A Risk-Based Decision Tool to Support Remediation Decision-Making for Groundwater Contaminated with Chlorinated Solvents

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ABSTRACT

Selection of remediation alternatives for large groundwater plumes containing chlorinated solvents are often complex and difficult, in part because they involve competing objectives, e.g. reduction of health risk vs. increased cost. The Department of Energy (DOE) supported development of a Decision Tool to provide a risk-based process for evaluating and comparing remedial options fairly and consistently. The Decision Tool is also intended to provide a process for constructive discussion of alternatives among the appropriate stakeholders.

To use the Decision Tool, which is implemented in an Excel spreadsheet, a site manager must evaluate each alternative being considered against six objectives using detailed performance metrics. The impacts of each alternative on the individual objectives are combined through a formal multi-attribute utility analysis. Predetermined or user-specified relative weights for the objectives can be used, and a variety of visual outputs are generated.

The usefulness and validity of the Decision Tool was demonstrated through a Pilot Study application for the A-Area Burning Rubble Pits/Miscellaneous Chemical Basin groundwater plume at the DOE Savannah River Site. The Pilot Study results provided a new perspective on the alternatives and objectives by demonstrating: 1) the relatively small public health risks associated with groundwater contamination at this site, 2) that more active approaches had benefits over monitored natural attenuation (MNA) in reducing time required to meet the maximum contaminant level (MCL) and maximizing regulatory responsiveness, 3) that MNA has acceptable public and worker health and safety risks, while enabling a reduction in costs. Use of the Decision Tool also promoted valuable discussion among the various stakeholders, and provided options for sensitivity analyses that can quickly be visualized to assess relative benefits of each of the alternatives.

INTRODUCTION

The U.S. Department of Energy (DOE) Office of Environmental Management (EM) authorized an Alternatives Project at the Savannah River Site (SRS) to develop cost effective and environmentally protective solutions for the challenge of large and complex groundwater plumes of chlorinated volatile organic compounds (cVOCs) at DOE sites. The DOE Monitored Natural Attenuation/Enhanced Attenuation (MNA/EA) for Chlorinated Solvents Project goals include development of new tools for transitioning from active remediation to a protective, long-term monitoring state by achieving a favorable balance between the release of contaminants from sources (source loading) and processes that destroy or retard migration of contaminants in resultant plumes (attenuation capacity) through targeted intervention. The Project also recognized that our ability to predict engineered and natural remediation in the subsurface continues to involve significant challenges. As such, tools that can enhance our ability to evaluate and compare alternative remediation approaches are needed.

Environmental decision-making is a significant challenge, in part because of competing needs and interests ranging from environmental and economic to socio-political. In many instances, comparative risk assessment and cost-benefit analyses are used in some integrated fashion to evaluate remedial alternatives. However, because the evaluation criteria (e.g., safety, risk, environmental impact, and cost) are complex, remedial alternatives cannot be easily compared to one another. Because trade-offs must be made to select a preferred alternative, comparative risk assessments and cost-benefit analyses do not always produce results satisfactory to the various stakeholder interests.

Decisions about the appropriate remediation approach for any given site are influenced by both technical and non-technical factors, such as economics, regulatory requirements and expectations, and stakeholder interests. Decisions specific to transitioning from active to an MNA/EA approach are further complicated by cognitive biases that invest stakeholders in the status quo solution and make them reluctant to modify an approach that seems to be working. The lack of a formal, tested basis for determining whether, when, and how to transition to passive or attenuation-based approaches often results in active remediation being continued longer than is necessary to meet remedial objectives and goals.

The objective of this project was to develop and test a decision tool and process to support responsible decision-making regarding alternative remedial approaches at sites containing groundwater contaminated with chlorinated volatile organic compounds (cVOCs). The primary application for this tool is to support discussion, evaluation, and comparison of alternatives when an existing active remedy is believed to no longer be effective or efficient, and when it may be desirable to transition to a more passive treatment approach; however, it can be applied at any point in time during the lifecycle of a project. The cVOC Tool can be used as a stand-alone decision aid or it can supplement other evaluation methods.

Interest in exploring alternative remedial approaches may be prompted by a variety of events, such as:

- discovery of previously unknown contamination;

- findings from periodic review of ongoing remediation activity outside of the anticipated performance of the system, e.g.,
    - active pump and treat systems yielding diminishing marginal returns;
    - monitoring results for an MNA solution not demonstrating the anticipated decrease in concentrations over time;
    - technical information suggesting that other remedies may be more effective and less costly than the ongoing remedy.

DESCRIPTION OF THE cVOC TOOL

The cVOC Tool is based upon a structured analytic approach for comparing alternatives, involves a well-defined process for applying that approach, and is implemented through an easy-to-use Excel spreadsheet. The analytic approach is a proven, rigorous, and technically defensible method known as multi-attribute utility analysis (MAU), which is part of the practice of Decision Analysis (DA). DA is specifically designed to promote consistent and rational decision making in the face of technical complexity, significant uncertainties, and multiple, competing objectives. MAU helps the decision-maker balance competing objectives through application of value judgments reflecting the tradeoffs the decision-maker is willing to make between those objectives.

The MAU process is straightforward, although there is considerable flexibility in the scope and role of different stakeholder groups. To apply the process, a user (who e.g., the site remediation manager, regulatory-agency staff, a public stakeholder group, or some combination) will follow these steps:

- describe site characteristics and conditions;
- identify and specify a set of alternatives to be considered for the site;
- evaluate how well each alternative is expected to perform, using the objectives and performance metrics specified within the cVOC Tool;
- compare the evaluated alternatives using different techniques with a variety of visual outputs that are generated automatically:
    - comparison and consequences tables;
    - relative value of the alternatives using any of the value judgments built into the tool;
    - relative value of the alternatives using value judgments the user specifies.

The cVOC Tool recognizes that both technical and management value judgments are a necessary part of decision making and that different people may have different roles in the decision-making process. When no single alternative dominates the others (i.e., when no alternative is better than all others on all criteria), the management value judgments can be used to translate the evaluation on diverse criteria into a common, dimensionless scale of value. Decision makers can then compare disparate alternatives consistently and transparently.

Steps in Developing an MAU Model

There are three basic steps in developing a multi-attribute utility (MAU) model for a specific decision problem:

- ***Identify the fundamental objectives of the decision makers and/or the stakeholders.*** These objectives represent the basic reasons why people care about the problem being considered, and the ultimate goals that an “ideal” decision or alternative would accomplish.

- ***Develop performance metrics for each objective.*** Objectives are defined at a relatively high level: performance metrics specify how those objectives can be used to evaluate specific alternatives. Performance metrics are much more detailed than objectives, and are sometimes referred to as “scoring scales,” because they are used to “score” the alternatives on the objectives.

- ***Specify necessary value functions*** to allow quantification of the value of each alternative. Management value judgments include judgments about the relative value of improving on a single objective (e.g., is it more important to reduce the time to closure from 100 years to 50 years, or from 50 years to 1 year?), and about the relative value of improvements on one objective relative to another (e.g., is it more important to reduce the time to closure from 100 years to 50 years, or to reduce the total costs of the remediation from $50 million to $30 million?)

Objectives

The cVOC Tool includes six objectives that are broadly applicable for managing and remediating cVOC plumes at any site, but which are also detailed enough to allow for consistent and logical evaluation of alternatives. An ideal alternative would accomplish all of the following objectives:

- minimize public health and safety risks
- minimize risk to worker safety
- minimize adverse environmental impacts
- maximize regulatory responsiveness
- minimize total cost, and
- minimize time to completion.

Performance Metrics

Performance metrics are a consistent set of measurement scales used to evaluate how well a specific alternative will meet a given objective. Performance metrics must accurately reflect the meaning of the fundamental objective and be defined in such a way that they are feasible to use. They should be clear and unambiguous, so that different individuals can interpret them consistently. The cVOC Tool performance metrics are designed to allow use of whatever type of information is available, from expert judgment to numerical modeling results.

Natural metrics exist for some of the objectives, and where such metrics exist, they are used. For example, cost is measured in dollars, and time to completion is measured in years. For other objectives, no natural metrics exist and special scales have been constructed.

Public health and safety. For cVOC groundwater plumes, the main human health risk concern is that people may be exposed to elevated levels of VOCs in groundwater through ingestion, inhalation, or dermal contact. The impact on public health and safety is a function of several factors:

- likelihood of exposure (likelihood that anyone will be exposed to contaminants via the exposure pathway being evaluated);
- number of people potentially exposed via that pathway;
- timing of exposure;
- risks to those individuals, if they are exposed. This in turn is a function of:
  - likelihood of health impact, assuming exposure occurs, and
  - severity of the effect, assuming it occurs.

Worker health and safety. In evaluating risks to site remediation workers, users are asked to consider all potential pathways and mechanisms by which workers could be exposed to risks, and identify the most likely worker risk pathway. Examples of potentially relevant worker risks include:

- occupational injuries associated with construction activities,
- transportation-related risks associated with driving (e.g., transporting equipment and/or materials to and from a job site; driving to and from sampling locations required for long-term monitoring),
- inadvertent exposures to contaminants while conducting maintenance or monitoring activities.

Risk to worker safety is a function of three factors:

- likelihood of worker injury or illness;
- number of workers potentially affected; and,
- severity of effect or seriousness of the most likely injury, assuming such injury occurs.

Impact on the environment. The overall impact on the natural environment is a function of:

- type of environmental resources potentially affected;
- likelihood of an adverse impact on those resources;
- severity and duration of the impact.

To evaluate the impact on the environment, the user must first indicate what types of environmental resources might be affected by the contaminant plume, using a list of potential sensitive resources provided, and then use the performance metrics to estimate the likelihood and severity of the impact on each of the identified environmental resources.

Regulatory responsiveness. To be considered viable, an alternative must comply with all applicable regulatory requirements. Although all viable alternatives are compliant, there may be a difference in how each alternative is perceived by the regulators, and how responsive to regulatory concerns they believe the alternative to be.

The scale for the Regulatory Responsiveness performance metric is used to estimate the degree to which an alternative will be seen as responsive to regulatory concerns.

Time to completion. Time to completion is defined as the time at which further action aimed specifically at the site or problem being addressed will no longer be required. This includes any ongoing monitoring. The time to completion is often identified as the time at which contaminant concentrations in the groundwater are consistently below regulatory maximum contaminant limits. Time to completion is estimated in years, although the performance metric also accommodates uncertainty in the time required to reach closure.

Costs. The final objective is to minimize total costs to reach completion for the problem being evaluated. Users are asked to provide an estimate of the total costs for the alternative being considered, assuming the alternative is implemented and continues through the end of the “time to completion” as defined above. Total costs include capital costs, operations and maintenance costs, and costs associated with any ongoing monitoring.

The estimated costs for any alternative are expected to be uncertain, and the level of uncertainty about the total cost may be a relevant factor in decision-making. Scales for estimating the potential for both cost overruns and under-runs are provided in the tool.

Value Judgments

In addition to evaluating how an alternative performs for each performance metric, two types of management value judgments are required to calculate a MAU value for an alternative: single-attribute scaling functions and multi-objective value weights. Both types of value judgments reflect the relative value to a decision-maker of improvements in the alternatives. Single-attribute scaling functions quantify the benefit of improvements within a single objective, while multi-objective value weights quantify the tradeoffs a decision-maker is willing to make amongst the objectives.

Single-attribute scaling functions are used to quantify the importance or value of changes within a single objective. For example, an alternative that reduces the time to reach closure from 100 years to 5 years is a better alternative than one that reduces the time to reach closure from 100 years to 50 years. All scaling functions are defined so that higher risks are indicated by higher values, and thus, alternatives with lower “risk scores” are preferred.

Public health and safety. The impact of an alternative (A) on public health and safety is evaluated using five metrics:

1) likelihood of exposure (p_e),
2) number of people exposed (n),
3) likelihood of an adverse health effect occurring given exposure ($p_{effect|exposure}$),
4) time at which those effects would occur (t), and
5) a scale describing the severity of the health impact, if one occurs (S_{PHS}).

The risk to public health and safety if alternative A is implemented and if the health impacts are assumed to occur within the next 5 years ($R_{PHS,\ t<5}$), is calculated as:

$$R_{PHS,\ t<5}\ (A) = p_e * p_{effect|exposure} * n * V(S_{PHS}) \qquad \text{(Eq. 1)}$$

where $V(S_{PHS})$ is a scaling function defined on the metric for the severity of health impacts, as shown in Figure 1. By convention, the "worst" outcome is assigned a value of 100 (highest risk), and the "best" outcome is assigned a value of 0 (lowest risk). This scaling function indicates that the value of reducing the severity of an anticipated health effect from a "serious" effect to a "moderate" effect is much greater than the value of reducing the severity of a health effect from "moderate" to "temporary and minor."

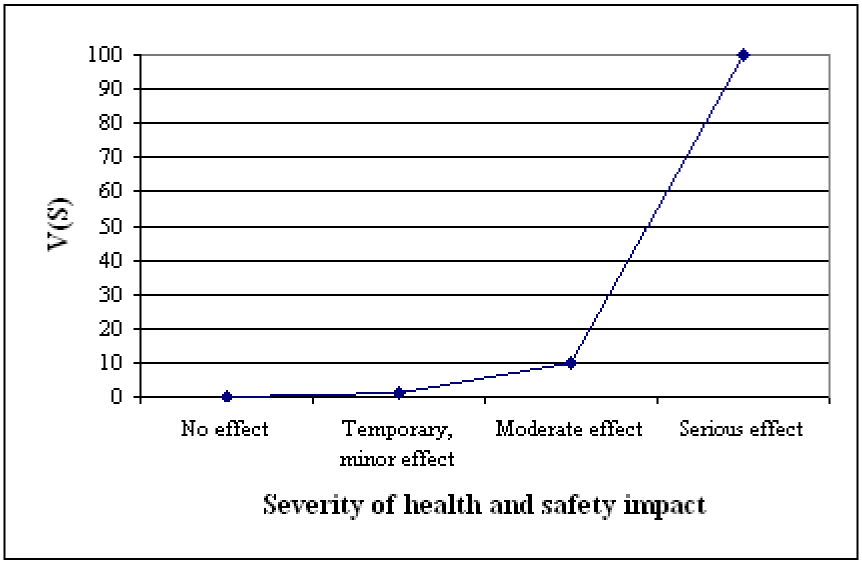

Figure 1. Scaling function indicating relative value of reducing severity of public health and safety impacts

Worker health and safety

The impact of an alternative on worker health and safety is evaluated using three metrics:

1) likelihood of worker injury/injuries (p_{wi}),
2) number of workers at risk (n_w), and
3) a constructed scale describing the severity of the health impact, if one occurs (S_{WS}).

The risk to worker safety value [R_{WS} (A)] if alternative A is implemented is calculated as:

$$R_{WS}(A) = p_{wi} * n_w * V(S_{WS}) \quad \text{(Eq. 2)}$$

where $V(S_{WS})$ is a scaling function defined on the metric for the severity of worker safety impacts.

Impact on the environment

The seriousness of the impact of an alternative on the environment is a function of the:

- environmental resources affected [r]
- relative value associated with avoiding or eliminating impacts on each type of resource [Vr]
- likelihood of adverse impacts on those resources [$p_{ei,r}$]
- a value function for the severity of those impacts [$V(S_{E,r})$].

The risk to the natural environment [R_E (A)}if alternative A is implemented is calculated as the sum of the impacts on each affected environmental resource:

$$R_E(A) = \sum_r (Vr * p_{ei,r} * V(S_{E,r}) \qquad \text{(Eq. 3)}$$

There is a wide range of opinions on the relative value of eliminating impacts on various environmental resources, and the tool includes the option for the user to modify these relative resource values to better match local values and conditions.

Regulatory responsiveness

The regulatory responsiveness of an alternative is evaluated using a single performance metric, and the value associated with improving from one level of impact to another is taken directly from the scaling function.

Time to completion

Time to completion is evaluated using a single performance metric in terms of years to closure. The value associated with reducing the time required to reach closure is assumed to be in direct proportion to the reduction in years. For each scale descriptor, the mid-point of the range of years is used, and the value function for time to completion (R_t) is linear in years, reflecting a judgment that the value of reducing the time to completion from, say, 50 years to 40 years is the same as the value of reducing the time to completion from 20 years to 10 years. If the user has preferences for reducing time to completion that are significantly different from linear in years, an option is available for the user to modify this function.

Total estimated costs

In translating the total estimated costs into a value that can be combined with the values for the other objectives, both the total cost estimate and the uncertainty in the estimated total costs are used. Remediation costs are often thought to follow a lognormal distribution, where there is the potential, though small, for costs to far exceed the best estimate. The value associated with the cost estimate for Alternative A [$R_{c(}$A)] is calculated by assuming that the total estimated cost value represents what the user believes will be the most likely cost, and the low and high cost estimates represent the 10^{th} and 90^{th} percentiles of a probability distribution on total costs. The mean value of the distribution is then calculated assuming the cost probability distribution is lognormal and used in the overall value calculation.

Multi-attribute value weights

The second set of management value judgments are judgments about the importance of improvements on one objective relative to the others. The establishment of weights for each of the objectives results in a consistent evaluation of the alternatives. There are, however, no universally applicable weights that should necessarily be used for all sites under all conditions; the weights represent judgments by the responsible decision-makers about the tradeoffs they consider to be appropriate for their situation, and are typically the result of considerable discussion.

To facilitate evaluation and comparison of alternatives, the cVOC Tool includes three sets of weights specified to represent various stakeholder viewpoints. There is also an option for the user to specify his/her own set of weights. By performing the evaluation using the three sets of specified weights and also setting his own weights, the user can assess the results from multiple viewpoints, which will provide useful information about sensitivity of the results.

The three sets of weights were selected to represent three different viewpoints:

- *Weight Set 1*
    - places high value on reducing risks to public health and worker risks;
    - balances those values against costs in a manner consistent with values derived from a wide range of studies of tradeoffs implied in public spending and federal regulation[1].
- *Weight Set 2*
    - increases the value on reducing risks to public health and worker safety, and reducing adverse environmental impacts, by a factor of 10 over Weight Set 1;
    - places strong emphasis on risk reduction over any of the other objectives.
- *Weight Set 3*
    - places high value on regulatory responsiveness and decreasing time to closure;
    - tradeoffs between reducing public and worker risks and cost reduction are similar to that in Weight Set 1, but the values on improving regulatory responsiveness and reducing time are increased by a factor of five.

Table I shows the three sets of weights specified in the cVOC Tool.

Calculating an MAU value

The final step in the evaluation process is to calculate a single measure of value that represents all of the objectives for each of the alternatives, thus enabling an overall comparison among the alternatives. This step combines the technical judgments of knowledgeable site experts, encoded as the evaluation of the alternatives using the performance metrics with the management value judgments encoded in the cVOC Tool or provided by the responsible decision makers.

The objectives were selected to meet a special independence criterion known as preferential independence[2], which allows a simple additive form for calculating the value of an alternative, A:

$$V(A) = W_{PHS}*R_{PHS}(A) + W_{WR}*R_{WR}(A) + W_E *R_E(A) + W_R*R_R(A) + W_C *R_C(A) + W_T *R_T(A) \quad \text{(Eq. 4)}$$

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[1] Based upon OMB Circular A-4 [1], the willingness to pay for reductions in small risks of premature fatality, expressed as the "value of statistical life" from a broad range of studies, is between $1 million and $10 million. The weights used here represent a "value of statistical life" of $5 million.

[2] Objectives are preferentially independent if the value of improvements within an objective do not depend on the level of any other objective, as viewed by the decision maker. For example, if the value of reducing environmental impacts from a moderate to a low level is the same regardless of whether the alternative will lead to completion in 10 or 20 years, the two objectives are said to be preferentially independent.

Where the W’s represent the weights on each objective, and the R’s represent the single attribute value functions for each objective.

Table I. Three Alternative Sets of Weights Represented in the Decision Tool.

	What is the relative value of improving from this level of performance…	…to this level of performance	Weight set 1	Weight set 2	Weight set 3
Maximize public health and safety, minimize worker risks	Chances are likely (1 chance in 10) that about 1000 people will be exposed to elevated levels of contamination within the next 5 years. If such exposures occur, health effects are relatively likely (about 1 chance in 100), and such health effects will be serious.	Chances of exposure to elevated levels of contamination are about 1 in a million. If exposures occur, only 1-2 people will be exposed and such exposures will be more than 500 years in the future. Health effects from the exposure are extremely unlikely (1 chance in a million), and such health effects will be minor and temporary.	25	250	25
Minimize adverse environmental risks	There is about a 50% chance that a highly valued environmental resource, such as habitat for a threatened or endangered species will suffer a severe level of impact (i.e., widespread and potentially permanent) due to contamination from the site.	There is less than a 10% chance that valued environmental resources suffer any adverse impacts due to contamination from the site. If such impacts occur they will be minor and self-correcting within a year.	12.5	125	12.5
Maximize regulatory responsivene	The current solution is viewed as marginally responsive to regulatory concerns	The proposed solution will be viewed as highly responsive to regulatory concerns	10	10	50
Minimize time to completion	The time to reach completion for the site is estimated to be about 100 years	Completion is expected within 5 years	10	10	50
Minimize total estimated costs	The estimated discounted total cost to reach completion for the site is about $10 million	The estimated discounted total cost to reach completion for the site is about $5 million	25	25	25

APPLYING THE cVOC TOOL

There are five steps to applying the cVOC Tool.

- ***Identify alternatives to be evaluated***. Alternatives describe what can be done to remedy the contamination at a site. They need to be identified by the decision-maker or other user, and defined with sufficient clarity that they can be evaluated.

- ***Evaluate how well each alternative meets the objectives.*** The performance metrics are used to evaluate (or "score") expected performance of each alternative. Where significant uncertainties that may affect performance of several alternatives exist, separate evaluations for different future states of the world may be necessary.

- ***Review consequence table***. The inputs can be summarized in a "consequence table," which compares the alternatives on each of the objectives, based on the scores provided by the evaluation team. There are two typical uses of the consequence matrix. The first is to look for dominant or dominated alternatives; if an alternative exists that is better than another on all objectives, the latter alternative need not be considered further. The second use is to stimulate creative thinking about new alternatives.

- **C*alculate a value for each alternative (if necessary).*** If a dominated alternative does not exist, alternatives can be compared by using the evaluation and value judgments to calculate a value for each alternative. Once the evaluation step is completed, a value for each alternative is calculated and the alternatives can be compared in terms of their calculated values. This provides a single metric that can be used to compare alternatives on a consistent basis.

- ***Conduct sensitivity analyses.*** Model outputs depend, of course, on model assumptions and inputs. In cases where the user is uncertain about the evaluation of a given alternative, they may wish to conduct the evaluation with several different scores for that alternative. Other key model assumptions are the scaling functions and weights on the objectives. The cVOC Tool has alternative sets of weights built in, and results under different weight sets should be considered and compared.

Recommended sensitivity analyses include:

- Compare the alternatives one objective at a time: this allows the user to see the relative "value" of each alternative from a single perspective, and is equivalent to giving all other objectives zero weight.
- Compare the relative value of the alternatives using the three built-in weight sets. In some cases, the best alternative might not vary with the different weights. If the three sets span or encompass the value judgments of the decision-makers for the site, then selection of a single set of weights might not be necessary.
- Consider whether the evaluation team wants to define alternative value functions or an alternative set of weights to calculate the value of each alternative.

THE PILOT TEST

Site Description

A pilot test of the cVOC Tool was conducted using the A-Area Burning Rubble Pit/Metals Burning Pit and Miscellaneous Chemical Basin (ABRP/MBP/MCB) Operable Unit (OU) at the DOE Savannah River Site (SRS) in South Carolina. The pilot test is recognized as only a test of the cVOC Tool, and does not imply any regulatory acceptance of the results in term of final remediation actions for the site.

The site is underlain by Atlantic Coastal Plain sediments in a southeast-dipping wedge of sands, silts, and clays. Groundwater flows easily through the sand layers, but is retarded by less permeable clay beds, creating a complex system of aquifers. Groundwater contamination under the ABRP/MCB/MBP OU is found in the M-Area aquifer zone (MAAZ) and in the deeper Lost Lake aquifer zone (LLAZ) [2]. Depth to the water table is approximately 150 feet. Flow is principally vertically downward from the MAAZ to the LLAZ. The cVOC groundwater plume is approximately one mile in length in the LLAZ. Measured concentrations in 2005 are significantly lower than in previous years, with a maximum concentration less than 500 µg/l.

Final source control actions, including soil vapor extraction, excavation, and capping have been completed or will be expanded as part of the CERCLA final Record of Decision. An interim action for groundwater (three lines of recirculation wells) has been operating in the LLAZ since 2002.

The Evaluation Process

One of the key components of the remedial evaluation process using the cVOC Tool was involvement of the South Carolina Department of Health and Environmental Control (SCDHEC) regulators. After the meeting with SCDHEC, the project team met for about five hours to conduct a preliminary evaluation, which included: 1) selection of alternatives to be considered, 2) use of the metrics to evaluate the alternatives, 3) review of preliminary results, and 4) conduct of sensitivity studies. Because an FS had been conducted for the site, a strong data base, including groundwater modeling predictions of time to cleanup and detailed cost estimates, was available to support the evaluation.

The alternatives considered were a modified sub-set of those used in the CERCLA FS plus one additional alternative, that of continuing with current operations. The sub-set of alternatives from the CERCLA FS was modified to reflect the improvement in water quality that has occurred since the FS evaluation. As such, the treatment target was lowered from100 µg/l to 50 µg/l and alternatives with 500 µg/l treatment targets were not included. All alternatives, except for "No Action," include institutional controls and groundwater monitoring. Nine alternatives were considered for the Pilot Test evaluation:

- No action (stop interim treatment, no institutional controls, no monitoring)
- Continue with operation of current recirculation wells to 50 µg/l
- MNA in LLAZ and MAAZ
- Active treatment to 50 µg/l in the LLAZ, MNA in the MAAZ and residual LLAZ
    - Groundwater recirculation (new wells to be installed)
    - Chemical oxidation

  - Permeable reactive barrier
- Active treatment to 50 µg/l in the LLAZ and MAAZ and MNA in residual
  - Groundwater recirculation in the LLAZ and MAAZ
  - Chemical oxidation in the LLAZ and groundwater recirculation in the MAAZ
  - Permeable reactive barrier in the LLAZ and groundwater recirculation in the MAAZ.

Evaluation Results

The results of the evaluation were provided in a consequence table and displayed separately for each of the objectives. Because no one alternative was preferable for all of the objectives, an evaluation was performed using the three sets of multi-attribute weights to compare the alternatives. Figure 2 illustrates the overall value calculated for each alternative using Weight Set 1. Contributions from each objective are color coded, so that it is easy to see what the largest contributors to the calculated value are. Lower values indicate lower overall "risk," and thus are preferred. The preferred alternative under Weight Set 1 is MNA in the MAAZ and LLAZ.

With greatly increased weight on minimizing health, safety, and environmental risks (Weight Set 2), groundwater recirculation in the LLAZ to 50 ppb and MNA in the residual plume becomes

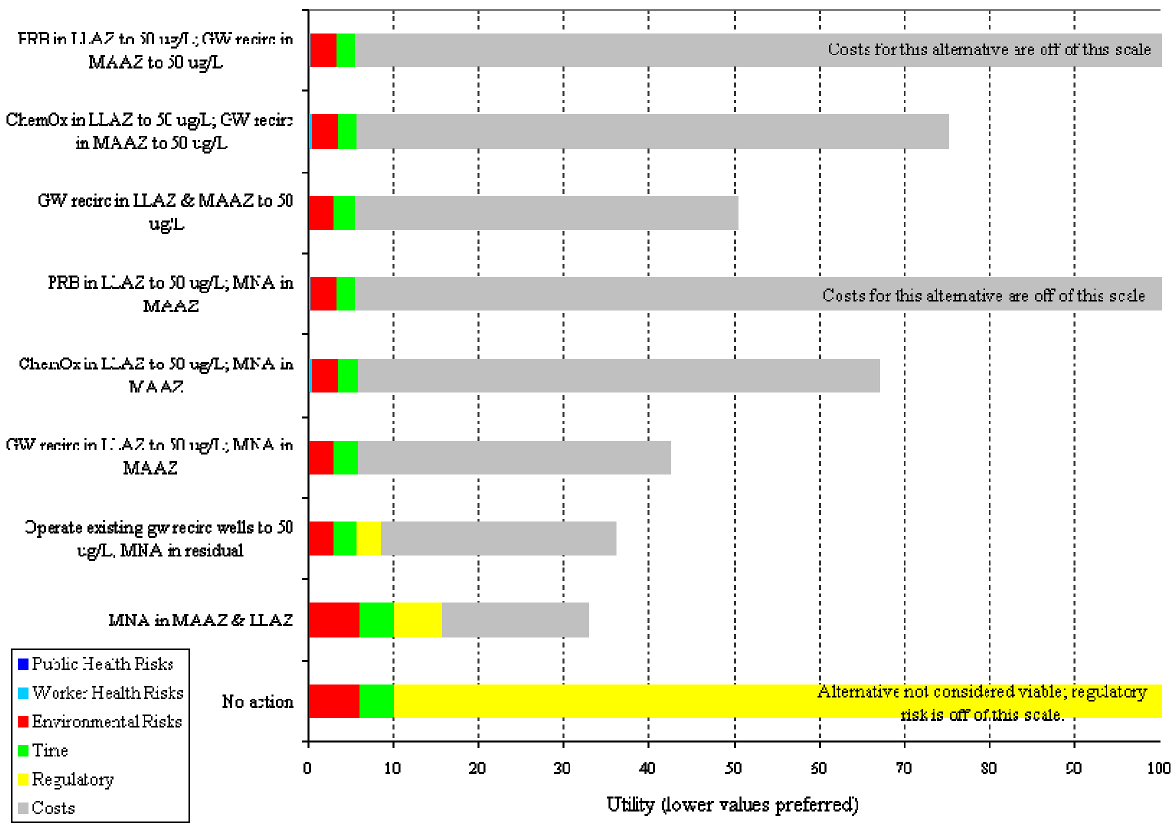

Figure 2. Comparison of pilot test alternatives incorporating all objectives, using Weight Set 1

marginally preferred over 1) MNA in the MAAZ and the LLAZ and 2) groundwater recirculation in the LLAZ and MAAZ. It is preferred over MNA, because it reduces the environmental impact sooner, and it is preferred over groundwater recirculation in both aquifers, because it is less costly and delivers the same benefits. With increased weight on minimizing time to completion and maximizing regulatory responsiveness (Weight Set 3), groundwater recirculation in the LLAZ to 50 ppb and MNA in the MAAZ and residual plume becomes preferred by a small amount over groundwater recirculation in the LLAZ and MAAZ. The relative advantage of this alternative under this weight set is that it is perceived to be more responsive to regulatory concerns.

Sensitivity analyses

The primary sensitivity analyses of interest to the evaluation team were those described above – the comparison of alternatives using different sets of weights. Several other questions arose, however, suggesting additional sensitivity analyses might be useful. These included:

- Sensitivity to estimated impact on public health and safety. To address reviewer concerns that the Decision Tool was insufficiently sensitivity to public health and safety risks, the team evaluated a hypothetical situation in which baseline risks to public health and safety were assumed to be significantly higher than for the pilot study site. In this case, the reduction in health and safety risks associated with each alternative became a driving factor in the overall comparison.
- Sensitivity to potential overlap between objectives. For the Pilot Study, the evaluation of reduction in environmental impacts and the evaluation of time to completion were based on the same fundamental evaluation – the time required for groundwater to reach MCLs. This lead to the potential for "double counting" of those impacts. The team eliminated the possibility of double counting by setting the weight on time to completion to 0. In this case, the relative comparison of the alternatives was unchanged.
- Sensitivity to changes in management preferences for time to completion. Finally, the team wanted to consider what impact, if any, a significant change in the value function for time to completion would have on the results. They suggested a threshold type time preference – where the most benefit is derived from reducing the time to completion from more than 30 years to less than 30 years. This was implemented by using the option available in the cVOC Tool to modify the time to completion value function: 70% of the total benefit available for reducing time to completion was place on reducing the time from "about 50 years" to "10 to 20 years." This maximized the distinction between alternatives on the time to completion criterion, but did not change the overall ranking of alternatives.

REFERENCES

[1] OMB Circular A-104, http:www.whitehouse.gov/omb/circulars/a004/a-4.pdf, September 2003.

[2] Westinghouse Savannah River Company (WSRC), Statement of Basis/Proposed Plan for the A-Area Burning/Rubble Pits (731-A, -1A) and Rubble Pit (731-2A) and the Miscellaneous

Chemical Basin/Metals Burning Pit (731-4A, -5A) Operable Unit (OU), WSRC-RP-2005-4054, August 2005.