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# Application of risk assessment and decision analysis to the evaluation, ranking and selection of environmental remediation alternatives

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## Abstract

A single framework integrating risk assessment and decision analysis methods for evaluating, ranking and selecting preferred remediation alternatives at a contaminated site was developed and demonstrated. The methodology used relies on stakeholder inputs throughout the entire process and employs those inputs to combine the results of multiple risk assessments to arrive at a total impact for each remediation alternative. The total impact values allow the ranking of the alternatives, which in turn, serves as the basis for deliberations among the stakeholders in order to identify the preferred alternative. Six major risk or impact categories were considered in the evaluation of the alternatives: human health and safety, environmental protection, life cycle cost, socio-economics, cultural, archeological and historical resources, and programmatic assumptions. © 2000 Elsevier Science B.V. All rights reserved.

*Keywords:* Risk assessment; Decision analysis; Stakeholder involvement; Environmental remediation

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## 1. Introduction

Since the early 1990s there has been a surge in literature written about the decision-making process for environmental management (Bonano [1], National Research Council (NRC) [2,3], Cothern [4], NRC [5], Presidential/Congressional Commission on Risk Assessment and Risk Management [6], American Institute of Chemical Engineers [7]). Many authors have advocated the use of risk assessment and decision analysis in the selection of implementable solutions to environmental problems. The involvement of stakeholders (i.e. individuals or groups with an interest in the solution of the problem) has been identified as a critical aspect of the decision-making process as the stakeholder input lends credibility to the process, and enhances its defensibility and acceptability.

There exists a plethora of technical articles, books, conference proceedings, and papers describing policy positions on risk-based decision-making with strong stakeholder involvement. However, there are very few examples reported in the literature of actual applications of the principles outlined in many of those publications. Consequently, while those principles may be intuitively sensible, there are many questions as to their practicality and implementability. For example, there are unanswered questions about the role of stakeholders vis-à-vis the technical analysts, the nature of the risk assessment (i.e. quantitative vs. qualitative), and the type of risks that influence the decisions, to name a few. This paper summarizes a 2-year study aimed at addressing these and similar questions, application of theories, and testing of the guiding principles presented in the literature [8].

Our study focused on the application of risk assessment and decision analysis to the evaluation and ranking of remedial action alternatives (RAAs) at hazardous waste sites. The study sought and obtained stakeholder involvement throughout the entire process. Some of the aforementioned questions associated with the environmental management decision-making process were addressed, but certainly not all. The study also raised other questions that will require further research.

Finally, the study only dealt with decision-making at the bottom of the hierarchical environmental management process. That is, the evaluation, ranking, and selection of RAAs is the lowest level in a decision hierarchy which constitutes the environmental management process. At the top of the hierarchy is the identification, evaluation and ranking of existing environmental management problems. Because resources for environmental remediation are limited, decisions must be made regarding which problems should be addressed first, second, third, and so forth. Often this ranking is based on the actual risk the problem poses or the perception of that risk. Once the high-risk problems are identified, recommendations are made about the type of actions (e.g. capping of the site, removal of the contaminated soil, or in situ remediation, among others) required to reduce the risk to acceptable levels. Within each type of proposed action, there may be several remedial alternatives (i.e. systems of technologies) that could be implemented; each alternative has a different impact or sets of impacts. Decisions must be made about the preferred alternative for each type of action. Our study addressed this last level in the environmental management decision-making process.

The remainder of this paper consists of the project's background (Section 2), its goals and objectives (Section 3), preliminary analysis (Section 4), decision analysis framework

(Section 5), impacts assessments and integration of assessment results (Section 6), stakeholder deliberation of integration results (Section 7), and concluding remarks (Section 8).

## 2. Background

After decades of supporting the U.S. nuclear defense program, the U.S. Department of Energy (DOE) now faces the challenge of cleaning up many contaminated or hazardous waste sites across the nation. Difficult decisions must be made to determine which sites should be addressed first, and the preferred approach to cleaning up high priority sites. The decision-makers must consider the costs of cleanup at a selected site, and which technology or group of technologies will most effectively achieve cleanup goals, while minimizing the cost of such cleanup. The cost of a cleanup is figured in terms of dollars; the risks to the public and to workers; socio-economic impacts; impacts to cultural, historical and archeological resources; and impacts of a programmatic nature associated with the implementation of a given cleanup strategy.

In 1993, the DOE's Office of Environmental Management (EM) commissioned a study by the NRC of the U.S. National Academy of Science to determine the value of applying risk assessment and risk management tools to the decision-making process in the DOE's EM Program. In 1994, the NRC published the findings of its study [2], suggesting that the use of risk, assessment and risk management was feasible and also appropriate. As a result, the DOE requested proposals for research to develop risk assessment and risk management tools for use by DOE EM decision-makers. The work described herein summarizes one of the projects funded by DOE EM in this area.

The NRC issued another report [5] later in which it recommended that the decision maker incorporate all relevant stakeholders in the decision-making process from the start. They recommend an analytical/deliberative process for dealing with decisions that involve substantial risk assessment. Risk assessments used to understand and quantify risk need to be utilized in conjunction with input from the affected parties so that assumptions underlying the evaluation are clarified, understood, and validated. The basic premise is that, by involving the stakeholders in the risk assessment (the analytical part of the process) and by including deliberation, the decision-making process will be enhanced and the previous failings and causes for mistrust will be overcome.

This project entailed the development and demonstration of a methodology incorporating risk assessment and decision analysis tools with stakeholder participation to evaluate and rank RAAs for the cleanup of a selected contaminated site. The analytic/deliberative process that the NRC recommended provided the basic framework for our approach.

## 3. Project goals and structure

We set out to develop and demonstrate a prototypical methodology for evaluating and ranking environmental restoration (ER) and waste management (WM) technologies from a variety of risk perspectives. The methodology was to integrate impact assessment techniques and decision theory components in a framework that emphasizes and incorporates input from stakeholders, leading to defensible decisions regarding ER and WM actions.

The specific goals of the project were:

- To develop and demonstrate a methodology for evaluating the impact of RAAs on six major impact categories: human health and safety, the environment, life cycle cost (LCC), programmatic assumptions, socio-economic issues, as well as cultural, archaeological, and historic resources;
- To integrate the multiple risk/impact assessments into a framework that would facilitate ranking RAAs;
- To involve stakeholders interactively throughout all phases of impact assessment and decision making;

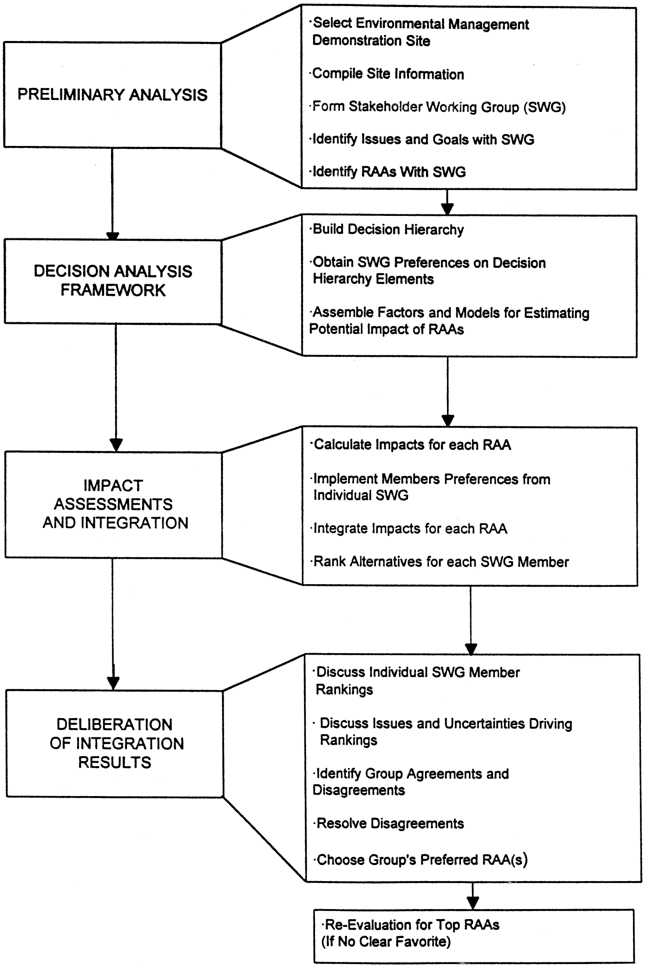

Fig. 1. Project components.

- To develop new ways to successfully communicate risk concepts to stakeholders; and
- To develop a technology evaluation framework for use by decision-makers that produces defensible decisions.

The project was organized into four major components: Preliminary Analysis, Decision Analysis Framework, Impact Assessments and Integration, and Deliberation of Integration Results. These components are shown in Fig. 1, including the salient sub-components. More detailed discussion follows in each of these components. The manner in which the methodology was implemented after selection of the contaminated demonstration site is shown in Fig. 2.

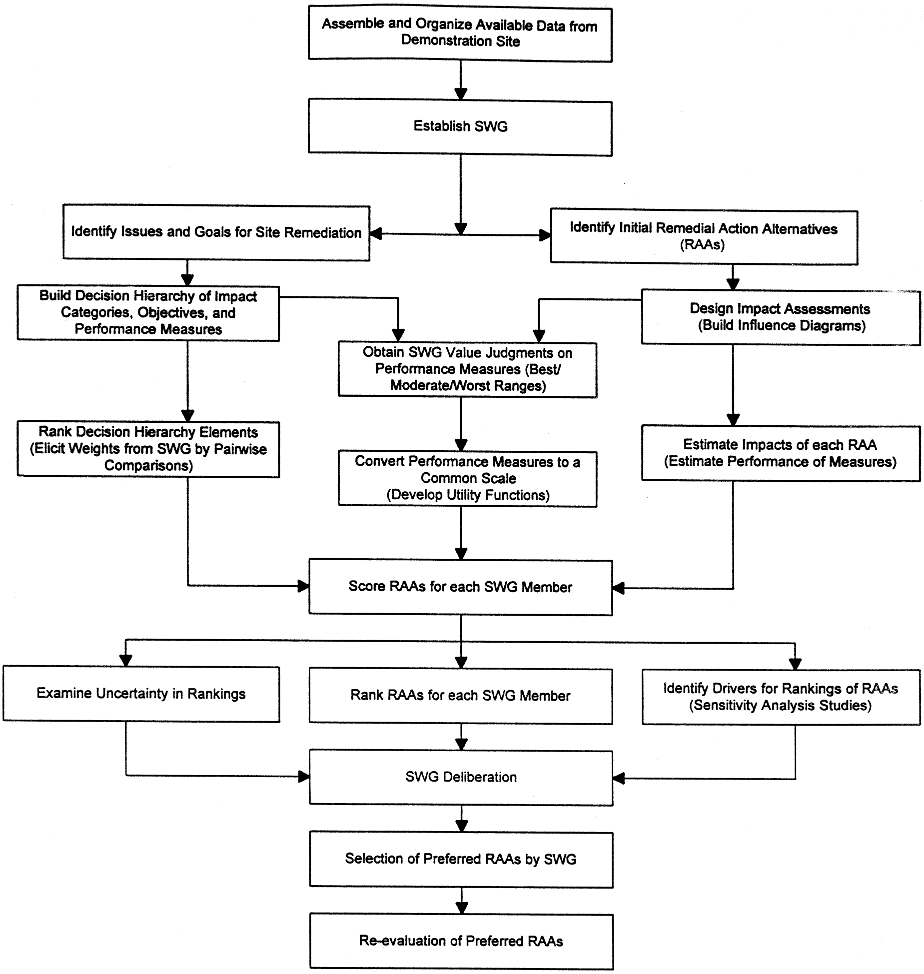

Fig. 2. Methodology implementation flowchart.

Stakeholders were actively involved throughout the project and were an integral part of the development and demonstration of the methodology. For that reason the stakeholders were called the ‘Stakeholder Working Group’ (SWG). The term ‘stakeholders’ was defined in the broadest possible sense to include site/facility owners and operators, decision makers, technical experts, regulators, local, state, and federal government representatives, traditional and non-traditional ‘publics’, environmental activists, and anyone else who was interested in the project. To demonstrate the methodology every stakeholder represented an institutional rather than an individual viewpoint when providing preferences.

## 4. Preliminary analysis

A key component of the project was the use of data and information from an existing contaminated site for purposes of demonstrating the methodology. After extensive discussions with staff and management from both DOE-Albuquerque Operations Office (DOE-AL) and Sandia National Laboratories/New Mexico (SNL/NM), a contaminated site at SNL/NM was selected as the demonstration testbed. It was agreed with both DOE-AL and SNL/NM that because the use of the site’s data and information was for demonstration purposes only, the results of the project would not be binding on either DOE-AL or SNL/NM. [1]

DOE-AL and SNL/NM also suggested an initial list of stakeholder candidates for potential SWG participation. These stakeholders were individually interviewed to establish issues and concerns. From the initial list of potential stakeholders (48 individuals), those that expressed interest in the project were invited to join the SWG. Initially the SWG consisted of 11 members. Because this project was not governed by any regulatory action, it was not mandated to follow specific public participation requirements as outlined in various U.S. laws and regulations.

While the SWG was being assembled, we compiled available technical information on the site. Our review indicated that DOE-AL, SNL/NM, and the State of NM had already agreed to implement Voluntary Correction Measures (VCMs) at the site. The key VCMs, insofar as this project was concerned, would remove (1) the top 15 ft of contaminated soil at the site and replace it with uncontaminated soil, and (2) most of the volatile organics. However, following the implementation of the VCMs, trichloroethylene (TCE) and hexavalent chromium ($Cr^{+6}$) would still remain at the site. Thus, the project focused on the post-VCM contaminants at the site.

The information collected was used to identify and preliminarily screen technology options applicable to the post-VCM contaminants and contaminated media at the site. These technologies, in turn, were combined to form a representative set of candidate RAAs for the demonstration. The representative RAAs selected for the demonstration are listed in Table 1. It should be noted that (1) RAA ‘F,’ the No Action alternative, was included for completeness and comparison purposes, and (2) ‘No Action’ refers to

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[1] For these reasons, the specific site is not named herein. We simply refer to it as ‘‘the site.’’

Table 1
List of representative remedial action alternatives

| RAA | Remediation technology for Cr | Remediation technology for TCE | Other technologies |
|---|---|---|---|
| A | In Situ Vitrification | Soil Vapor Extraction | |
| B | In Situ Stabilization | In Situ Bioremediation | |
| C | Stabilization/Solidification | Thermal Desorption | Excavation; On-site Disposal of Treatment Residuals |
| D | Stabilization/Solidification | Thermal Desorption | Excavation; Off-site Disposal of Treatment Residuals |
| E | Off-site Treatment | Off-site Treatment | Excavation; Off-site Disposal |
| F | No Action | No Action | |

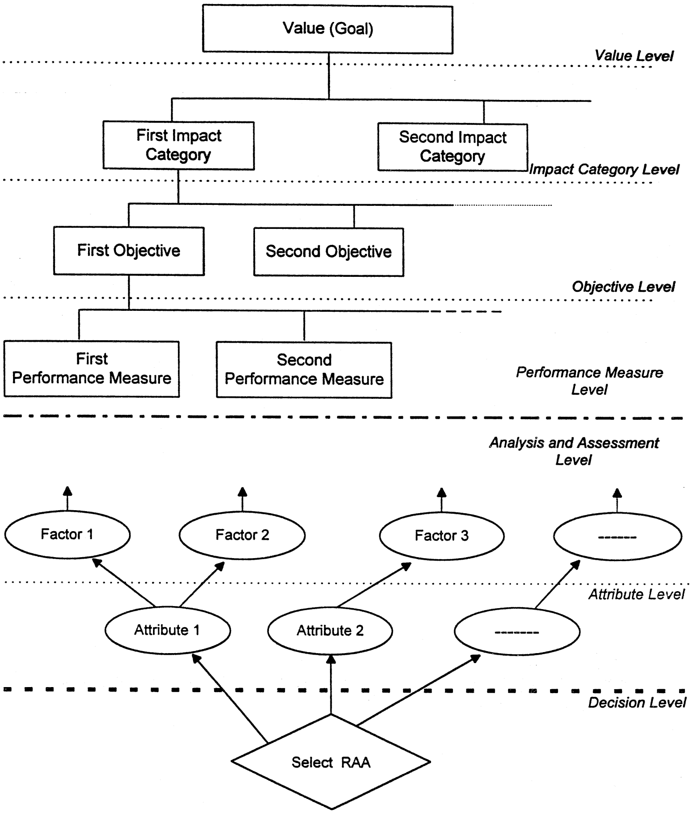
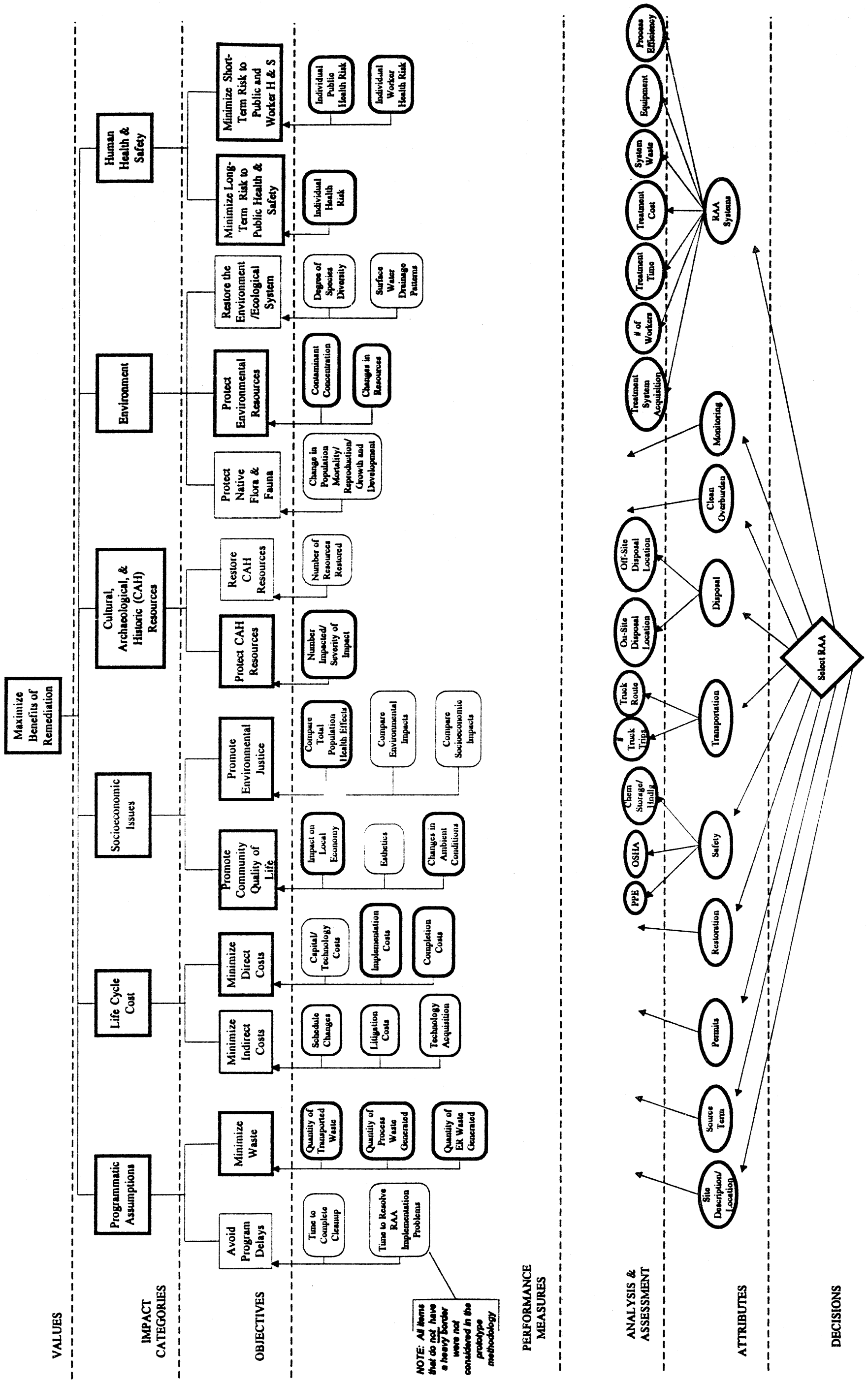


Fig. 3. Generic decision diagram comprised of decision hierarch (top) and influence diagram (bottom).



NOTE: All items that do not have a heavy border were not considered in the prototype methodology

Fig. 4. Decision hierarchy "1".

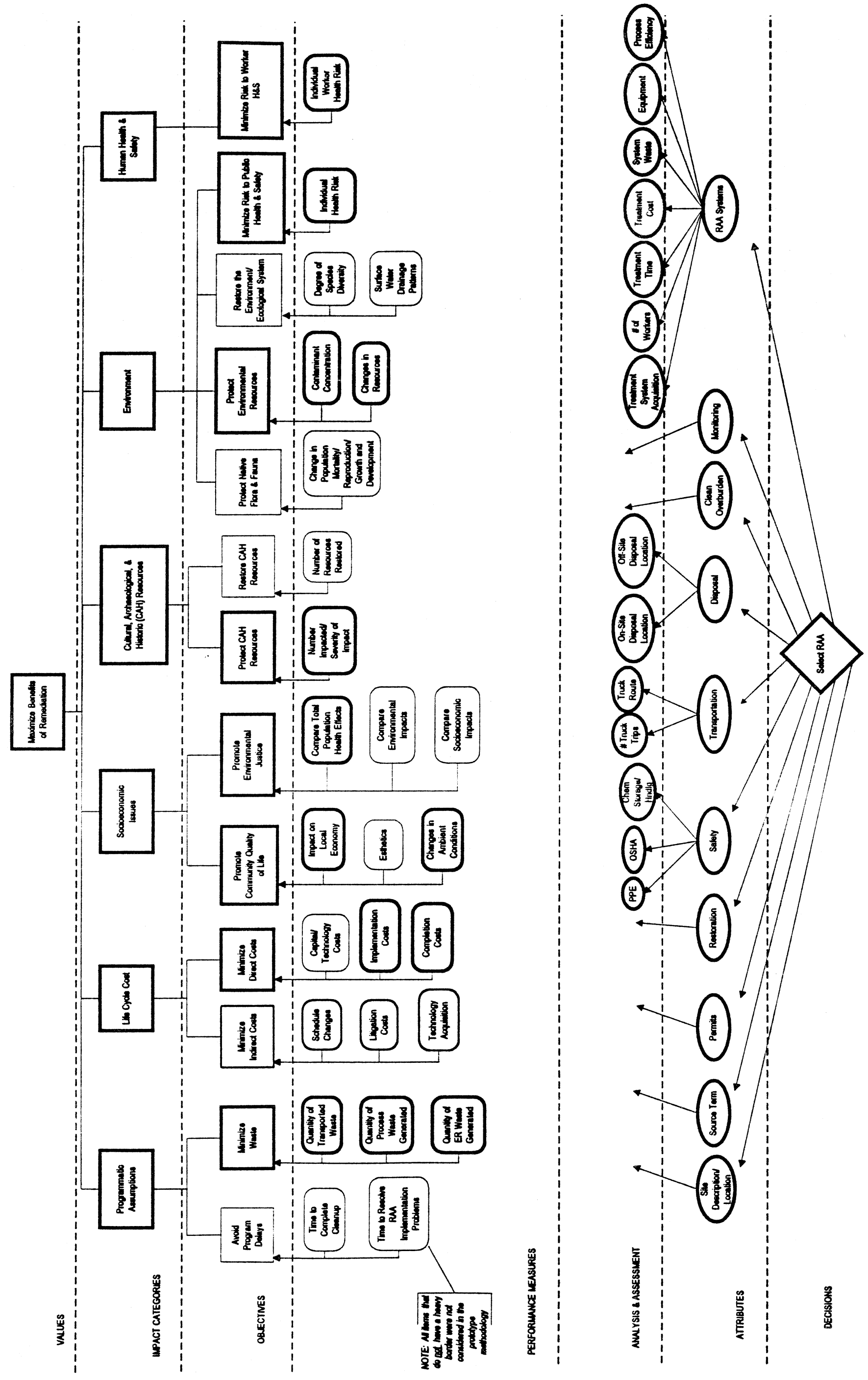


Fig. 5. Decision hierarch ‘‘A’’.

remediation with respect to contaminants remaining at the site after implementation of the VCMs.

## 5. Decision analysis framework

To reach a solution, (i.e. evaluation and ranking of the RAAs, and identification of the ‘preferred’ RAA), the problem was structured using a decision diagram [9] that consisted of a decision hierarchy in the top half and influence diagrams in the bottom half (e.g. Fig. 3). The decision hierarchy consisted of four levels.

The top level, commonly known as ‘the value’ of the decision, represented the overall problem-solving goal. After discussion, the consensus of the SWG was to place the ‘value’ of the decision as ‘Maximize Benefits of Remediation’. That is, the RAA that provides the highest overall benefit should be ranked at the top. The six impact categories affecting the evaluation and ranking of the RAAs (i.e. human health and safety, environment, socio-economics, as well as cultural, archeological and historic resources, LCC, and programmatic assumptions) constituted the second level of the decision hierarchy. These categories defined the different benefits derived from the implementation of a particular RAA. It should be noted that the term ‘benefit’ as employed here denotes an impact, whether the impact is positive or negative. By assigning relative weights to the benefits reaped for each of the categories, a ‘total benefit’ for each RAA was estimated. This total benefit was used to compare and rank the RAAs.

For each impact category, a number of objectives were identified, and these appear in the third level of the decision hierarchy. An objective represented specific SWG-desired action goals that would lead to maximizing the benefits of remediation. Examples of objectives used in this project are: minimize worker risks, minimize direct cost of RAA implementation, and minimize amount of ER waste generated. The fourth level of the decision hierarchy consists of performance measures that indicate how well an RAA meets the objectives. One or more performance measures were defined for each objective.

At the bottom of the decision tree is the decision node ‘Select RAA’. Right above the decision node is a list of attributes for the RAAs and factors that could affect the different risk assessments for each impact category. The connection between the attributes and factors and the performance measures were influence diagrams describing the impact assessments performed for each impact category.

During the first SWG meeting, we presented a preliminary decision hierarchy for comments, revisions, and eventual finalization of the hierarchy. As a result of input from the SWG, the preliminary decision hierarchy resulted in two decision hierarchies. Decision Hierarchy ‘‘1’’ (Fig. 4), included both public health and safety, and worker health and safety under the ‘Human Health and Safety’ impact category. The other decision hierarchy, denoted Decision Hierarchy ‘‘A’’ (Fig. 5), included public health and safety under the ‘Environment’ impact category, with the ‘Human Health and Safety’ impact category only including worker health and safety. It should be noted that these hierarchies were denoted ‘‘1’’ and ‘‘A’’ to indicate that the SWG did not express preference of one over the other; i.e. they were treated as two equally preferable ways of

Table 2
Rankings by SWG using decision hierarchy 1

| SWG member | Impact category | | | | | |
|---|---|---|---|---|---|---|
| | Programmatic | Cost | Socio-economic | Cultural | Environment | Human health |
| 1 | 7.8 | 11.5 | 3.9 | 4.2 | 34.0 | 38.6 |
| 3 | 2.6 | 7.0 | 4.2 | 7.8 | 38.7 | 39.8 |
| 4 | 5.0 | 7.7 | 24.9 | 4.1 | 16.8 | 41.5 |
| 6 | 12.0 | 4.5 | 12.7 | 10.4 | 27.2 | 33.3 |
| 7 | 2.0 | 1.9 | 5.2 | 26.6 | 50.7 | 13.7 |
| 8 | 3.5 | 2.9 | 8.0 | 15.5 | 39.3 | 30.8 |
| 9 | 3.3 | 5.3 | 10.0 | 2.6 | 31.7 | 47.1 |
| 10 | 19.6 | 14.8 | 21.1 | 6.0 | 10.7 | 27.7 |
| 11 | 4.6 | 4.5 | 5.5 | 7.8 | 27.6 | 50.0 |
| Mean | 6.71 | 6.68 | 10.61 | 9.44 | 30.74 | 35.83 |
| Ranking | 5 | 6 | 3 | 4 | 2 | 1 |
| Minimum | 2.0 | 1.9 | 3.9 | 2.6 | 10.7 | 13.7 |
| Maximum | 19.6 | 14.8 | 24.9 | 26.6 | 50.7 | 50.0 |

structuring the problem. All other aspects of these two decision hierarchies were identical.

We selected the Analytic Hierarchy Process (AHP) [10] as the technique to obtain SWG input regarding the relative importance of the elements in the decision hierarchies: impact categories, objectives, and performance measures. The AHP is a pairwise comparison technique that focuses on a specific level of the decision hierarchy, and only two members of the hierarchy at that level are addressed at a time.

First, the SWG provided input on their preferences at the impact category level by comparing two impact categories at a time and determining the relative importance between the two members by establishing if the more important member was ‘equally as important’, ‘slightly more important’, ‘strongly more important,’ or ‘very strongly more important’ as the other member. A numerical scale was assigned to these qualitative indicators of relative importance. This process was repeated for all possible pairs of the impact categories. The results of the pairwise comparisons at the impact category level are listed in Tables 2 and 3 for Decision Hierarchy ‘‘1’’ and Decision Hierarchy ‘‘A’’, respectively. Note that individual SWG members elected one decision hierarchy or the

Table 3
Rankings by SWG using decision hierarchy A

| SWG member | Impact category | | | | | |
|---|---|---|---|---|---|---|
| | Programmatic | Cost | Socio-economic | Cultural | Environment | Human health |
| 2 | 2.2 | 14.7 | 2.1 | 5.9 | 37.6 | 37.6 |
| 5 | 3.2 | 10.0 | 4.2 | 10.6 | 19.5 | 52.4 |
| Mean | 2.7 | 12.35 | 3.15 | 8.25 | 28.55 | 45 |
| Ranking | 6 | 3 | 5 | 4 | 2 | 1 |
| Minimum | 2.2 | 10.0 | 2.1 | 5.9 | 19.5 | 37.6 |
| Maximum | 3.2 | 14.7 | 4.2 | 10.6 | 37.6 | 52.4 |

other to express their preferences, but not both. We converted the preferences in relative importance at the impact-category level to relative weights for each of the SWG members.

The AHP was then moved to the next level of the decision hierarchy; i.e. to the objective level. The purpose of the AHP at this point was to distribute the relative weight for each impact category among its associated objectives. It should be noted that the pairwise comparisons were restricted to objectives within a single impact category. That is, no inter-impact category pairwise comparisons were performed at the objective level. Thus, there were six applications of the AHP at the objective level. Following the applications of the AHP at the objective level, the process was repeated to distribute the relative weight of each objective among the performance measures associated with the objective.

One of the challenges encountered in this project was the need to define many of the performance measures and develop appropriate scales/ranges of values that could be realistically estimated for each performance measure in the impact assessments. We researched the pertinent literature and developed preliminary scales for each performance measure. The preliminary scales were presented to, and discussed with, the SWG. Some of the scales were revised based on input from the SWG. The next step was to

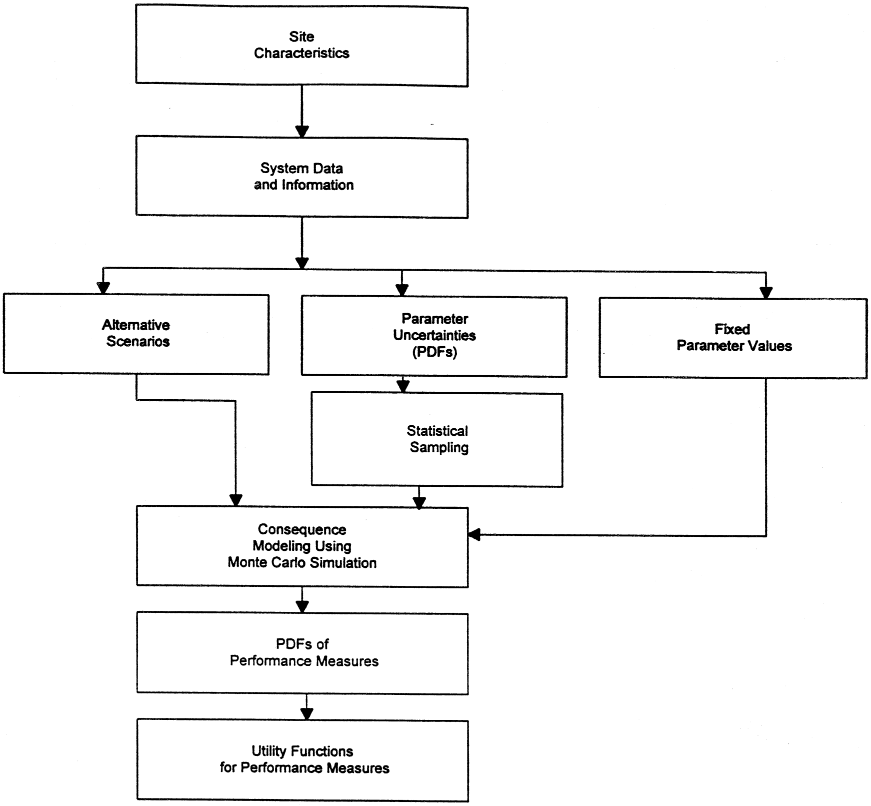


Fig. 6. Common framework for all impact assessments.

obtain input from the SWG regarding the definition of a measure of ‘goodness’ depending on the numerical value estimated for each of the performance measures. To do this, each member of the SWG was asked to divide the scale (i.e. range of possible values) for each performance measure into three segments: best values, moderate values, and worst values. The SWG was informed that, if their preferences so required, there was no need for a definitive demarcation between the three segments; i.e. the segments could overlap with each other.

Each SWG member was then asked to express preferences with respect to how important it was for the value of a given performance measure to fall within the range of ‘best values’ as opposed to the range of ‘worst values’. Similar comparisons were made for ‘‘moderate’’ and ‘‘worst’’ values, and for ‘‘moderate’’ and ‘‘best’’ values. This step was necessary for the integration of results from the impact assessments due to the difference in units for the scales of the performance measures. The input gathered from the SWG was used to define a ‘‘utility function’’ for each performance measure defining the relative goodness of the value of each performance measure.

To arrive at the utility functions we used a combination of fuzzy logic and AHP. Fuzzy logic [11] was used to capture the linguistic imprecision within the SWG concerning the boundaries between the ‘‘best’’, ‘‘moderate’’ and ‘‘worst’’ segments for each performance measure. To derive the utilities for each segment, the SWG used AHP in pairwise comparisons of ‘‘best’’, ‘‘moderate’’ and ‘‘worst’’ values for each performance measure in a similar manner to the pairwise comparisons performed for the

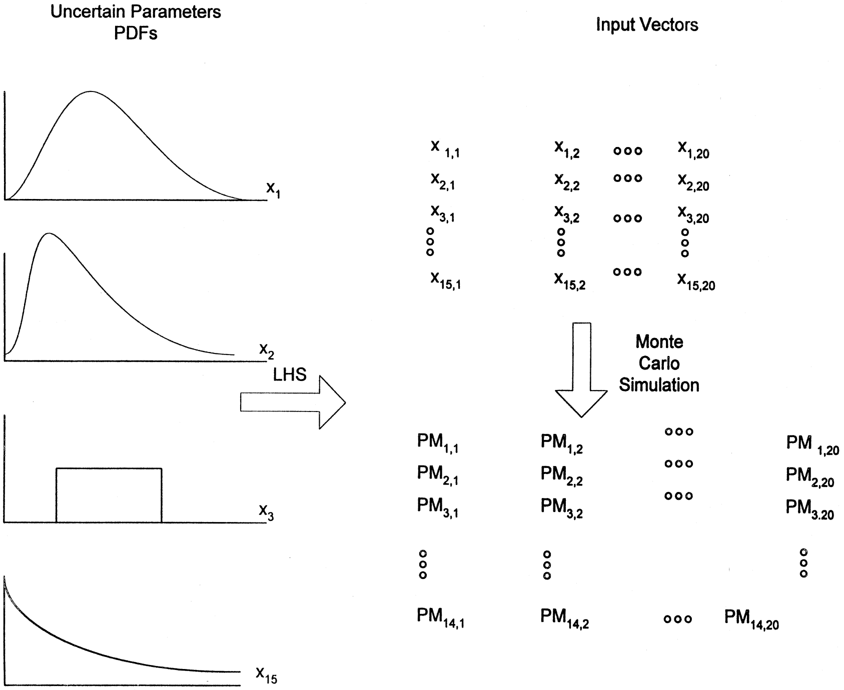


Fig. 7. Latin hypercube sampling and Monte Carlo simulation procedures.

elements of the decision hierarchies. An example of this procedure is provided in the project's final report, [8] which can be obtained by contacting Ms. Stephanie Jennings at Commodore Advanced Sciences.

## 6. Impact assessments and integration

The next component of the project was the impact assessments to estimate the values of the performance measures. This project was a demonstration of a prototype methodology. For that reason as well as due to the limited resources (i.e. time and money) available, impact assessments were not performed for all the performance measures in Figs. 4 and 5. Only those objectives and performance measures highlighted with bold lines as borders in Figs. 4 and 5 were included in the demonstration. The selection of the objectives and performance measures for the demonstration was with the consent of the SWG.

The common risk assessment framework shown in Fig. 6 was used for all impact assessments. The risk assessment framework is a simplified version of the common probabilistic risk assessment methodology used in safety assessments of waste management systems (see Bonano [1]). It decomposes the risk assessment into what could occur (e.g. scenarios), how likely it is that these will occur (e.g. probabilities), and what are the possible consequences if they were to occur (e.g. consequence modeling). To address

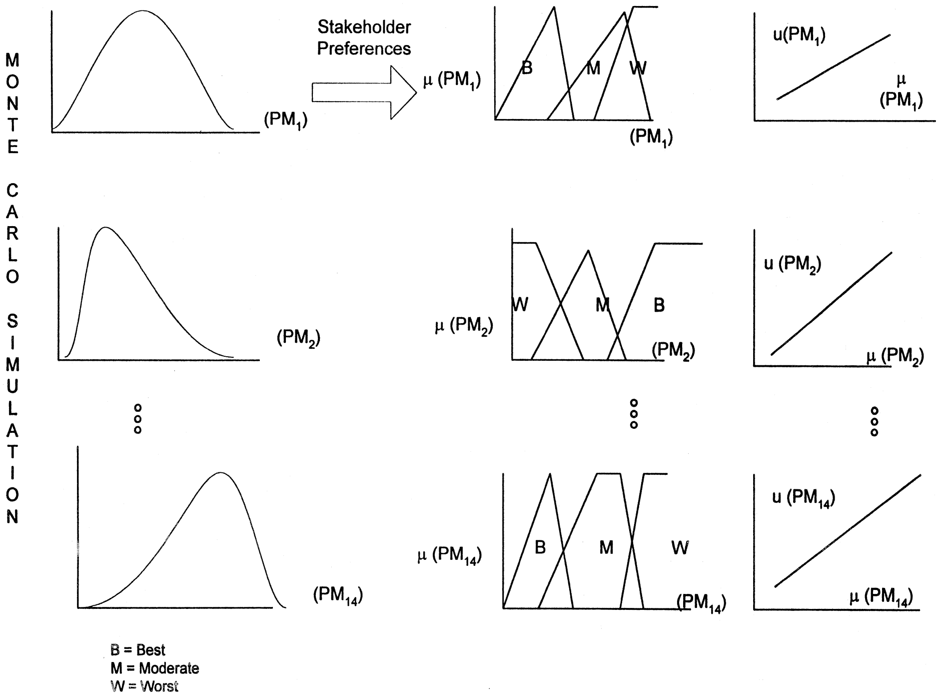


Fig. 8. Translation of the probability density function for performance measures into utility functions.

Table 4
General scenarios for impact assessments

| Scenarios | Programmatic assumptions | Life cycle costs (LCC) | Socio-economic issues | Cultural, archeological and historic resources | Environment | Human health and safety |
|---|---|---|---|---|---|---|
| 1. Future land use #1 (RAA F1): DOE ownership/industrial, Future land use #2 (RAA F2): rural residential/agricultural | | | ● | | ● | ● |
| 2. Post VCMs (1. Remove top 15 ft; backfill with clean soil), (2. SVE for worst TCE concentrations) | ● | ● | | | ● | ● |
| 3. LCC calculations based only on data from other impact categories (i.e., no independent assumptions) | | ● | | | | |
| 4. LCC-Base year for cost estimates is FY 97; no escalations | | ● | ● | | | |
| 5. Single off-site disposal option (Utah) | ● | ● | ● | | ● | ● |
| 6. Single on-site disposal option (CAMU)[a] | ● | ● | ● | | ● | |
| 7. Spill scenario | | | | | ● | ● |
| 8. Socio-economic impacts calculated within 50-mile radius of the site | | | ● | | | ● |
| 9. Environmental transport radius of influence based on results of the transport model | | | ● | | ● | ● |
| 10. RAA systems are assumed to be a single design point (i.e., no different scenarios on RAA designs) | ● | ● | ● | ● | ● | ● |
| 11. Project boundary conditions apply | ● | ● | ● | ● | ● | ● |
| 12. Cr VI and TCE source-term calculations will be used by all impact categories | ● | ● | ● | ● | ● | ● |

[a] CAMU, corrective action management unit.
● Scenario characteristics modeled explicitly in the impact assessment.

these three basic questions, one starts with a description of the site, the problem of interest and all the pertinent information and data about the site and problem (i.e. the system). This information is then used to determine what could occur to impact the system (scenarios) and the parameters, both fixed and uncertain, needed to estimate the likely consequences of the scenarios. Once appropriate models have been selected to capture the salient features of the system and of the scenarios, the possible consequences of the scenarios are estimated using the models. Consequence modeling includes the propagation of uncertainties in input parameters to the values of the performance measures.

Fig. 7 illustrates the process used to propagate uncertainty in input parameter values, to uncertainty in the performance measures. Fig. 8 illustrates the procedure used to transform the estimated values of the performance measures into utility functions.

To demonstrate how uncertainties are handled in the methodology and how these could impact the decision, 15 of the parameters contained in the impact assessment models were treated as uncertain parameters. For each uncertain parameter, a plausible range of values and a probability density function (pdf) within that range were defined. The pdfs were sampled using Latin hypercube sampling (LHS) to generate 20 realizations of the uncertain input parameter values. The 20 realizations were combined with the values of the fixed-value parameters. Monte Carlo simulation was performed to propagate the uncertainty in input parameters to the uncertainty in the values of the performance measures. The uncertainty in the value of the performance measures was represented using pdfs. The pdfs for the performance measures were converted using the utility function for each performance measure into pdfs of utility values, and the latter were used in the integration of the results and in the ranking of the RAAs. It is worth mentioning that the uncertainty analysis (i.e. the uncertain parameters sampling and the Monte Carlo simulation) was performed in an integrated manner across all six impact categories. This was necessary to preserve the integrity of the uncertainty analysis for integration purposes.

Twelve different general scenarios were considered in the impact assessments. These scenarios are listed in Table 4. Summary results for the assessments for the impact categories are presented in Tables 5–8. It is important to note that: (1) the ‘Environment’ and ‘Human Health and Safety’ impact categories were combined in one table

Table 5
Assessment results for the programmatic assumptions impact category

| PM | Quantity ($yd^3$) of transported waste | | | Quantity ($yd^3$) of process waste generated | | | Quantity ($yd^3$) of ER waste generated | | |
|---|---|---|---|---|---|---|---|---|---|
| RAA | Minimum | Average | Maximum | Minimum | Average | Maximum | Minimum | Average | Maximum |
| A | 222 | 231 | 239 | 208 | 217 | 225 | 14 | 14 | 14 |
| B | 161 | 163 | 165 | 153 | 155 | 157 | 8 | 8 | 8 |
| C | 119 | 122 | 126 | 119 | 122 | 126 | 0 | 0 | 0 |
| D | 7299 | 7442 | 7618 | 119 | 122 | 125 | 0 | 0 | 0 |
| E | 11,828 | 11,927 | 12,013 | 20 | 20 | 20 | 11,808 | 11,907 | 11,993 |
| F | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 6
Assessment results for the life-cycle cost impact category

| PM | Completion cost (US$ in millions) | | | Implementation cost (US$ in millions) | | |
|---|---|---|---|---|---|---|
| RAA | Minimum | Average | Maximum | Minimum | Average | Maximum |
| A | 3.62 | 4.68 | 5.68 | 2.70 | 2.73 | 2.75 |
| B | 0.36 | 1.03 | 2.24 | 0.99 | 1.01 | 1.04 |
| C | 1.70 | 3.52 | 5.95 | 2.85 | 2.88 | 2.91 |
| D | 1.96 | 3.81 | 6.64 | 3.07 | 3.10 | 3.14 |
| E | 0.54 | 0.60 | 0.66 | 6.34 | 6.37 | 6.39 |
| F | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

(Table 8); and (2) no significant impacts to cultural, archeological and historic resources from remediation were estimated at the site. The latter was due to no resources found below the top 15 ft of soil (removed under the VCMs) meeting the criteria set forth in the National Historic Preservation Act of 1966 as amended [12] and the Archeological and Historic Preservation Act of 1979 as amended [13].

The summary results were extracted from the pdfs for each performance measure. Those pdfs, accompanied by detailed descriptions of the associated impact assessments, are discussed in the final report for this project [8]. Due to space limitations, those details could not be presented here. The interested reader is encouraged to examine the final report.

Upon completion of the assessments, we produced individual rankings of the RAAs for each member of the SWG using the relative weights for the performance measures, objectives and impact categories derived from their expressed preferences. A mean ranking of the RAAs for the entire SWG was also produced. Both of these rankings were critical for the deliberation of results. The aggregate ranking of the RAAs resulted in RAA ‘F’ (the No Action alternative) ranked highest, followed by RAA ‘E’, RAA ‘C’, RAA ‘B’, RAA ‘D’, and RAA ‘A’. Table 9 summarizes these results in terms of the expected utility for each RAA and overall ranking. It should be noted that, due to situations beyond our control, only 6 of the 11 members of the SWG were able to provide input at this stage of the project.

Table 7
Assessment results for socio-economic impact category

| PM | Impact to local economy (US$ millions in 1997) | | | % Change in ambient conditions | | |
|---|---|---|---|---|---|---|
| RAA | Minimum | Average | Maximum | Minimum | Average | Maximum |
| A | 19.1 | 21.8 | 24.7 | 0.1 | 6.8 | 13.4 |
| B | 4.1 | 6.0 | 9.6 | 0.1 | 6.8 | 13.4 |
| C | 13.4 | 18.8 | 25.9 | 0.1 | 6.8 | 13.4 |
| D | 14.9 | 20.3 | 28.6 | 0.1 | 6.8 | 13.4 |
| E | 20.3 | 20.5 | 20.7 | 0.1 | 6.8 | 13.4 |
| F | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table 8
Assessment results for environment and human health and safety impact categories

| RAA | F1 | F2 | A, F2 | B, F2 | C, F2 | D, F2 | E, F2 |
|---|---|---|---|---|---|---|---|
| *Performance measure: groundwater concentration (mg / l)* | | | | | | | |
| TCE | | | | | | | |
| High | 8 e−10 | 1 e−02 | 3 e−03 | 6 e−03 | 6 e−04 | 6 e−04 | 4 e−03 |
| Average | 2 e−10 | 1 e−02 | 1 e−03 | 3 e−03 | 4 e−04 | 4 e−04 | 5 e−04 |
| Low | 1 e−12 | 1 e−06 | 5 e−04 | 7 e−04 | 2 e−04 | 2 e−04 | 2 e−04 |
| Cr | | | | | | | |
| High | < 1 e−09 | 5 e−00 | 5 e−01 | 8 e−01 | 4 e−00 | 1 e−01 | 1 e−01 |
| Low | < 1 e−09 | 5 e−01 | 3 e−02 | 6 e−02 | 3 e−01 | 1 e−02 | 1 e−02 |
| Average | < 1 e−09 | 1 e−32 | 1 e−33 | 1 e−33 | 1 e−32 | 1 e−34 | 1 e−34 |
| *Performance measure: modification of surface soil — not a discriminator* | | | | | | | |
| *Performance measure: long-term public health* | | | | | | | |
| Risk (incremental cancer incidence) | | | | | | | |
| High | 9 e−14 | 1 e−06 | 3 e−07 | 6 e−07 | 6 e−08 | 6 e−08 | 4 e−07 |
| Average | 2 e−14 | 1 e−06 | 2 e−07 | 3 e−07 | 4 e−08 | 4 e−08 | 5 e−08 |
| Low | 1 e−16 | 1 e−10 | 5 e−08 | 8 e−08 | 3 e−08 | 3 e−08 | 2 e−08 |
| Hazard index (HI) | | | | | | | |
| High | 1 e−08 | 3 e+01 | 4 e−02 | 5 e−00 | 2 e+01 | 7 e−01 | 1 e−00 |
| Average | 3 e−09 | 3 e−00 | 2 e−02 | 4 e−01 | 2 e−00 | 7 e−02 | 7 e−02 |
| Low | 1 e−11 | 1 e−01 | 7 e−03 | 1 e−02 | 3 e−03 | 3 e−03 | 3 e−03 |
| *Performance measure: short-term public health* | | | | | | | |
| Risk (incremental cancer incidence) | | | | | | | |
| High | 0 | 0 | 3 e−09 | 5 e−14 | 7 e−12 | 7 e−12 | 8 e−13 |
| Average | 0 | 0 | 1 e−09 | 3 e−14 | 3 e−12 | 3 e−12 | 4 e−13 |
| Low | 0 | 0 | 1 e−11 | 3 e−16 | 3 e−14 | 3 e−14 | 4 e−15 |
| Hazard index (HI): not applicable | | | | | | | |
| Risk of death by accident: not a discriminator | | | | | | | |
| RAA | F1 | F2 | A | B | C | D | E |
| *Performance measure: worker health risk* | | | | | | | |
| Risk from accidents/routine worker exposure (incremental cancer incidence) | | | | | | | |
| High | 0 | 0 | 3 e−07 | 1 e−11 | 2 e−09 | 2 e−09 | 2 e−10 |
| Average | 0 | 0 | 8 e−08 | 4 e−12 | 5 e−10 | 5 e−10 | 7 e−11 |
| Low | 0 | 0 | 8 e−09 | 4 e−13 | 5 e−11 | 5 e−11 | 7 e−12 |
| RAA | F1 | F2 | A, F2 | B, F2 | C, F2 | D, F2 | E, F2 |
| Number of fatalities (no exposure) | | | | | | | |
| High | 0 | 0 | 3 e−03 | 2 e−03 | 2 e−03 | 4 e−03 | 2 e−03 |
| Average | 0 | 0 | 2 e−03 | 1 e−03 | 2 e−03 | 3 e−03 | 1 e−03 |
| Low | 0 | 0 | 8 e−04 | 6 e−04 | 9 e−04 | 2 e−03 | 1 e−03 |
| Number of injuries (no exposures) | | | | | | | |
| High | 0 | 0 | 6 e−02 | 1 e−01 | 2 e−01 | 7 e−01 | 6 e−01 |
| Average | 0 | 0 | 4 e−02 | 7 e−02 | 1 e−01 | 4 e−01 | 3 e−01 |
| Low | 0 | 0 | 2 e−02 | 2 e−02 | 3 e−02 | 3 e−02 | 1 e−02 |

Table 9
Expected utility and ranking by SWG member. SH1 = SWG member 1

| RAA | SH1 | SH2 | SH3 | SH4 | SH5 | SH6 | Mean |
|---|---|---|---|---|---|---|---|
| *Expected utility* | | | | | | | |
| A | 0.0936 | 0.0475 | 0.0711 | 0.0529 | 0.0501 | 0.1297 | 0.0742 |
| B | 0.2045 | 0.1718 | 0.1543 | 0.1111 | 0.0910 | 0.1594 | 0.1487 |
| C | 0.2157 | 0.1281 | 0.1771 | 0.1217 | 0.0908 | 0.1547 | 0.1480 |
| D | 0.1829 | 0.1152 | 0.1786 | 0.1200 | 0.0820 | 0.1385 | 0.1362 |
| E | 0.2225 | 0.1852 | 0.1324 | 0.1353 | 0.1065 | 0.1135 | 0.1492 |
| F | 0.2576 | 0.2052 | 0.1808 | 0.1276 | 0.0888 | 0.1944 | 0.1757 |
| *Rankings* | | | | | | | |
| A | 6 | 6 | 6 | 6 | 6 | 5 | 5.83 |
| B | 4 | 3 | 4 | 5 | 2 | 2 | 3.33 |
| C | 3 | 4 | 3 | 3 | 3 | 3 | 3.17 |
| D | 5 | 5 | 2 | 4 | 5 | 4 | 4.17 |
| E | 2 | 2 | 5 | 1 | 1 | 6 | 2.83 |
| F | 1 | 1 | 1 | 2 | 4 | 1 | 1.67 |

RAA ‘F’ came on top due to three factors: (1) low risk to the environment and to the public’s health and safety posed by the post-VCM residual contamination; (2) zero risk to workers; and (3) zero cleanup costs. RAA ‘A’ was ranked lowest because of: (1) high worker and short-term public risks due to the release of Cr particles into the air during cleanup; (2) potentially high worker risks due to injuries; and (3) high cleanup completion costs.

## 7. Deliberation of integration results

The rankings of the RAAs based on expressed preferences of each member of the SWG were presented in both written and graphical form to the SWG and served as the basis for the deliberation component of the project. Another paper [14] discusses in detail this component. Therefore, we only summarize that paper herein.

The main goal of deliberation was to reach agreement among the stakeholders concerning the preferred RAAs for remediation of the site. The results of the deliberation caused the modification of two of the original RAAs. These modifications were called ‘hybrid RAAs’ because they combined different aspects from the original six RAAs. The hybrid RAAs are summarized in Table 10.

Table 10
Summary of hybrid RAAs

| Hybrid RAA | Description | Changes from original |
|---|---|---|
| $A^+$ | Soil vapor extraction of TCE | No in situ vitrification |
| $F^+$ | Continue with VCMs as indicated in the base assumptions, with the addition of focused soil vapor extraction for the TCE in liquid form | Added action of focused soil vapor extraction on the TCE in liquid form |

The No-Action RAA (RAA 'F') was modified to be a combination of no action for Cr and soil vapor extraction for TCE. This modified RAA was called RAA 'F + '. In general, the SWG disliked the concept of 'no action'; however, they agreed that Cr did not pose a long-term public health and safety risk. Therefore, they were willing to trade off no action with respect to Cr in exchange for removal of the TCE.

The SWG also disliked RAA 'A' as originally described because of the irreversible geological changes that would be caused by in situ vitrification. However, they were willing to accept RAA 'A' if it was modified to replace in situ vitrification with in situ stabilization for the remediation of the Cr. Based on this proposal from the SWG, a modified RAA 'A', called RAA 'A + ', emerged as a strong candidate for the preferred alternative. RAA 'A + ' consisted of in situ stabilization for Cr and soil vapor extraction for TCE.

A comparison between the two hybrid RAAs showed that the major difference between them was no action for Cr in RAA 'F + ' vs. in situ stabilization for Cr in RAA 'A + '. The SWG agreed that the former would be preferable over the latter because:

- With the passage of time, the available evidence indicated that $Cr^{+6}$ would evolve to $Cr^{+3}$, which poses minimal risks; and
- Lower overall costs for cleanup associated with leaving the post-VCM Cr in place.

## 8. Conclusions

The study summarized herein led to a number of conclusions. Various conclusions were reached regarding the development and demonstration of the integrated risk assessment-decision making methodology. Other conclusions specifically pertain to stakeholder involvement in the environmental management decision-making process.

### *8.1. Development and demonstration of the methodology*

The following conclusions were drawn from this study regarding the development and demonstration of the methodology.

- A methodology that allows the integration of multiple risks or impacts, both qualitative and quantitative, in a single framework providing a 'total impact' estimate for each remediation alternative was developed. It captures dependencies among the different impacts that will not be accounted for otherwise.
- A single risk assessment framework for all six risk/impact areas considered was employed that enhanced our ability to integrate all six risk/impact areas.
- Inclusion of uncertainties in the risk assessment, and the manner in which a single global uncertainty analysis can be performed for all impact areas using Monte Carlo simulation was demonstrated.
- The combination of results from multiple risk/impact assessments by defining and using utility functions was demonstrated.
- The consideration of multiple risks/impacts was key to the selection of the preferred alternatives. It reenforced the fact that the implementation of a particular RAA can bring about both positive impacts (e.g. reduction of risk to the public) and negative impacts (e.g. increased worker injuries and costs). Their consideration within a single

framework forces decision makers to weigh the positive benefits against the negative ones, make tradeoffs, and reach informed decisions.

- This methodology allowed the elucidation of how specific inputs — whether they were technical data or stakeholder preferences — influenced the individual or global rankings of the RAAs. This, in turn, provided important feedback to the SWG during deliberation of results, and could be of considerable importance for decision-makers.
- The application of the methodology developed and demonstrated in this project in real cases is iterative in nature. In this project, we performed only the initial iteration of the methodology; however, we demonstrated how the transition from that iteration to the next one would take place. The identification and analysis of the hybrid RAAs constituted this transition. In a real application, refined models and additional data would have been collected for analysis of the hybrid RAAs and the entire process repeated.

### 8.2. Stakeholder involvement

To a large extent the success of the project was due to the key role played by the SWG during the development and demonstration of the methodology. Because this was a research and development project, we had a representative, but not necessarily comprehensive, group of stakeholders assembled in what we have herein referred to as the ‘Stakeholder Working Group’ or ‘SWG’. Our SWG was actively involved in all aspects of the project as described in this paper.

The SWG (1) offered preferences regarding the relative importance of the risk/impact categories, their objectives, and the associated performance measures; and (2) were active participants in the deliberative process that led to the identification of two hybrid RAAs. Both types of input were significant.

Based on feedback from the SWG, the stakeholder involvement in this project was, in general, successful. Notwithstanding this success, one key issue that surfaced numerous times during the project — and still remains unresolved — is a definition of the role of stakeholders vis-à-vis the role of the technical analysts. Every attempt was made in this project to involve stakeholders as much as possible in every aspect of the project. Some members of the SWG thought the analysts were too involved, while others expected more involvement from the analysts as the technical experts in some specific aspects of the project.

This study revealed that the roles of the participants regarding deliberations, goals, and their own individual roles must be explicit and understood by all the participants. The study also showed that there are specific aspects of the environmental management decision making process, in which stakeholders may not want or may not need to be involved in an in-depth manner. How to determine when in-depth stakeholder involvement is warranted is an open issue that should be the subject of further research. Moreover, one of the experiences from this project shows that the level of involvement or the request for detailed information varied among the members of the SWG. Therefore, it was not possible to discern, with any degree of generality, what the appropriate role of stakeholders should be in every specific aspect of a risk-based decision making process.

We can state with confidence that in this project we clearly demonstrated how valuable and critical the input of stakeholders is to the completeness, credibility, defensibility, and efficiency of the environmental management decision making process.

### *8.3. Closing remarks*

In summary, we have developed a risk assessment/risk management methodology for the evaluation and ranking of RAAs at hazardous waste sites that explicitly, and in a traceable manner, incorporates stakeholder inputs. The methodology was successfully demonstrated using data and information from an existing DOE contaminated site. Several innovative concepts were used for eliciting, incorporating, and tracing stakeholder inputs.

This project is one of the first applications of (1) the analytic–deliberative process suggested by the NRC in 1996 [5] for the incorporation of social values into the decision making and (2) the guiding principles recently outlined by the Presidential/Congressional Commission on Risk Assessment and Risk Management in 1997 [6] for environmental risk assessment.

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