25	5	0	0
-100	0	-50	0	0	0	0

SUF Parameters: if c = 0, U(x) = a + bx, if c # 0, U(x) = a + b(EXP(-cx))

What does change between LDW models are the technology or train scores for performance, cost and time. Tables H.2 and H.3 demonstrate the evaluation measures that are impacted by volume and their scores from a 50,000 gallon spill.

Table H.2 Varying Evaluation Measure Scores (Data from a 50,000 gallon Spill)

Trains	Net Present Cost	Yr Protect Achieved	%TCE Irr Treated	Percent TCE in Sub	%Tc-99 Irr Treated
Train #1	4661241	2003.33	90	10	100
Train #2	19874448	2032	26.45	70	97.84
Train #3	19986501	2032	27.73	70	100
Train #4	32113745	2032	23.95	70	100
Train #5	2697842	2007.7	90	10	100
Train #6	10430921	2007.7	90	10	100
Train #7	9255230	2007.7	90	10	100
Train #8	7395690	2007.7	90	10	100
Train #9	4030652	2009.25	90	10	60.42
Train 10	14804185	2032	23.83	70	100
Train 11	2159602	2003.7	90	10	100
Train 12	9759951	2003.12	90	10	100
Train 13	8606073	2003.12	90	10	100
Train 14	6770288	2003.7	90	10	100
Train 15	3553454	2004.26	90	10	25.09
Train 16	13209947	2032	22.6	70	100
Train 17	1228989	2009.72	90	10	100
Train 18	7913753	2009.14	90	10	100
Train 19	6930784	2009.14	90	10	100
Train 20	5156755	2009.72	90	10	100
Train 21	2416388	2010.28	90	10	65.3
Train 23	1228989	2032	0	70	97.84
Train 22	3629236	2003.83	90	10	20.86

Table H.3 Varying Evaluation Measures (Data from a 50,000 gallon Spill)

Trains	%Tc-99 Destroyed	%TCE Destroyed	Activity of Tc-99
Train #1	100	90	0
Train #2	97.84	30	948.87
Train #3	100	30	0
Train #4	100	30	0
Train #5	100	90	0
Train #6	100	90	0
Train #7	100	90	0
Train #8	100	90	0

Trains	%Tc-99 Destroyed	%TCE Destroyed	Activity of Tc-99
Train #9	60.42	90	17385.7
Train 10	100	30	0
Train 11	100	90	0
Train 12	100	90	0
Train 13	100	90	0
Train 14	100	90	0
Train 15	25.09	90	32901.54
Train 16	100	30	0
Train 17	100	90	0
Train 18	100	90	0
Train 19	100	90	0
Train 20	100	90	0
Train 21	65.3	90	15240.91
Train 23	97.84	30	948.87
Train 22	20.86	90	34760.67

It seems reasonable to assume that cost and time will be impacted by spill volume, but the calculation for Activity of Tc-99 may not be so intuitive. As explained in Appendix G, the Activity of Tc-99 is calculated off the time the remedial action is operational using a standard decay equation.

In total, only eight evaluation measures are impacted by differing spill volumes. The remaining 20 evaluation measures are constant. Tables H.4, H.5, and H.6 present the 20 evaluation measures that do not vary with volume, hence the scores presented are those used with all the LDW spill models. Note that this appendix addresses only raw scores. The actual values that are calculated from the scores, and are part of the analysis, are presented in Appendix J.

Table H.4 Constant Evaluation Measures and Scores

Trains	Treat/Store/ Dispose	Contractors /Subs	Applications	Impact on RA	Exposure Risk	Community Protect
Train #1	1 or More	2	2	2	5	3
Train #2	1 or More	3 or more	10	3	2	3
Train #3	1 or More	3 or more	10	0	2	3
Train #4	1 or More	3 or more	10	0	2	3
Train #5	1 or More	None	3	1	2	3
Train #6	1 or More	2	3	0	4	3
Train #7	1 or More	3 or more	3	0	3	3
Train #8	1 or More	None	0	6	2	3
Train #9	1 or More	3 or more	3	4	2	3
Train 10	1 or More	1	4	0	6	3
Train 11	1 or More	None	3	2	6	3
Train 12	1 or More	1	3	1	6	3
Train 13	1 or More	1	3	1	6	3
Train 14	1 or More	None	0	7	6	3
Train 15	1 or More	1	3	5	6	3
Train 16	1 or More	1	1	1	3	3
Train 17	1 or More	None	1	4	3	4
Train 18	1 or More	1	1	3	4	3
Train 19	1 or More	1	1	3	3	3
Train 20	1 or More	None	0	9	3	4
Train 21	1 or More	1	1	7	3	4
Train 23	1 or More	3 or more	10	5	0	1
Train 22	1 or More	3 or more	2	4	3	3

Table H.5 Constant Evaluation Measures and Scores

Trains	Worker Protection	Surface Releases	Sub-Surface Inject	PCOCs Addressed	Replace Components	TCE Mobility Red	Reduce Toxicity
Train #1	4 Exposures	4	4	3	No Replacement	Increase	3
Train #2	2 Exposures	5	6	2	Replace No Risk	No Change	2
Train #3	3 Exposures	4	7	3	Replace No Risk	No Change	2
Train #4	3 Exposures	4	7	3	Replace No Risk	No Change	2
Train #5	3 Exposures	4	7	3	Replace With Risk	No Change	3
Train #6	3 Exposures	4	2	3	No Replacement	Increase	2
Train #7	3 Exposures	4	3	3	No Replacement	Increase	2

Trains	Worker Protection	Surface Releases	Sub-Surface Inject	PCOCs Addressed	Replace Components	TCE Mobility Red	Reduce Toxicity
Train #8	3 Exposures	4	1	3	Replace With Risk	No Change	3
Train #9	3 Exposures	4	4	3	No Replacement	No Change	3
Train 10	4 Exposures	4	7	3	Replace No Risk	Increase	2
Train 11	4 Exposures	4	7	3	Replace With Risk	Increase	3
Train 12	4 Exposures	4	2	3	No Replacement	Increase	2
Train 13	4 Exposures	4	3	3	No Replacement	Increase	2
Train 14	4 Exposures	4	1	3	Replace With Risk	Increase	3
Train 15	4 Exposures	5	4	2	No Replacement	Increase	3
Train 16	4 Exposures	4	7	3	Replace No Risk	No Change	3
Train 17	3 Exposures	7	7	3	Replace With Risk	No Change	3
Train 18	4 Exposures	4	2	3	No Replacement	Increase	3
Train 19	4 Exposures	4	3	3	No Replacement	Increase	3
Train 20	2 Exposures	7	1	3	Replace With Risk	No Change	3
Train 21	2 Exposures	7	4	3	No Replacement	No Change	3
Train 23	1 Exposure	7	7	0	No Replacement	No Change	2
Train 22	4 Exposures	4	4	2	No Replacement	Increase	3

Table H.6 Constant Evaluation Measures and Scores

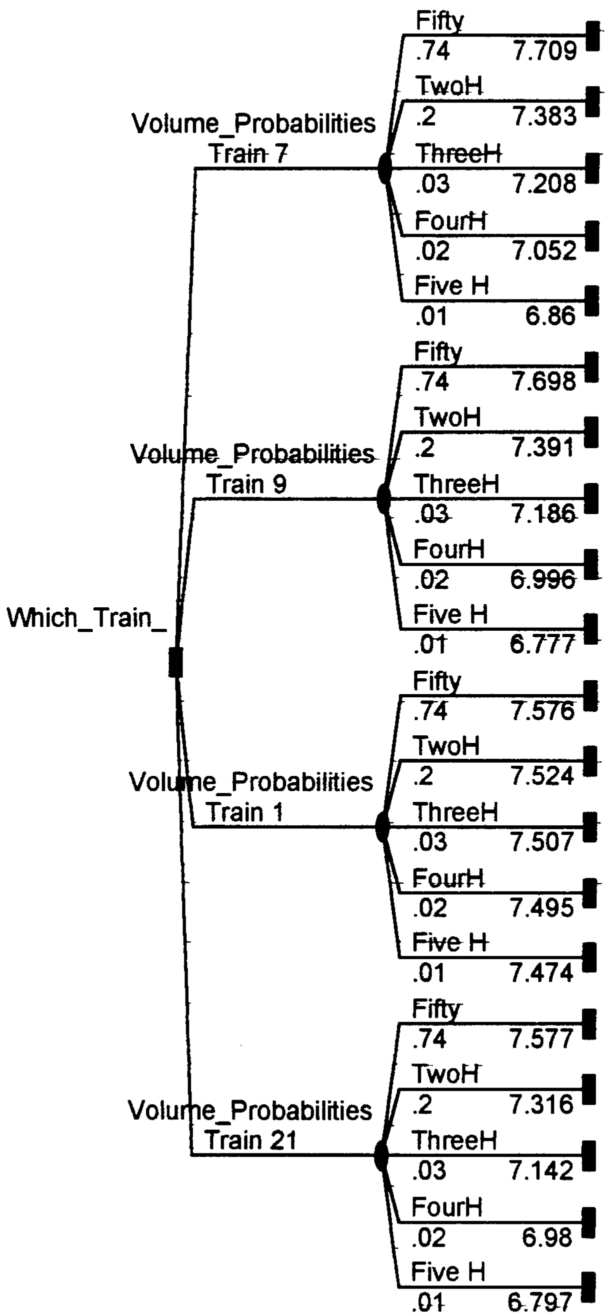
Trains	Effort Obtain Approval	HM in Sub-Surface	Tc-99 Mobility Red	Tc-99 Volume Red	TCE Volume Red	# of System Equiv.	Ability to Construct
Train #1	4	no	Increase	0	0	10	2
Train #2	1	no	No Change	0	0	3	1
Train #3	1	no	No Change	0	0	5	1
Train #4	1	no	No Change	0	0	8	1
Train #5	2	no	Decrease	0	0	10	2
Train #6	3	yes	No Change	0	0	12	2
Train #7	3	yes	Increase	0	0	12	2
Train #8	3	yes	Decrease	0	0	8	1
Train #9	3	yes	Increase	0	0	7	1
Train 10	5	no	No Change	0	0	13	2
Train 11	5	no	Decrease	0	0	14	3
Train 12	5	yes	No Change	0	0	16	3
Train 13	5	yes	Increase	0	0	16	3
Train 14	5	yes	Decrease	0	0	12	3
Train 15	5	yes	Increase	0	0	11	2
Train 16	5	no	No Change	0	0	9	2
Train 17	5	no	Decrease	0	0	10	3
Train 18	5	yes	No Change	0	0	12	3
Train 19	5	yes	Increase	0	0	12	3
Train 20	5	yes	Decrease	0	0	8	3
Train 21	5	yes	Increase	0	0	7	2
Train 23	0	yes	No Change	0	0	0	0
Train 22	5	yes	Increase	0	0	8	2

Appendix I: Probabilistic Models

As mentioned in Chapter 3, DPL software is used to model the uncertainty surrounding spill volume in the decision opportunity. The deterministic analysis revealed four top trains, which are further examined using DPL. Chapter 4 presents the risk profiles that are generated from the decision trees created in DPL (Figures I.1-I.3).

Figure I.1 displays the DPL decision tree that is used to determine how the Overall CERCLA value is impacted by uncertainty in volume. Each main branch of the tree represents one of the top four trains. The next set of branches correspond to the various spill volumes. The values assigned to each tree branch correspond to the CERCLA values derived from the deterministic analysis run at each spill volume and the probabilities associated with those spill volumes.

Similarly, Figure I.2 is the decision tree that reflects how the four trains' net present cost are impacted by spill volume. Instead of the branches containing CERCLA values, they now have the trains' net present cost (in dollars) at each spill volume with the same associated probabilities. Likewise, Figure I.3 is the decision tree that represents how the four trains' time to remediate is influenced by spill volume. The branches now hold the time to remediate (in years) for each of the spill volumes with the same associated probabilities.



Spill volumes are denoted by Fifty, TwoH, etc. which represents 50,000, 200,000, 300,000 gallons, etc.

The first number on the branch represents the spill volumes probability and the second number reflects the Overall CERCLA value (or cost or time) for that spill volume

The sum of the probabilities must sum to one on each of the branches. For example, Train 7 (and all the trains) probabilities are: .74 + .2 + .03 + .02 + .01 = 1

Figure I.1 DPL Decision Tree for Overall CERCLA Value

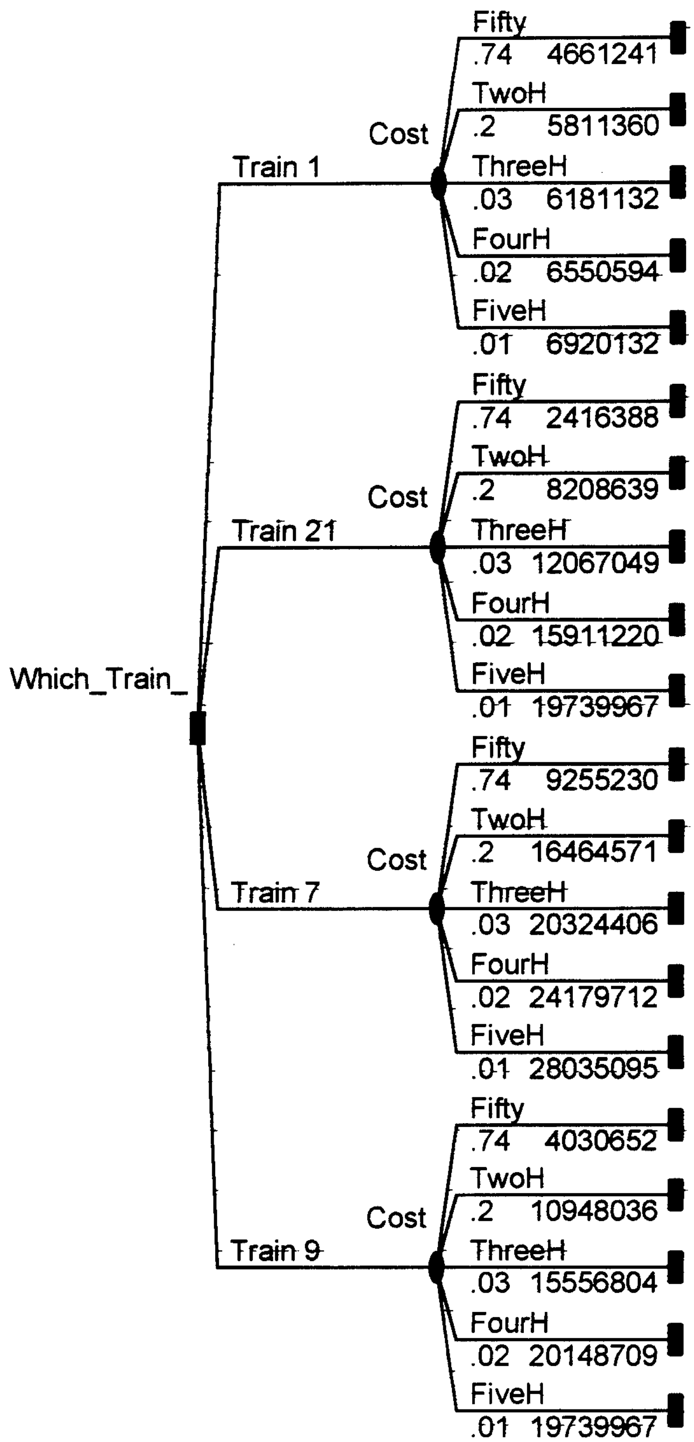


Figure I.2 DPL Decision Tree for Net Present Cost

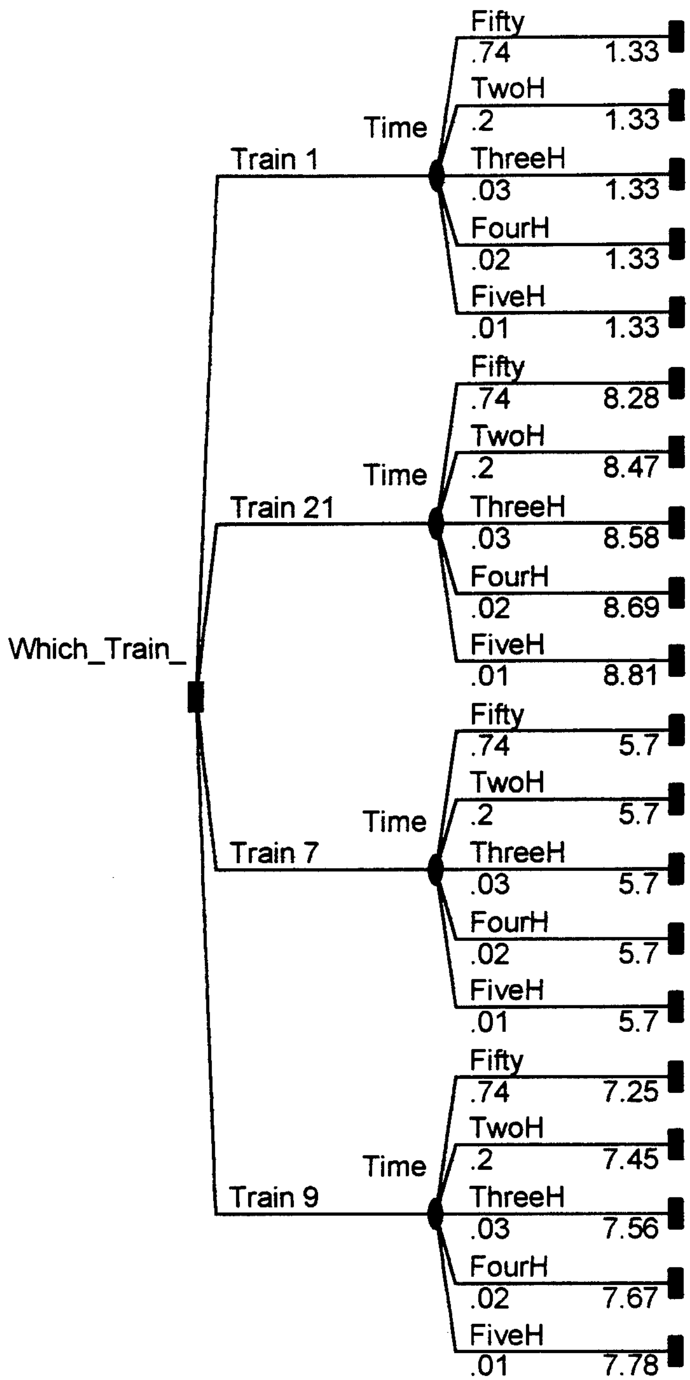


Figure I.3 DPL Decision Tree for Time to Remediate

Appendix J: Deterministic Results

The following tables demonstrate train values calculated for each of the five CERCLA balancing criteria at differing spill volumes.

Table J.1 Overall CERCLA and Balancing Criteria Values at 50,000 gallons

Train	CERCLA VALUE Goal	Long-Term Effect Goal	TMV Reduction Goal	Cost Goal	Short-Term Effect Goal	Implementability Goal
7	7.709	9.231	7.958	7.828	5.625	7.003
9	7.698	8.848	7.271	9.242	5.75	7.005
21	7.577	8.897	7.334	9.679	7.843	3.541
1	7.576	9.731	7.625	9.071	5.25	5.066
6	7.49	9.231	7.979	7.51	5.5	6.097
13	7.137	9.231	7.958	8.004	5.125	3.866
19	7.089	9.231	7.625	8.457	5.125	3.625
12	7.069	9.231	7.979	7.692	5	3.866
18	7.015	9.231	7.646	8.191	5	3.539
5	6.939	5.231	7.813	9.603	6.376	6.077
22	6.899	8.444	5.891	9.351	5.25	5.265
17	6.798	5.231	7.813	10	8.001	3.175
15	6.703	8.487	5.945	9.371	5.375	3.782
11	6.409	5.231	7.688	9.748	5.876	3.416
20	6.273	4.731	7.813	8.937	7.249	2.59
23	6.252	5.999	2.966	10	4.502	9.603
8	6.14	4.731	7.813	8.332	5.124	4.546
14	5.701	4.731	7.688	8.501	4.625	2.412
3	5.699	5	5.999	4.925	3.877	8.931
2	5.555	4.999	5.212	4.955	4.376	8.724
4	5.122	5	5.928	1.644	3.877	8.864
10	5.027	5	5.801	6.327	3.377	4.246
16	5.001	5	5.57	6.758	3.377	3.999

Table J.2 Overall CERCLA and Balancing Criteria Values at 100,000 gallons

Train	CERCLA VALUE Goal	Long-Term Effect Goal	TMV Reduction Goal	Cost Goal	Short-Term Effect Goal	Implementability Goal
9	7.596	8.852	7.277	8.618	5.75	7.005
7	7.557	9.231	7.958	6.921	5.625	7.003
1	7.541	9.731	7.625	8.86	5.25	5.066
21	7.49	8.901	7.338	9.156	7.835	3.541
6	7.313	9.231	7.979	6.45	5.5	6.097
13	6.988	9.231	7.958	7.113	5.125	3.866
19	6.963	9.231	7.625	7.698	5.125	3.625
5	6.939	5.231	7.813	9.603	6.376	6.077
12	6.895	9.231	7.979	6.652	5	3.866
18	6.867	9.231	7.646	7.305	5	3.539
22	6.83	8.451	6.025	8.73	5.25	5.265
17	6.798	5.231	7.813	10	8.001	3.175
15	6.635	8.494	6.079	8.757	5.375	3.782
11	6.409	5.231	7.688	9.748	5.876	3.416
20	6.273	4.731	7.813	8.937	7.249	2.59
23	6.252	5.999	2.966	10	4.502	9.603
8	6.14	4.731	7.813	8.332	5.124	4.546
14	5.701	4.731	7.688	8.501	4.625	2.412
3	5.475	5	5.717	4.009	3.877	8.931
2	5.38	4.999	5.073	4.112	4.376	8.724
10	5.064	5	5.575	6.885	3.377	4.246
16	5.043	5	5.361	7.322	3.377	3.999
4	4.943	5	5.701	0.916	3.877	8.864

Table J.3 Overall CERCLA and Balancing Criteria Values at 200,000 gallons

Train	CERCLA VALUE Goal	Long-Term Effect Goal	TMV Reduction Goal	Cost Goal	Short-Term Effect Goal	Implementability Goal
1	7.524	9.731	7.625	8.76	5.25	5.066
9	7.391	8.858	7.284	7.37	5.75	7.005
7	7.383	9.231	7.958	5.878	5.625	7.003
21	7.316	8.906	7.344	8.112	7.821	3.541
6	7.088	9.231	7.979	5.102	5.5	6.097
5	6.939	5.231	7.813	9.603	6.376	6.077
13	6.817	9.231	7.958	6.09	5.125	3.866
19	6.817	9.231	7.625	6.826	5.125	3.625
17	6.798	5.231	7.813	10	8.001	3.175
18	6.679	9.231	7.646	6.178	5	3.539
12	6.674	9.231	7.979	5.329	5	3.866
22	6.63	8.463	6.041	7.49	5.25	5.265
15	6.437	8.505	6.093	7.531	5.375	3.782
11	6.409	5.231	7.688	9.748	5.876	3.416
20	6.273	4.731	7.813	8.937	7.249	2.59
23	6.252	5.999	2.966	10	4.502	9.603
8	6.14	4.731	7.813	8.332	5.124	4.546
14	5.701	4.731	7.688	8.501	4.625	2.412
3	5.423	5	5.593	3.882	3.877	8.931
2	5.314	4.999	4.954	3.895	4.376	8.724
10	5.049	5	5.464	6.962	3.377	4.246
16	5.029	5	5.254	7.401	3.377	3.999
4	4.895	5	5.589	0.792	3.877	8.864

Table J.4 Overall CERCLA and Balancing Criteria Values at 300,000 gallons

Train	CERCLA VALUE Goal	Long-Term Effect Goal	TMV Reduction Goal	Cost Goal	Short-Term Effect Goal	Implementability Goal
1	7.507	9.731	7.625	8.66	5.25	5.066
7	7.208	9.231	7.958	4.834	5.625	7.003
9	7.186	8.863	7.291	6.123	5.75	7.005
21	7.142	8.911	7.351	7.068	7.809	3.541
5	6.939	5.231	7.813	9.603	6.376	6.077
6	6.853	9.231	7.979	3.698	5.5	6.097
17	6.798	5.231	7.813	10	8.001	3.175
19	6.671	9.231	7.625	5.953	5.125	3.625
13	6.646	9.231	7.958	5.065	5.125	3.866
18	6.483	9.231	7.646	5.004	5	3.539
12	6.444	9.231	7.979	3.951	5	3.866
22	6.43	8.475	6.056	6.25	5.25	5.265
11	6.409	5.231	7.688	9.748	5.876	3.416
20	6.273	4.731	7.813	8.937	7.249	2.59
23	6.252	5.999	2.966	10	4.502	9.603
15	6.239	8.517	6.108	6.306	5.375	3.782
8	6.14	4.731	7.813	8.332	5.124	4.546
14	5.701	4.731	7.688	8.501	4.625	2.412
3	5.413	5	5.554	3.882	3.877	8.931
2	5.287	4.999	4.915	3.796	4.376	8.724
10	5.039	5	5.427	6.955	3.377	4.246
16	5.019	5	5.218	7.395	3.377	3.999
4	4.884	5	5.552	0.782	3.877	8.864

Table J.5 Overall CERCLA and Balancing Criteria Values at 400,000 gallons

Train	CERCLA VALUE Goal	Long-Term Effect Goal	TMV Reduction Goal	Cost Goal	Short-Term Effect Goal	Implementability Goal
1	7.495	9.731	7.625	8.585	5.25	5.066
7	7.052	9.231	7.958	3.896	5.625	7.003
9	6.996	8.869	7.298	4.968	5.75	7.005
21	6.98	8.916	7.356	6.095	7.796	3.541
5	6.94	5.231	7.813	9.609	6.376	6.077
17	6.798	5.231	7.813	10	8.001	3.175
6	6.644	9.231	7.979	2.442	5.5	6.097
19	6.539	9.231	7.625	5.165	5.125	3.625
13	6.492	9.231	7.958	4.143	5.125	3.866
11	6.41	5.231	7.688	9.753	5.876	3.416
18	6.306	9.231	7.646	3.949	5	3.539
20	6.276	4.731	7.813	8.955	7.249	2.59
23	6.252	5.999	2.966	10	4.502	9.603
22	6.244	8.486	6.069	5.1	5.25	5.265
12	6.238	9.231	7.979	2.715	5	3.866
8	6.144	4.731	7.813	8.36	5.124	4.546
15	6.054	8.527	6.12	5.169	5.375	3.782
14	5.706	4.731	7.688	8.526	4.625	2.412
3	5.407	5	5.535	3.872	3.877	8.931
2	5.284	4.999	4.896	3.805	4.376	8.724
10	4.916	5	5.409	6.248	3.377	4.246
16	4.908	5	5.2	6.759	3.377	3.999
4	4.777	5	5.534	0.173	3.877	8.864

Table J.6 Overall CERCLA and Balancing Criteria Values at 500,000 gallons

Train	CERCLA VALUE Goal	Long-Term Effect Goal	TMV Reduction Goal	Cost Goal	Short-Term Effect Goal	Implementability Goal
1	7.474	9.731	7.625	8.46	5.25	5.066
5	6.939	5.231	7.813	9.603	6.376	6.077
7	6.86	9.231	7.958	2.747	5.625	7.003
17	6.798	5.231	7.813	10	8.001	3.175
21	6.797	8.921	7.363	4.992	7.783	3.541
9	6.777	8.874	7.305	3.644	5.75	7.005
11	6.409	5.231	7.688	9.748	5.876	3.416
6	6.388	9.231	7.979	0.913	5.5	6.097
19	6.38	9.231	7.625	4.209	5.125	3.625
13	6.304	9.231	7.958	3.017	5.125	3.866
20	6.273	4.731	7.813	8.937	7.249	2.59
23	6.252	5.999	2.966	10	4.502	9.603
8	6.14	4.731	7.813	8.332	5.124	4.546
18	6.094	9.231	7.646	2.675	5	3.539
22	6.03	8.497	6.083	3.785	5.25	5.265
12	5.987	9.231	7.979	1.217	5	3.866
15	5.843	8.537	6.133	3.869	5.375	3.782
14	5.701	4.731	7.688	8.501	4.625	2.412
3	5.386	5	5.524	3.767	3.877	8.931
2	5.247	4.999	4.885	3.599	4.376	8.724
10	4.902	5	5.398	6.181	3.377	4.246
16	4.896	5	5.19	6.701	3.377	3.999
4	4.746	5	5.523	0	3.877	8.864

The following bar graphs (Figures J.1 - J.3) present the remaining balancing criteria of Long-Term Effectiveness and Permanence, Reduction of Toxicity, Mobility or Volume, and Implementability at 100,000 gallons.

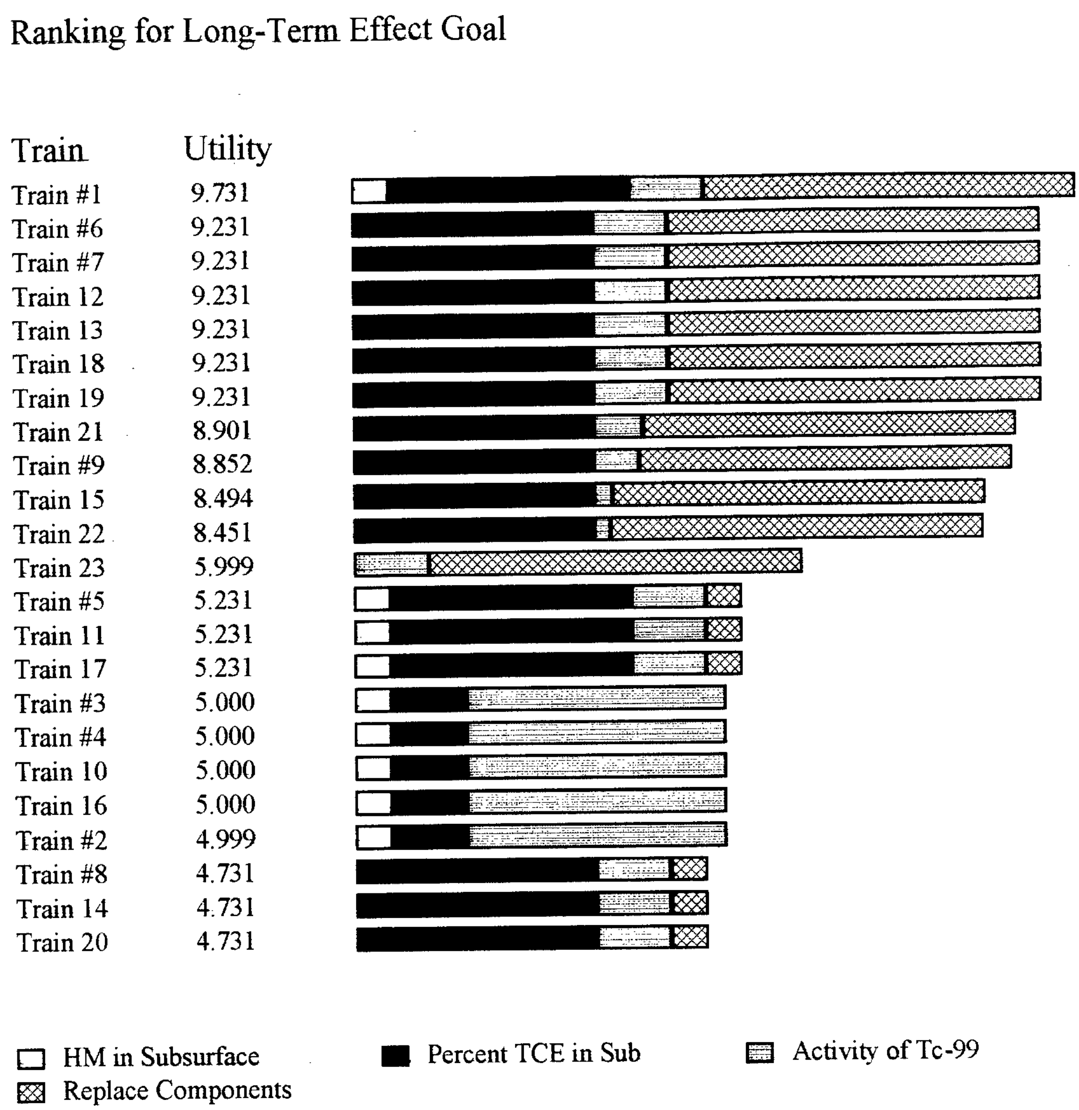


Figure J.1 Long-Term Effectiveness and Permanence Rankings at 100,000 gals.

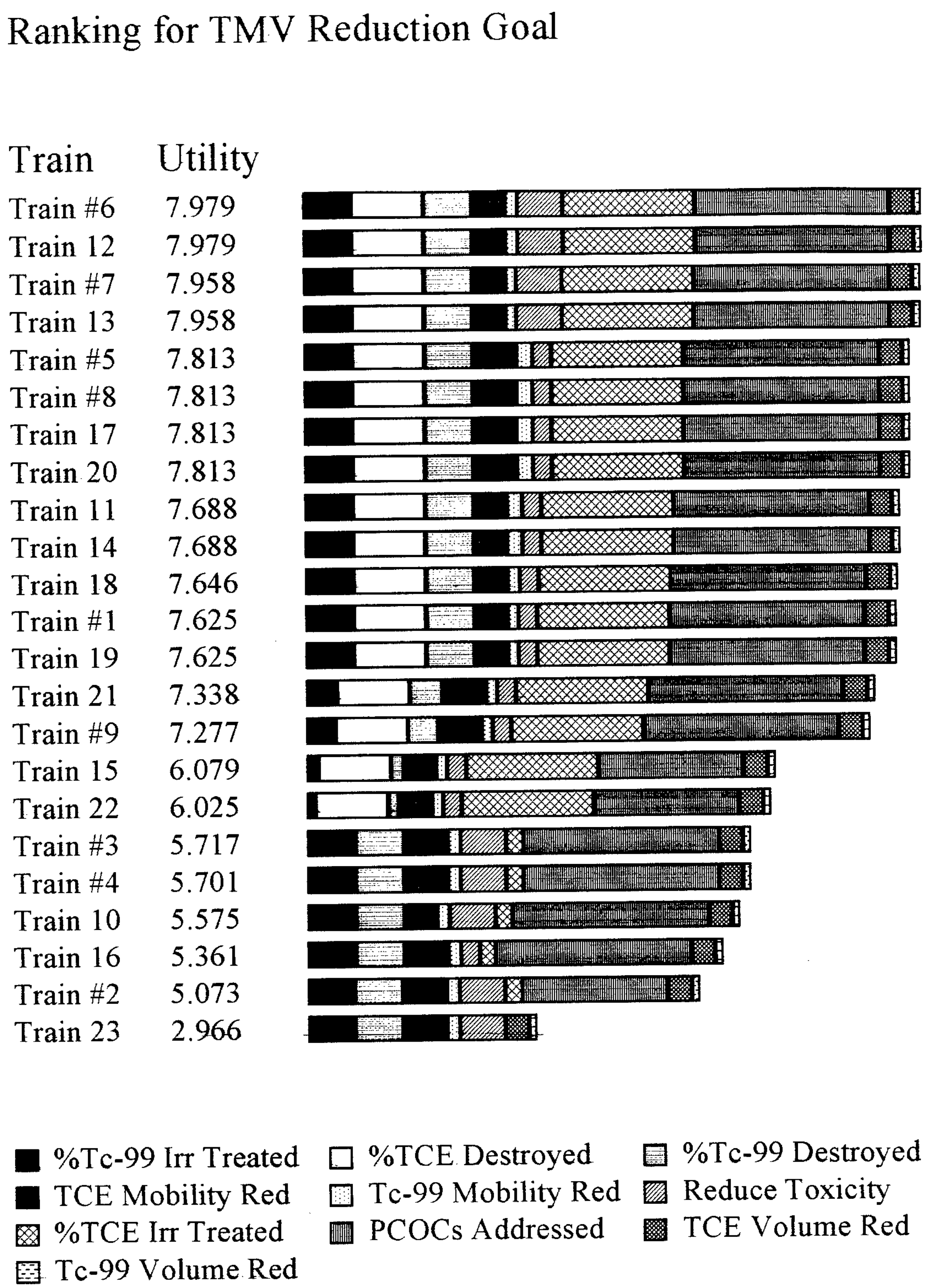


Figure J.2 Reduction of TMV Rankings at 100,000 gals.

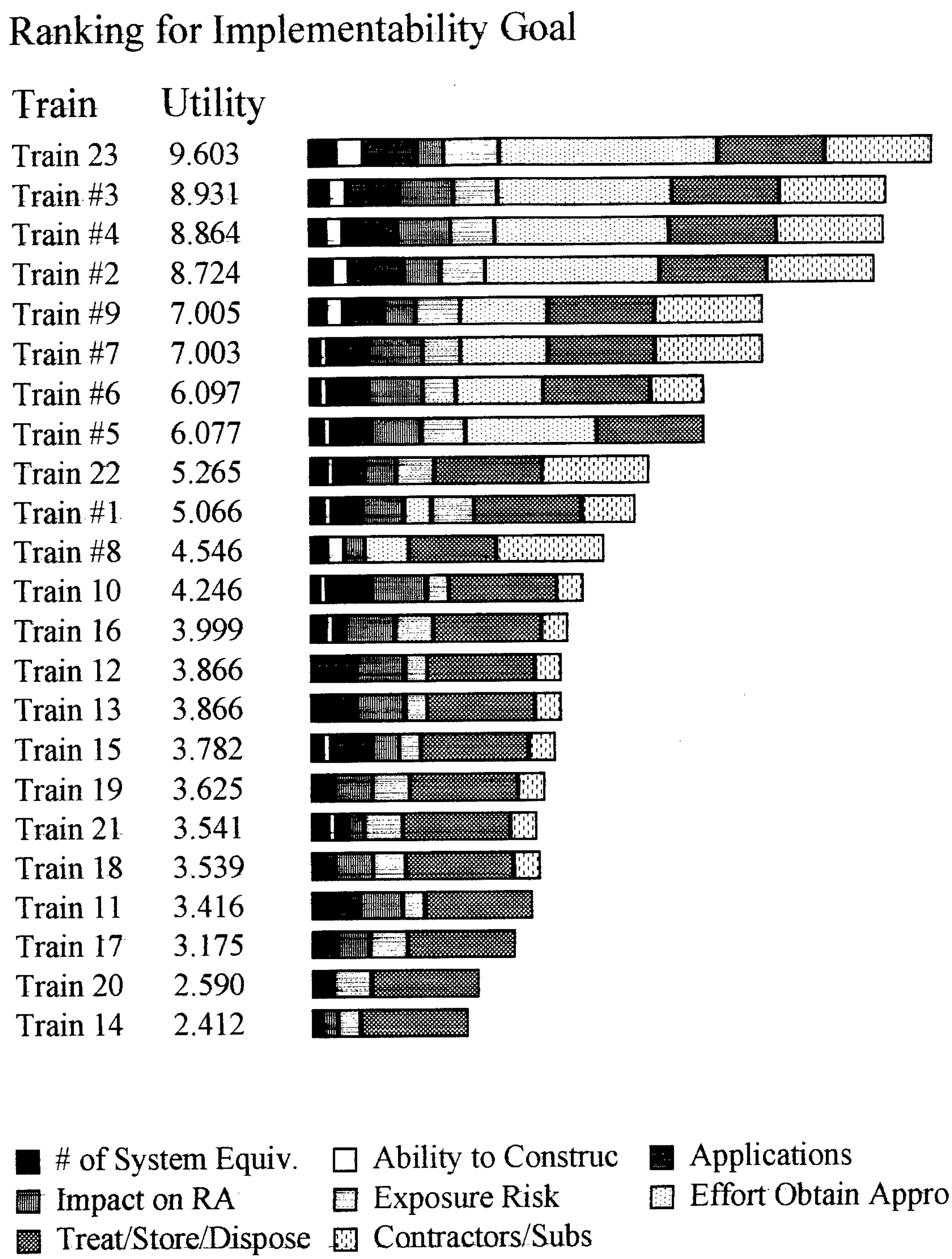


Figure J.3 Implementability Rankings at 100,000 gals.

Table J.7 provides the train rankings at each spill volume, from this table, Figure 4.8 is generated.

Table J.7 Train Rankings at all Spill Volumes

Trains	50K	100K	200K	300K	400K	500K
Train 1	4	3	1	1	1	1
Train 2	20	20	20	20	20	20
Train 3	19	19	19	19	19	19
Train 4	21	23	23	23	23	23
Train 5	10	8	6	5	5	2
Train 6	5	5	5	6	7	8
Train 7	1	2	3	2	2	3
Train 8	17	17	17	17	16	13
Train 9	2	1	2	3	3	6
Train 10	22	21	21	21	21	21
Train 11	14	14	14	13	10	7
Train 12	8	9	11	11	15	16
Train 13	6	6	7	9	9	10
Train 14	18	18	18	18	18	18
Train 15	13	13	13	16	17	17
Train 16	23	22	22	22	22	22
Train 17	12	12	9	7	6	4
Train 18	9	10	10	10	11	14
Train 19	7	7	8	8	8	9
Train 20	15	15	15	14	12	11
Train 21	3	4	4	4	4	5
Train 22	11	11	12	12	14	15
Train 23	16	16	16	15	13	12

Appendix K: Criteria Weight Sensitivity Analysis

The following figures demonstrate the sensitivity of the top train, Train 9, to changes in the criteria weights at a 100,000 gallon spill volume. These figures demonstrate how a train's total value changes as the weight assigned to a specific balancing criteria changes. For example, in Figure K.1, the criterion weight for Long-Term Effectiveness and Permanence is varied between 0 and 100%. The vertical line represents the current weight assigned to this criterion (25%). As the criterion weight increases (decreases), the other criteria weights decrease (increase) proportionally, thus changing the overall value for each train.

The trains listed to the right of the figures are listed in order of decreasing overall value based on the initial weights. Therefore, Train 9 is always the highest train in the figures, because it ranked first at these weights for the 100,000 gallon spill scenario. Whenever another train crosses Train 9, then that train becomes the top ranked train with the greatest overall value. Train 9 remains the top ranked train as long as it is the highest line on the graph.

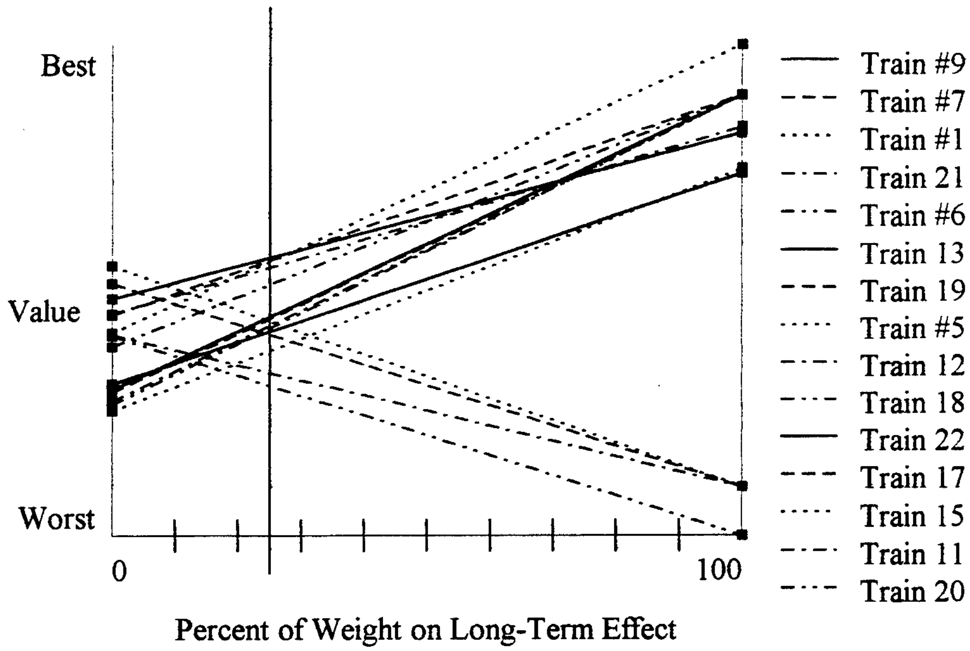


Figure K.1 Sensitivity of Long-Term Effectiveness Weight

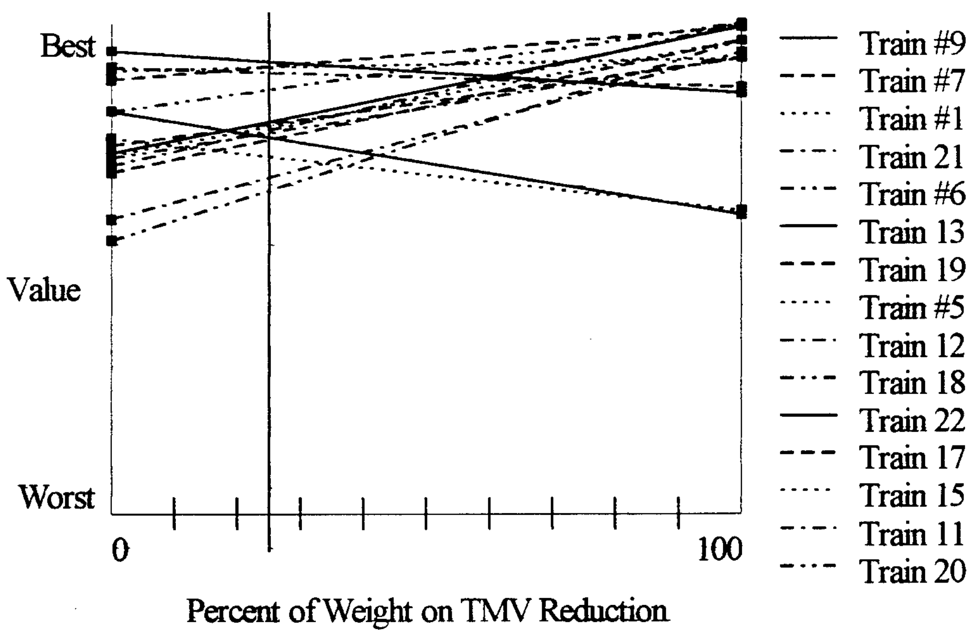


Figure K.2 Sensitivity of Reduction of TMV Weight

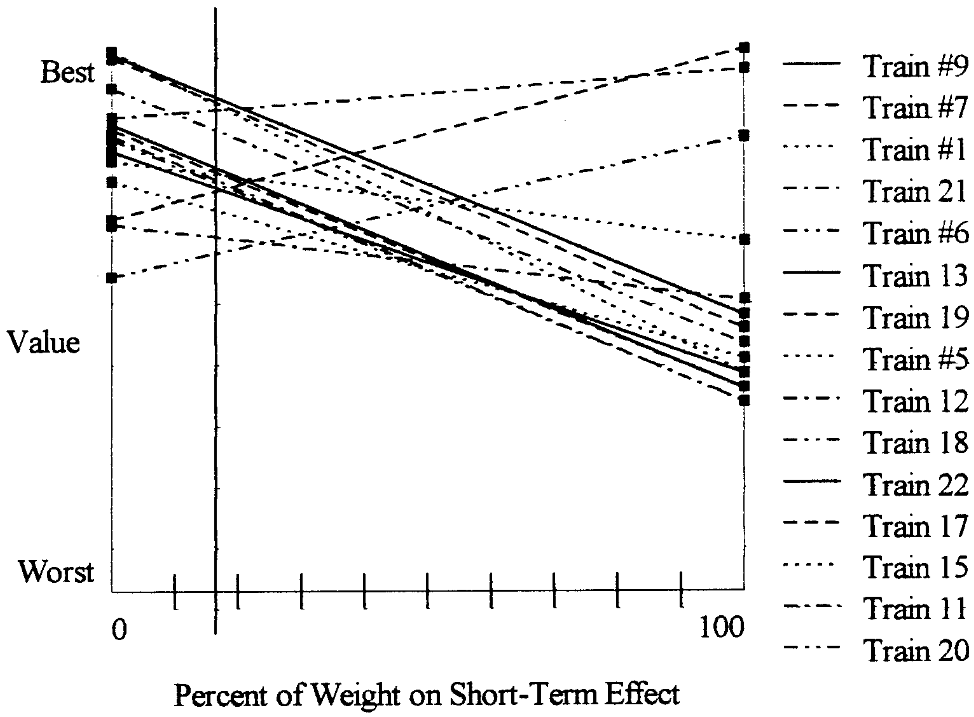


Figure K.3 Sensitivity of Short-Term Effectiveness Weight

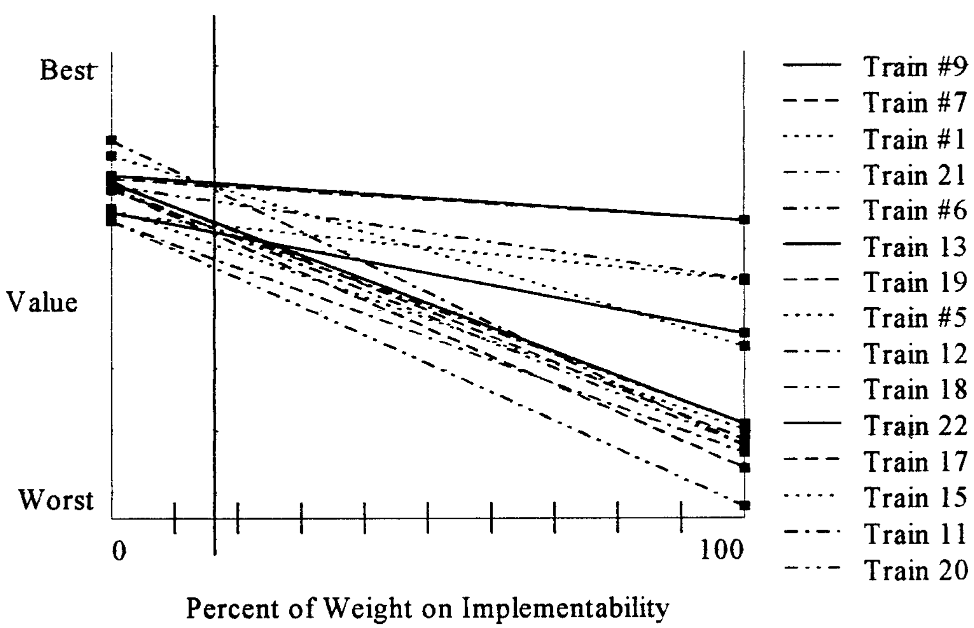


Figure K.4 Sensitivity of Implementability Weight

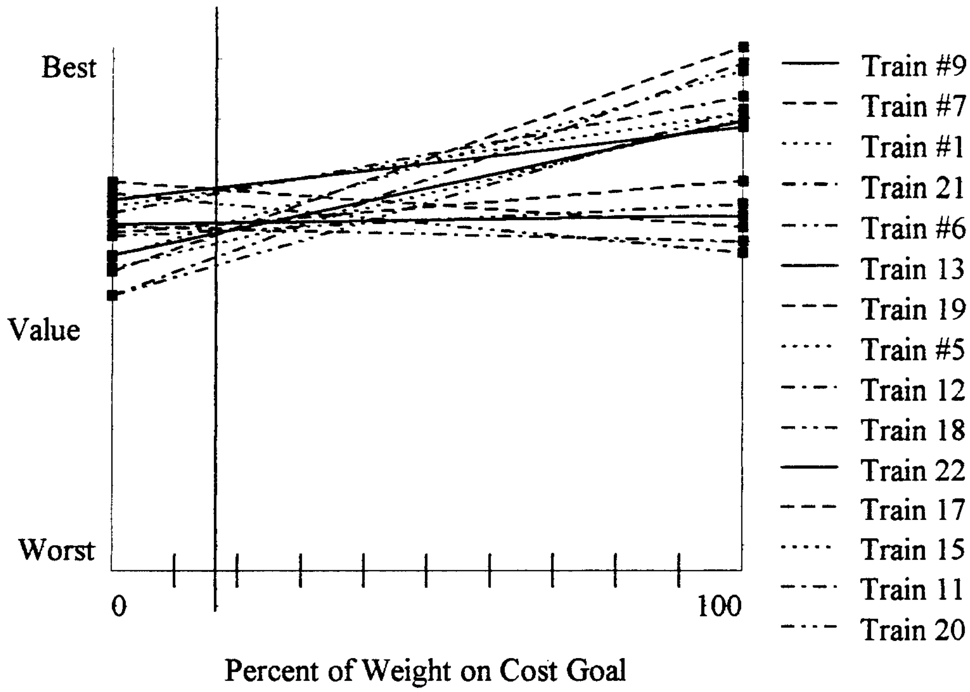


Figure K.5 Sensitivity of Cost Weight

Appendix L: Probabilistic Results

The following tables summarize the expected values obtained from the probabilistic analysis of overall CERCLA utility, net present cost and time for the top four trains.

Table L.1 Expected CERCLA Utility for Top Four Trains

TRAIN	Expected CERCLA Utility
Train 7	7.607
Train 9	7.598
Train 1	7.561
Train 21	7.492

Table L.2 Expected Net Present Cost for Top Four Trains

TRAIN	Expected Net Present Cost ($M)
Train 7	15.160
Train 9	6.239
Train 1	4.997
Train 21	4.307

Table L.3 Expected Time Until Protection Achieved

TRAIN	Expected Time Until Protection Achieved (years)
Train 7	5.70
Train 9	7.31
Train 1	1.33
Train 21	8.34

Appendix M: MSE Life Cycle Cost Data

				Source Remedi Tech Train	60%	Source Remedi	70%	Source Remedi	80%	Source Remedi	90%	Source Remedi	99%
Train #	Unsaturated	Saturated	Aquifer	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time
1	Dynamic Under	Dynamic Under	Dynamic Under	3,057,338	1.13	3,467,889	1.17	4,087,696	1.23	4,661,241	1.33	5,786,899	1.66
2	UVB	UVB	UVB	19,874,448	68.05	20,857,154	79.98	21,594,309	92.41	22,159,504	106.09	22,645,982	125.65
3	Dual Phase	Dual Phase	Dual Phase	19,986,501	64.92	20,985,933	75.87	21,737,988	86.92	22,307,641	98.23	22,731,739	109.93
4	2 Phase	2 Phase	Pump and Trea	32,113,745	75.17	33,183,492	89.33	34,034,702	104.92	34,769,120	123.98	35,656,566	161.44
5	2 Phase	2 Phase	Permeable Trea	1,924,175	2.27	2,134,755	2.98	2,377,595	3.98	2,697,842	5.70	3,407,096	11.39
6	2 Phase	2 Phase	Cosolvents	8,231,800	2.27	8,675,672	2.98	9,460,742	3.98	10,430,921	5.70	16,223,722	11.39
7	2 Phase	2 Phase	Surfactants	7,056,108	2.27	7,499,981	2.98	8,285,050	3.98	9,255,230	5.70	15,048,031	11.39
8	2 Phase	2 Phase	In Situ Redox N	6,622,023	2.27	6,832,602	2.98	7,075,442	3.98	7,395,690	5.70	8,104,943	11.39
9	2 Phase	2 Phase	Oxidation	2,704,199	3.76	3,101,846	4.48	3,529,847	5.51	4,030,652	7.25	4,876,025	13.06
10	6 Phase Heatin	6 Phase Heatin	Pump and Trea	14,804,185	75.55	14,166,154	89.78	13,651,823	105.46	13,197,941	124.68	12,929,794	162.68
11	6 Phase Heatin	6 Phase Heatin	Permeable Trea	1,634,532	1.38	1,801,486	1.45	1,973,845	1.54	2,159,602	1.70	2,836,405	2.24
12	6 Phase Heatin	6 Phase Heatin	Cosolvents	7,889,123	0.44	8,276,844	0.53	8,968,653	0.70	9,759,951	1.12	13,761,933	12.31
13	6 Phase Heatin	6 Phase Heatin	Surfactants	6,725,276	0.44	7,115,073	0.53	7,809,801	0.70	8,606,073	1.12	12,624,423	12.31
14	6 Phase Heatin	6 Phase Heatin	In Situ Redox N	6,285,050	1.38	6,443,710	1.45	6,604,405	1.54	6,770,288	1.70	7,381,685	2.24
15	6 Phase Heatin	6 Phase Heatin	Oxidation	2,459,634	1.87	2,818,644	1.95	3,181,293	2.07	3,553,454	2.26	4,378,234	2.91
16	Lasagna	Lasagna	Pump and Trea	13,209,947	79.65	12,277,182	94.56	11,476,004	110.89	10,750,185	130.70	9,868,699	168.83
17	Lasagna	Lasagna	Permeable Trea	1,129,983	5.48	1,164,572	6.23	1,197,554	6.97	1,228,989	7.72	1,256,004	8.39
18	Lasagna	Lasagna	Cosolvents	6,864,742	4.54	7,014,742	5.31	7,422,739	6.13	7,913,753	7.14	11,274,686	18.46
19	Lasagna	Lasagna	Surfactants	5,821,326	4.54	5,991,877	5.31	6,420,020	6.13	6,930,784	7.14	10,309,159	18.46
20	Lasagna	Lasagna	In Situ Redox N	5,299,285	5.48	5,251,754	6.23	5,204,236	6.97	5,156,755	7.72	5,114,075	8.39
21	Lasagna	Lasagna	Oxidation	1,869,707	5.97	2,060,114	6.73	2,242,322	7.50	2,416,388	8.28	2,564,721	9.07
22	Radio Frequenc	Radio Frequenc	Oxidation	12,507,639	75.42	12,557,710	89.59	12,589,184	105.18	12,580,210	124.25	12,373,809	161.75

100K

				Source Remedi	60%	Source Remedi	70%	Source Remedi	80%	Source Remedi	90%	Source Remedi	99%
				Tech Train									
Train #	Unsaturated	Saturated	Aquifer	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time
1	Dynamic Under	Dynamic Under	Dynamic Under	3,241,953	1.13	3,652,360	1.17	4,271,953	1.23	5,442,374	1.33	9,476,923	1.66
2	UVB	UVB	UVB	22,991,216	145.04	23,213,743	169.79	23,328,194	195.06	23,383,963	221.56	23,394,589	252.68
3	Dual Phase	Dual Phase	Dual Phase	23,370,432	141.91	23,607,955	165.68	23,733,936	189.56	23,800,107	213.70	23,829,242	236.95
4	2 Phase	2 Phase	Pump and Trea	34,803,534	152.16	35,180,888	179.15	35,486,348	207.56	35,795,977	239.46	36,330,993	288.47
5	2 Phase	2 Phase	Permeable Tre	1,924,175	2.27	2,134,755	2.98	2,377,595	3.98	2,697,842	5.70	3,407,096	11.39
6	2 Phase	2 Phase	Cosolvents	10,720,171	2.27	11,163,980	2.98	11,948,902	3.98	14,348,475	5.70	20,577,220	11.39
7	2 Phase	2 Phase	Surfactants	8,981,468	2.27	9,425,277	2.98	10,210,199	3.98	12,609,772	5.70	18,838,517	11.39
8	2 Phase	2 Phase	In Situ Redox N	6,622,023	2.27	6,832,602	2.98	7,075,442	3.98	7,395,690	5.70	8,104,943	11.39
9	2 Phase	2 Phase	Oxidation	4,308,967	3.83	4,941,069	4.55	5,603,231	5.58	6,337,529	7.33	7,389,530	13.14
10	6 Phase Heatin	6 Phase Heatin	Pump and Trea	12,740,825	152.54	12,672,222	179.60	12,686,121	208.11	12,717,964	240.16	13,023,924	289.70
11	6 Phase Heatin	6 Phase Heatin	Permeable Tre	1,634,532	1.38	1,801,486	1.45	1,973,845	1.54	2,159,602	1.70	2,836,405	2.24
12	6 Phase Heatin	6 Phase Heatin	Cosolvents	10,352,424	0.44	10,735,689	0.53	11,421,175	0.70	13,604,821	1.12	17,974,047	12.31
13	6 Phase Heatin	6 Phase Heatin	Surfactants	8,631,238	0.44	9,017,573	0.53	9,707,376	0.70	11,898,377	1.12	16,291,809	12.31
14	6 Phase Heatin	6 Phase Heatin	In Situ Redox N	6,285,050	1.38	6,443,710	1.45	6,604,405	1.54	6,770,288	1.70	7,381,685	2.24
15	6 Phase Heatin	6 Phase Heatin	Oxidation	4,050,713	1.94	4,638,942	2.02	5,228,259	2.14	5,821,365	2.33	6,815,123	2.98
16	Lasagna	Lasagna	Pump and Trea	11,126,640	156.64	10,758,044	184.38	10,478,492	213.54	10,229,099	246.18	9,904,809	295.86
17	Lasagna	Lasagna	Permeable Tre	1,129,983	5.48	1,164,572	6.23	1,197,554	6.97	1,228,989	7.72	1,256,004	8.39
18	Lasagna	Lasagna	Cosolvents	9,073,152	4.54	9,179,599	5.31	9,544,831	6.13	11,189,132	7.14	14,849,963	18.46
19	Lasagna	Lasagna	Surfactants	7,530,066	4.54	7,666,907	5.31	8,061,932	6.13	9,735,441	7.14	13,422,066	18.46
20	Lasagna	Lasagna	In Situ Redox N	5,299,285	5.48	5,251,754	6.23	5,204,236	6.97	5,158,755	7.72	5,114,075	8.39
21	Lasagna	Lasagna	Oxidation	3,296,148	6.04	3,662,771	6.80	4,013,499	7.57	4,348,383	8.35	4,633,172	9.14
22	Radio Frequenc	Radio Frequenc	Oxidation	12,701,093	152.40	12,769,630	179.40	12,827,064	207.82	12,860,959	239.73	12,767,123	288.78

200K

	Actual	199,941												
	Total Gallons of	200,000												
				Source Remedi Tech Train	60%	Source Remedi	70%	Source Remedi	80%	Source Remedi	90%	Source Remedi	99%	
Train #	Unsaturated	Saturated	Aquifer	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time	NPV Total	NPV Time	
1	Dynamic Under	Dynamic Under	Dynamic Under	3,611,906	1.13	4,022,124	1.17	4,641,441	1.23	5,811,360	1.33	10,698,385	1.66	
2	UVB	UVB	UVB	23,794,151	299.19	23,798,792	349.64	23,798,646	400.60	23,795,971	452.80	23,784,594	507.03	
3	Dual Phase	Dual Phase	Dual Phase	23,840,843	296.06	23,846,714	345.53	23,847,995	395.10	23,847,769	444.94	23,845,351	491.31	
4	2 Phase	2 Phase	Pump and Trea	35,261,394	306.31	35,465,103	359.00	35,691,958	413.11	35,981,034	470.69	36,576,938	542.82	
5	2 Phase	2 Phase	Permeable Tre	1,924,175	2.27	2,134,755	2.98	2,377,595	3.98	2,697,842	5.70	3,407,096	11.39	
6	2 Phase	2 Phase	Cosolvents	15,703,086	2.27	16,146,836	2.98	18,931,620	3.98	19,330,684	5.70	29,294,783	11.39	
7	2 Phase	2 Phase	Surfactants	12,836,993	2.27	13,280,743	2.98	14,065,527	3.98	16,464,571	5.70	26,428,690	11.39	
8	2 Phase	2 Phase	In Situ Redox M	6,622,023	2.27	6,832,602	2.98	7,075,442	3.98	7,395,690	5.70	8,104,943	11.39	
9	2 Phase	2 Phase	Oxidation	7,516,302	3.95	8,616,937	4.67	9,747,064	5.70	10,948,036	7.45	12,413,255	13.26	
10	6 Phase Heatin	6 Phase Heatin	Pump and Trea	12,459,295	306.69	12,590,822	359.45	12,717,997	413.65	12,826,489	471.40	13,242,175	544.06	
11	6 Phase Heatin	6 Phase Heatin	Permeable Tre	1,634,532	1.38	1,801,486	1.45	1,973,845	1.54	2,159,602	1.70	2,836,405	2.24	
12	6 Phase Heatin	6 Phase Heatin	Cosolvents	15,285,138	0.44	15,659,547	0.53	16,332,525	0.70	18,494,574	1.12	26,408,499	12.31	
13	6 Phase Heatin	6 Phase Heatin	Surfactants	12,447,920	0.44	12,827,389	0.53	13,507,483	0.70	15,681,656	1.12	23,635,484	12.31	
14	6 Phase Heatin	6 Phase Heatin	In Situ Redox M	6,285,050	1.38	6,443,710	1.45	6,604,405	1.54	6,770,288	1.70	7,381,685	2.24	
15	6 Phase Heatin	6 Phase Heatin	Oxidation	7,229,920	2.06	8,276,103	2.14	9,318,275	2.26	10,352,804	2.45	11,684,159	3.11	
16	Lasagna	Lasagna	Pump and Trea	10,835,307	310.79	10,664,083	364.23	10,494,190	419.08	10,315,940	477.41	10,088,508	550.22	
17	Lasagna	Lasagna	Permeable Tre	1,129,983	5.48	1,164,572	6.23	1,197,554	6.97	1,228,989	7.72	1,256,004	8.39	
18	Lasagna	Lasagna	Cosolvents	13,495,449	4.54	13,514,743	5.31	13,794,471	6.13	15,354,629	7.14	22,009,194	18.46	
19	Lasagna	Lasagna	Surfactants	10,951,814	4.54	11,021,208	5.31	11,350,049	6.13	12,958,352	7.14	19,655,437	18.46	
20	Lasagna	Lasagna	In Situ Redox M	5,299,285	5.48	5,251,754	6.23	5,204,236	6.97	5,156,755	7.72	5,114,075	8.39	
21	Lasagna	Lasagna	Oxidation	6,146,384	6.16	6,865,060	6.92	7,552,465	7.69	8,208,639	8.47	8,766,049	9.28	
22	Radio Frequenc	Radio Frequenc	Oxidation	12,796,159	306.56	12,875,226	359.25	12,948,040	413.37	13,009,038	470.97	13,001,355	543.14	

300K

Train #	Unsaturated	Saturated	Aquifer	Source Remedi Tech Train NPV Total	60% NPV Time	Source Remedi NPV Total	70% NPV Time	Source Remedi NPV Total	80% NPV Time	Source Remedi NPV Total	90% NPV Time	Source Remedi NPV Total	99% NPV Time
1	Dynamic Under	Dynamic Under	Dynamic Under	3,982,423	1.13	4,392,493	1.17	5,011,595	1.23	6,181,132	1.33	11,066,736	1.66
2	UVB	UVB	UVB	24,160,900	453.54	24,160,297	529.71	24,159,233	606.39	24,157,224	684.32	24,149,638	761.70
3	Dual Phase	Dual Phase	Dual Phase	23,840,037	450.41	23,840,003	525.60	23,839,789	600.90	23,839,360	676.45	23,837,715	745.98
4	2 Phase	2 Phase	Pump and Trea	35,299,001	460.66	35,501,952	539.07	35,733,214	618.90	36,032,036	702.21	36,662,492	797.49
5	2 Phase	2 Phase	Permeable Tre	1,924,175	2.27	2,134,755	2.98	2,377,595	3.98	2,697,842	5.70	3,407,096	11.39
6	2 Phase	2 Phase	Cosolvents	20,893,245	2.27	21,336,961	2.98	22,121,666	3.98	24,520,409	5.70	38,224,065	11.39
7	2 Phase	2 Phase	Surfactants	16,697,242	2.27	17,140,958	2.98	17,925,664	3.98	20,324,406	5.70	34,028,063	11.39
8	2 Phase	2 Phase	In Situ Redox N	6,622,023	2.27	6,832,602	2.98	7,075,442	3.98	7,395,690	5.70	8,104,943	11.39
9	2 Phase	2 Phase	Oxidation	10,724,056	4.06	12,292,493	4.79	13,889,861	5.81	15,556,804	7.56	17,434,714	13.37
10	6 Phase Heatin	6 Phase Heatin	Pump and Trea	12,484,327	461.04	12,624,216	539.51	12,757,945	619.44	12,876,390	702.91	13,324,929	798.73
11	6 Phase Heatin	6 Phase Heatin	Permeable Tre	1,634,532	1.38	1,801,486	1.45	1,973,845	1.54	2,159,602	1.70	2,836,405	2.24
12	6 Phase Heatin	6 Phase Heatin	Cosolvents	20,423,008	0.44	20,788,220	0.53	21,448,233	0.70	23,588,031	1.12	35,047,794	12.31
13	6 Phase Heatin	6 Phase Heatin	Surfactants	16,269,279	0.44	16,641,899	0.53	17,312,331	0.70	19,469,879	1.12	30,988,061	12.31
14	6 Phase Heatin	6 Phase Heatin	In Situ Redox N	6,285,050	1.38	6,443,710	1.45	6,604,405	1.54	6,770,288	1.70	7,381,685	2.24
15	6 Phase Heatin	6 Phase Heatin	Oxidation	10,409,243	2.17	11,912,613	2.26	13,406,877	2.37	14,882,077	2.57	16,550,402	3.22
16	Lasagna	Lasagna	Pump and Trea	10,857,098	465.14	10,693,298	544.29	10,528,706	624.87	10,358,439	708.93	10,158,748	804.88
17	Lasagna	Lasagna	Permeable Tre	1,129,983	5.48	1,164,572	6.23	1,197,554	6.97	1,228,989	7.72	1,256,004	8.39
18	Lasagna	Lasagna	Cosolvents	18,101,673	4.54	18,030,213	5.31	18,220,937	6.13	19,693,659	7.14	29,342,297	18.46
19	Lasagna	Lasagna	Surfactants	14,377,754	4.54	14,379,641	5.31	14,642,268	6.13	16,185,475	7.14	25,896,363	18.46
20	Lasagna	Lasagna	In Situ Redox N	5,299,285	5.48	5,251,754	6.23	5,204,236	6.97	5,156,755	7.72	5,114,075	8.39
21	Lasagna	Lasagna	Oxidation	8,996,724	6.27	10,066,775	7.03	11,090,207	7.80	12,067,049	8.58	12,896,555	9.37
22	Radio Frequenc	Radio Frequenc	Oxidation	12,827,598	460.91	12,910,361	539.32	12,988,662	619.16	13,059,595	702.48	13,086,184	797.81

400K

Train #	Unsaturated	Saturated	Aquifer	Source Remedi Tech Train NPV Total	60% NPV Time	Source Remedi NPV Total	70% NPV Time	Source Remedi NPV Total	80% NPV Time	Source Remedi NPV Total	90% NPV Time	Source Remedi NPV Total	99% NPV Time
1	Dynamic Under	Dynamic Under	Dynamic Under	4,352,537	1.13	4,762,477	1.17	5,381,391	1.23	6,550,594	1.33	11,434,986	1.66
2	UVB	UVB	UVB	24,523,494	607.69	24,522,965	709.56	24,522,164	811.93	24,520,667	915.55	24,515,000	1,016.06
3	Dual Phase	Dual Phase	Dual Phase	24,269,933	604.57	24,269,822	705.45	24,269,652	806.44	24,269,333	907.69	24,268,114	1,000.34
4	2 Phase	2 Phase	Pump and Trea	38,179,798	614.81	38,384,558	718.92	38,618,637	824.44	38,922,636	933.45	39,571,536	1,051.85
5	2 Phase	2 Phase	Permeable Tre	1,924,175	2.27	2,134,755	2.98	2,377,595	3.98	2,697,842	5.70	3,407,096	11.39
6	2 Phase	2 Phase	Cosolvents	26,021,437	2.27	26,465,129	2.98	27,249,780	3.98	29,648,311	5.70	47,086,834	11.39
7	2 Phase	2 Phase	Surfactants	20,552,838	2.27	20,996,531	2.98	21,781,181	3.98	24,179,712	5.70	41,618,235	11.39
8	2 Phase	2 Phase	In Situ Redox M	6,622,023	2.27	6,832,602	2.98	7,075,442	3.98	7,395,690	5.70	8,104,943	11.39
9	2 Phase	2 Phase	Oxidation	13,920,550	4.17	15,954,915	4.90	18,017,653	5.92	20,148,709	7.67	22,437,695	13.48
10	6 Phase Heatin	6 Phase Heatin	Pump and Trea	15,335,901	615.19	15,472,666	719.36	15,602,038	824.98	15,713,359	934.15	16,139,498	1,053.09
11	6 Phase Heatin	6 Phase Heatin	Permeable Tre	1,634,532	1.38	1,801,486	1.45	1,973,845	1.54	2,159,602	1.70	2,836,405	2.24
12	6 Phase Heatin	6 Phase Heatin	Cosolvents	25,499,535	0.44	25,855,670	0.53	26,502,896	0.70	28,620,794	1.12	43,622,737	12.31
13	6 Phase Heatin	6 Phase Heatin	Surfactants	20,086,031	0.44	20,451,821	0.53	21,112,625	0.70	23,253,656	1.12	38,331,736	12.31
14	6 Phase Heatin	6 Phase Heatin	In Situ Redox M	6,285,050	1.38	6,443,710	1.45	6,604,405	1.54	6,770,288	1.70	7,381,685	2.24
15	6 Phase Heatin	6 Phase Heatin	Oxidation	13,577,315	2.28	15,536,021	2.36	17,480,549	2.48	19,394,635	2.68	21,398,552	3.33
16	Lasagna	Lasagna	Pump and Trea	13,413,592	619.29	13,201,175	724.14	12,989,612	830.41	12,775,204	940.17	12,547,777	1,059.24
17	Lasagna	Lasagna	Permeable Tre	1,129,983	5.48	1,164,572	6.23	1,197,554	6.97	1,228,989	7.72	1,256,004	8.39
18	Lasagna	Lasagna	Cosolvents	22,652,902	4.54	22,491,780	5.31	22,594,582	6.13	23,980,983	7.14	36,620,778	18.46
19	Lasagna	Lasagna	Surfactants	17,799,565	4.54	17,734,035	5.31	17,930,546	6.13	19,408,810	7.14	32,129,733	18.46
20	Lasagna	Lasagna	In Situ Redox M	5,299,285	5.48	5,251,754	6.23	5,204,236	6.97	5,156,755	7.72	5,114,075	8.39
21	Lasagna	Lasagna	Oxidation	11,836,977	6.38	13,256,956	7.14	14,615,030	7.91	15,911,220	8.69	17,011,704	9.48
22	Radio Frequenc	Radio Frequenc	Oxidation	15,689,361	615.06	15,773,605	719.17	15,854,149	824.70	15,929,253	933.72	15,970,911	1,052.16

500K

Train #	Unsaturated	Saturated	Aquifer	Source Remedi Tech Train NPV Total	60% NPV Time	Source Remedi NPV Total	70% NPV Time	Source Remedi NPV Total	80% NPV Time	Source Remedi NPV Total	90% NPV Time	Source Remedi NPV Total	99% NPV Time
1	Dynamic Under	Dynamic Under	Dynamic Under	4,722,678	1.13	5,132,496	1.17	5,751,235	1.23	6,920,132	1.33	11,803,424	1.66
2	UVB	UVB	UVB	24,887,275	761.85	24,886,853	889.41	24,886,215	1,017.48	24,885,023	1,146.79	24,880,501	1,270.42
3	Dual Phase	Dual Phase	Dual Phase	24,267,319	758.72	24,267,230	885.30	24,267,095	1,011.98	24,266,842	1,138.93	24,265,874	1,254.70
4	2 Phase	2 Phase	Pump and Trea	38,189,234	768.97	38,395,140	898.77	38,630,938	1,029.98	38,938,100	1,164.68	39,598,456	1,306.21
5	2 Phase	2 Phase	Permeable Trea	1,924,175	2.27	2,134,755	2.98	2,377,595	3.98	2,697,842	5.70	3,407,096	11.39
6	2 Phase	2 Phase	Cosolvents	31,188,570	2.27	31,632,244	2.98	32,416,852	3.98	34,815,220	5.70	55,988,533	11.39
7	2 Phase	2 Phase	Surfactants	24,408,445	2.27	24,852,119	2.98	25,636,727	3.98	28,035,095	5.70	49,208,408	11.39
8	2 Phase	2 Phase	In Situ Redox N	6,622,023	2.27	6,832,602	2.98	7,075,442	3.98	7,395,690	5.70	8,104,943	11.39
9	2 Phase	2 Phase	Oxidation	17,102,958	4.28	19,601,706	5.01	22,128,270	6.03	24,721,886	7.78	27,420,522	13.59
10	6 Phase Heatin	6 Phase Heatin	Pump and Trea	15,345,238	769.35	15,483,122	899.21	15,614,162	1,030.53	15,728,536	1,165.38	16,165,544	1,307.45
11	6 Phase Heatin	6 Phase Heatin	Permeable Trea	1,634,532	1.38	1,801,486	1.45	1,973,845	1.54	2,159,602	1.70	2,836,405	2.24
12	6 Phase Heatin	6 Phase Heatin	Cosolvents	30,614,610	0.44	30,961,605	0.53	31,595,960	0.70	33,691,840	1.12	52,235,345	12.31
13	6 Phase Heatin	6 Phase Heatin	Surfactants	23,902,793	0.44	24,261,758	0.53	24,912,947	0.70	27,037,509	1.12	45,675,411	12.31
14	6 Phase Heatin	6 Phase Heatin	In Situ Redox N	6,285,050	1.38	6,443,710	1.45	6,604,405	1.54	6,770,288	1.70	7,381,685	2.24
15	6 Phase Heatin	6 Phase Heatin	Oxidation	16,731,620	2.40	19,144,189	2.48	21,537,526	2.59	23,889,086	2.79	26,227,562	3.44
16	Lasagna	Lasagna	Pump and Trea	13,421,963	773.45	13,210,381	903.99	13,000,103	1,035.96	12,788,134	1,171.40	12,569,885	1,313.60
17	Lasagna	Lasagna	Permeable Trea	1,129,983	5.48	1,164,572	6.23	1,197,554	6.97	1,228,989	7.72	1,256,004	8.39
18	Lasagna	Lasagna	Cosolvents	27,238,691	4.54	26,987,231	5.31	27,001,454	6.13	28,300,921	7.14	43,931,229	18.46
19	Lasagna	Lasagna	Surfactants	21,221,385	4.54	21,088,442	5.31	21,218,848	6.13	22,632,210	7.14	38,363,104	18.46
20	Lasagna	Lasagna	In Situ Redox N	5,299,285	5.48	5,251,754	6.23	5,204,236	6.97	5,156,755	7.72	5,114,075	8.39
21	Lasagna	Lasagna	Oxidation	14,664,887	6.50	16,433,718	7.26	18,125,408	8.03	19,739,967	8.81	21,110,607	9.60
22	Radio Frequenc	Radio Frequenc	Oxidation	15,698,733	769.22	15,784,116	899.02	15,866,365	1,030.24	15,944,605	1,164.95	15,997,606	1,306.52

Bibliography

Arquiett, Candy, Mark Gerke and Irene Datskou, "Evaluation of Contaminated Groudwater Cleanup Objectives", Water, Air, and Soil Pollution, Vol. 90. 1996.

Barry, William, Technical Expert, USAF, Hickam AFB HI, 10 Oct 97

Clayton, Bryan. Technical Expert, Lockheed Martin Energy Systems, Paducah, Kentucky. Scoring Meeting. 9 Sep 97.

Clemens R. T. Making Hard Decisions, 2nd edition, Duxbury Press, 1996.

Code of Federal Regulations, 40 CFR S300

Dakins, Maxine E. and John E. Toll and Mitchell J. Small, "Risk-Based Environmental Remediation: Decision Framework and Role of Uncertainty," Environmental Toxicology and Chemistry. Vol. 13. No. 12. 1994.

Datskou, I. and K. North, "Risks Due to Groundwater Contamination at a Plutonium Processing Facility," Water, Air, and Soil Pollution, Vol. 90. 1996.

Davis, K. R. Technical Expert, Jacobs Engineering Company, Paducah, Kentucky. Scoring Meeting. 9 Sep 97.

Deckro, Richard. F. Personal Interview. 1997.

Department of Energy. Contaminant Plumes Containment and Remediation Focus Area Technology Summary. June 1995. DOE/EM-0248.

Diekmann, James and David Featherman and Rhett Moody and Keith Molenar and Maria Rodriguez-Guy, "Project Cost Risk Analysis Using Influence Diagrams." Project Management Journal, December 1996.

DOE/OR/07-1243&D4, 1997.

EI00000-0197 Paducah Site Baseline Summary

Environmental Protection Agency. Remediation Technologies Screening Matrix. EPA/542/B-94/013. October, 1994.

Environmental Protection Agency. Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA. EPA/540/G-89/004, October 1989

Falta, R.W. and T.R. Jarosch and Kueper B.H. and Looney B.B. and Sabitini D.A. and Siegrist R.L. and K. S. Udell. Technical Evaluation of DNAPL Enhanced Removal Technologies. June 1996.

Freeze, R. Allan and David B. McWhorter, "A Framework for Assessing Risk Reduction Due to DNAPL Mass Removal from Low-Permeability Soils", Groundwater, Vol. 35. No. 1. January-February 1997.

Fruchter, John, "In-Situ Redox Manipulation" , Fact Sheet, PNNL-11372, VC-602, 1996.

Gelb, Dan, Technical Expert, Jacobs Engineering Company, Paducah, Kentucky. Scoring Meeting. 9 Sep 97.

Ginevan, Michael E. and Douglas E. Splitstone, "Improving Remediation Decisions at Hazardous Waste Sites with Risk-based Geostatistical Analysis", Environmental Science and Technology, Vol. 31. No. 2. 1997.

Grelk, Brian, J. A CERCLA-Based Decision Support System For Environmental Remediation Strategy Selection. Thesis, Masters of Science, Air Force Institute of Technology, AFIT/GOR/ENS/97M-10. 1997.

Hill, Darryl C., "Waste Remediation: Issues & Technologies for the Future", Professional Safety, American Society of Safety Engineers, March 1996.

Hong, Yuan and George Apostolakis, "Conditional Influence Diagrams in Risk Management", Risk Analysis. Vol. 13. No. 6. May 1993.

Howard, R. A. Decision Analysis: Practice and Promise." Management Science. 34, 679-695, 1988.

http:www.em.doe.gov/add2006/ores.html: June, 1997.

Jennings, A. A., Neel Mehta, and Sumet Mohan, "Superfund Decision Analysis in Prescence of Uncertainty." Journal Of Environmental Engineering, Vol. 120, No. 5, 1132-1151 September/October 1994.

Johnson, Frederick W., "Risk Assessment of Groundwater Contamination and Current Applications in the Decision-Making Process", Journal of Environmental Systems, Vol. 18. No. 4. 1988-89.

Keeney, R. L. Value Focused Thinking. Harvard University Press, 1992.

Keeney, Ralph L., "Creativity in Decision Making with Value-Focused Thinking", Sloan Management Review, Summer 1994.

Kloeber, Jack, M. Personal Interview. 1997.

Kirkwood, C. W. Strategic Decision Making: Multiobjective Decision Analysis With Spreadsheets. California: Wadsworth Publishing Co, 1997.

Lee, T, Robert, Ogletree, et al. "Comprehensive Environmental Response, Compensation, and Liability Act." Environmental Law Handook. Government Institutes. Rockville: 1995.

Maudline, Sarah. Project Manager for the Paducah Feasibility Study, 10 Oct 97 memo

Mather, John. "Technology Summary", September 1995 WWWeb. http://www.em.doe.gov/plumesfa/intech/dus/sum.hmtl.

Morti, Eric, Technical Expert, Lockheed Martin Energy Systems, Paducah, Kentucky. Scoring Meeting. 9 Sep 97.

National Research Council. Alternatives for Groundwater Cleanup. National Academy Press, Washington D. C. 1995.

Noonan, Frank and Charles A. Vidich, "Decision Analysis for Utilizing Hazardous Waste Site Assessments in Real Estate Acquisiton", Risk Analysis, Vol. 12. No. 2. 1992.

Okz, Joop P. and Leen Hordijk and Alfred Stein, "Managing Soil Remediation Problems", Environmental Science & Polution Resources, Vol. 3. No. 4. 1996.

Papatyi, Anthony, F. Analyzing Remediation Technologies for Department of Energy Sites Contaminated with DNAPL Pollutants. Thesis, Masters of Science, Air Force Institute of Technology, AFIT/GOR/ENS/97M-17. 1997.

Reichard, Eric D. and John S. Evans, "Assessing the Value of Hydrogeologic Information for Risk-Based Remedial Action Decisions." American Geophysical Union, 1989.

Timm, Christopher, M. "Systematic Decision Making A Route to Reasonable Remediation." The National Environmental Journal. November/December 1995.

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13. ABSTRACT *(Maximum 200 words)*

The Paducah Gaseous Diffusion Plant (PGDP) operated by the Department of Energy is challenged with selecting the appropriate remediation technology to cleanup contaminants at Waste Area Group (WAG) 6. This research utilizes value-focused thinking and multiattribute preference theory concepts to produce a decision analysis model designed to aid the decision makers in their selction process. The model is based on CERCLA's five primary balancing criteria, tailored specifically to WAG 6 and the contaminants of concern, utilizes expert opinion and the best available engineering, cost, and performance data, and accounts for uncertainty in contaminant volume. The model ranks 23 remediation technologies (trains) in their ability to achieve the CERCLA criteria at various contaminant volumes. A sensitivity analysis is performed to examine the effects of changes in expert opinion and uncertainty in volume. Further analysis reveals how uncertainty is expected to affect technology cost, time and ability to meet the CERCLA crtieria. The model provides the deciosn makers with a CERCLA based decision analysis methodology that is objective, traceable, and robust to support the WAG 6 Feasibilty Study. In addition, the model can be adjusted to address other DOE contaminated sites.

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