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PRELIMINARY ANALYSIS OF ALTERNATIVES FOR THE LONG TERM MANAGEMENT OF EXCESS MERCURY

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NOTICE

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FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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Hugh W. McKinnon, Director
National Risk Management Research Laboratory

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ACRONYMS AND SYMBOLS

AHP	Analytical Hierarchy Process
BNL	Brookhaven National Laboratory
CBD	Commerce Business Daily
DLA	Defense Logistics Agency
DNSC	Defense National Stockpile Center
DoD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
ETC	Environmental Technology Council
FAA	Federal Aircraft Administration
g	grams
GSA	General Services Administration
lb	pounds
LDR	Land Disposal Restrictions
LS	Liquid to Solid Ratio
mEq	milli-equivalents
mV	milli-volts
MMEIS	Mercury Management Environmental Impact Statement
NEI	Nuclear Energy Institute
ORD	Office of Research and Development
OSW	Office of Solid Waste
PBT	Persistent, Bio-accumulative, and Toxic
RCRA	Resource Conservation and Recovery Act
S/A	Sulfide/Amalgamation
SAIC	Science Applications International Corporation
SEK	Swedish Kroner
SPSS	Sulfur Polymer Solidification/Stabilization Process
TCLP	Toxicity Characteristic Leaching Procedure
TLV	Threshold Limit Value
USACE	US Army Corps of Engineers
UTS	Universal Treatment Standard
VA	Veterans Administration
WIPP	Waste Isolation Pilot Plant

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EXECUTIVE SUMMARY

This report is intended to describe the use of a systematic method for comparing options for the retirement of excess mercury. The results are presented in Section S.6 of this summary with conclusions and recommendations in Section S.7. Sections S.1 through S.5 discuss the background, approach and assumptions.

S.1 Background

Over the past decade, the Environmental Protection Agency (EPA) has promoted the use of alternatives to mercury because it is a persistent, bio-accumulative, and toxic (PBT) chemical. The Agency's long-term goal for mercury is the elimination of mercury released to the air, water, and land from anthropogenic sources. The use of mercury in products and processes has decreased. The Department of Defense (DoD) and the Department of Energy (DOE) have excess mercury stockpiles that are no longer needed. Mercury cell chlor-alkali plants, although still the largest worldwide users of mercury, are discontinuing the use of mercury in favor of alternative technologies. In EPA, the Office of Solid Waste (OSW), working with the Office of Research and Development (ORD) and DOE, is evaluating technologies to permanently stabilize and dispose of wastes containing mercury. Furthermore, OSW is considering revisions to the Land Disposal Restrictions (LDRs) for mercury. Therefore, there is a need to consider possible retirement options for excess mercury.

S.2 Approach

The approach chosen for the present work is the Analytical Hierarchy Process (AHP) as embodied in the Expert Choice software[1]. AHP was developed at the Wharton School of Business by Dr. Thomas Saaty and continues to be a highly regarded and widely used decision-making tool. The AHP engages decision-makers in breaking down a decision into smaller parts, proceeding from the goal to criteria to sub-criteria down to the alternative courses of action. Decision-makers then make simple pairwise comparison judgments throughout the hierarchy to arrive at overall priorities for the alternatives. The decision problem may involve social, political, technical, and economic factors. The AHP helps people cope with the intuitive, the rational and the irrational, and with risk and uncertainty in complex situations. It can be used to: a) predict likely outcomes; b) plan projected and desired futures; c) facilitate group decision making; d) exercise control over changes in the decision making system; e) allocate resources; f) select alternatives; and g) perform cost/benefit comparisons.

S.3 Sources of Information

The principal sources of information that were consulted to obtain data for this study are as follows.

Canadian Study: SENES Consultants (SENES, *The Development of Retirement and Long Term Storage Options of Mercury*, prepared for Environment Canada, 2001) has produced a draft report

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[1] Information on the Expert Choice software can be found at www.expertchoice.com. Most of the material about Expert Choice in this Executive Summary and in Section 1.2 of the main report is abstracted from that Web site.

for Environment Canada on the development of retirement and long-term storage options for mercury. The report provides comprehensive identification of the range of technologies that are potentially available for mercury storage or retirement, together with a wealth of references.

Mercury Management Environmental Impact Statement: The Defense Logistics Agency (DLA) is currently preparing a Mercury Management Environmental Impact Statement (MMEIS). In 2001, DLA published *Commercial Sector Provision of Elemental Mercury Processing Services – Request for Expressions of Interest* in the Commerce Business Daily (CBD). This announcement solicited expressions of interest in providing technologies for the permanent retirement of 4,890 tons of elemental mercury from the national stockpile. Five expressions of interest were received and, to the extent that this information is non-proprietary, it has been used in the present work. In addition, the MMEIS project has assembled a long list of references on mercury treatment.[2]

Mercury Workshop: EPA has prepared the proceedings of the mercury workshop that was held in March 2000 in Baltimore, Maryland. This workshop covered: a) the state of the science of treatment options for mercury waste; and b) the state of the science of disposal options for mercury waste, such as landfill disposal, sub-seabed emplacement, stabilization, and surface and deep geological repositories for mercury waste storage.

Other US EPA and US DOE Activities: For several years, both EPA and DOE have been evaluating the performance and feasibility of mercury treatment technologies. DOE has published various Innovative Technology Summary Reports that evaluate the treatment technologies applicable to mercury containing mixed wastes (i.e., wastes that are both hazardous and radioactive). The reports include environmental performance testing, cost information, and other operations information. In addition, EPA has conducted performance testing of mercury-containing wastes processed by various treatment technologies. Performance testing in these studies has involved both comprehensive analytical testing and standard Toxicity Characteristic Leaching Procedure (TCLP) tests.

S.4 Limitation of Scope

The resources available for this project required that the scope be limited to manageable proportions. To this end, certain ground rules and simplifications were developed:

- Industry-specific technologies are excluded on the grounds that they can only manage a small fraction of the total mercury problem and in any case should be regarded as an integral part of that specific industry's waste management practices
- The study focuses on options for retirement of surplus bulk elemental mercury on the grounds that: a) this alone is a large enough project to consume the available funding; b) that it anyway addresses a large fraction of the problem; and c) that it will provide an adequate demonstration of the decision-making technique that can readily be expanded in the future. Thus, for example, the treatment of wastewater streams is excluded.
- The chemical treatment options are limited and are chosen to be representative of major classes of treatment options, such as metal amalgams, sulfides, or selenides. The choice is to some extent driven by available information. If the decision analysis favors any one class of options, then in principal it will be possible later to focus on individual

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[2] Note that, in its MMEIS, the DLA is expected to analyze only three alternatives in detail: 1) consolidation and storage at one or more of the current mercury storage sites or other suitable locations, 2) sale of the mercury inventory, and 3) no action, maintaining storage at four existing sites. (Lynch 2002)

technologies within that class and perform a further decision analysis to choose between individual technologies.
- Only technologies that can in principal treat contaminated media as well as elemental mercury are considered. This compensates to some extent for the decision to focus on elemental mercury.
- Retorting is excluded as merely being a well-established prior step for producing elemental mercury, some of which may end up in the pool of surplus mercury
- Deep-sea disposal is excluded because obtaining the necessary modifications to international laws and treaties is regarded as too onerous a task
- Storage in pipelines is excluded because the project team could not find information about this option.

As a result of the above-described ground rules and simplifications, two types of treatment technologies were evaluated: sulfide/amalgamation (S/A) techniques and the mercury selenide treatment process. The S/A techniques were represented by: a) DeHg® amalgamation; b) the Sulfur Polymer Solidification/Stabilization (SPSS) process; and c) the Permafix sulfide process. These were grouped as a single class because they have very similar characteristics when compared against the criteria defined by the team (comprised of SAIC staff) and modeled in Expert Choice. Therefore, only these two general types of treatment technologies were evaluated. These were combined with four disposal options: a) disposal in a RCRA-permitted landfill; b) disposal in a RCRA-permitted monofill; c) disposal in an engineered belowground structure; and d) disposal in a mined cavity. In addition, there are three storage options for elemental mercury: a) storage in an aboveground RCRA- permitted facility; b) storage in a hardened RCRA-permitted structure; and c) storage in a mined cavity. Altogether, eleven options were chosen for examination with the decision-making tool:

- Storage of bulk elemental mercury in a standard RCRA-permitted storage building
- Storage of bulk elemental mercury in a hardened RCRA-permitted storage structure
- Storage of bulk elemental mercury in a mined cavity
- Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill
- Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill
- Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker
- Stabilization/amalgamation followed by disposal in a mined cavity
- Selenide treatment followed by disposal in a RCRA- permitted landfill
- Selenide treatment followed by disposal in a RCRA- permitted monofill
- Selenide treatment followed by disposal in an earth-mounded concrete bunker
- Selenide treatment followed by disposal in a mined cavity

Several of the more critical assumptions made in compiling these options include the following:

(1) The project team considered storage to be temporary. As a result, costs were considered as those associated with storage itself (e.g., initial costs and operating costs), as well as projected costs for subsequent treatment and disposal when storage is terminated. As is demonstrated in the sensitivity analyses in Table S-1 and Section 4.0, this is an assumption that has an important effect on the ranking of the storage options.

(2) Storage, treatment, or disposal of the mercury was assumed to require RCRA-permitting. There is uncertainty as to whether local and federal environmental authorities would require such permitting for all management steps; this is a conservative assumption. This is further discussed in Section 3.1.1 of this report.

(3) No distinction is made between individual stabilization and amalgamation technologies. As a result, the model is intended to identify the relative preference of this management

technique to other options rather than assessing the performance of individual treatment technologies.

S.5 Goals, Criteria and Intensities

Expert Choice requires the definition of a goal, criteria, and intensities. The goal in this case is simple, namely to "Select the best alternatives for mercury retirement." The team[3] developed two first-level criteria, benefits and costs. Initially, equal weights were assigned to them. This is a simple example of the pairwise comparison that is performed at every level in the hierarchy of criteria developed as input to Expert Choice.

Under costs, two-second level criteria were developed, implementation costs and operating costs. For each retirement option, the team then asked, whether the implementing costs would be low, medium, or high, and whether the operating costs would be low, medium, or high. These assignments of low, medium, or high are examples of intensities. Section 3 of the report explains in detail how the costs associated with each retirement option were determined, although this is an area in which there is considerable uncertainty.

Six second-level criteria were developed under the heading of benefits. Some of the second-level benefits were further split into third-level criteria. Intensities were then assigned to each of the lowest-level criteria. The six second-level criteria and associated sub-criteria are listed below. The figures in parentheses give the weights assigned to each of the criteria and sub-criteria using the process of pairwise comparison which is at the core of AHP (see Appendix A of the main report). Thus, it can be seen that, of the six second-level criteria, the analysts judged that environmental performance (0.336) and risks (0.312) are the most important. At the second level, the weights add to one. At each sub-criterion level, the weights are determined independently and also add to one.

- Compliance with Current Laws and Regulations (0.045)
- Implementation Considerations (0.154)
  - Volume of waste (0.143)
  - Engineering requirements (0.857)
- Maturity of the Technology (0.047)
  - State of maturity of the treatment technology (0.500)
  - Expected reliability of the treatment technology (0.500)
- Risks (0.312)
  - Public risk ((0.157)
  - Worker risk (0.594)
  - Susceptibility to terrorism/sabotage (0.249)
- Environmental Performance (0.336)
  - Discharges during treatment (0.064)
  - Degree of performance testing of the treatment technology (0.122)
  - Stability of conditions in the long term (0.544)
  - Ability to monitor (0.271)
- Public Perception (0.107)

As noted above, intensities were then assigned to each of these criteria and sub-criteria. For example, three intensities were assigned to the sub-criterion "State of maturity of the treatment

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[3] The team consisted of five analysts from SAIC. Their names and qualifications are described at the beginning of Section 2.0.

technology": a) experience with full-scale operation; b) pilot treatment technology with full-scale operation of disposal option; and c) pilot treatment technology with untested disposal. Brainstorming about the relative importance of each pair of these three intensities ("pairwise comparison") leads to the following relative ranking of the importance of these intensities: 0.731, 0.188, and 0.081 respectively. These are numerical weights that factor into the final AHP calculations. Details on the development of intensities for all criteria and sub-criteria are given in Chapter 2 of the main report. The assignment of individual retirement options to intensities is provided in Chapter 3. Pairwise comparison judgments made for intensities, criteria, and sub-criteria are provided in Appendix A.

S.6 Results

Table S-1 summarizes the results of the base-case analysis together with variations on the results assuming that only benefits (non-costs) or only costs are important. The ranking from the base-case analysis appears in the second column ("overall") and shows that the landfill options are preferred independent of the treatment technology. The storage options rank next, followed by the treatment technologies combined with monofills, bunkers, or mined cavities.

The reasons why the landfill options are preferred become apparent when costs are considered. The third column of results shows the rankings if only cost is taken into account. The landfill options are cheapest and this clearly outweighs the relatively unfavorable rankings that result from a focus on the benefits. However, if the costs are not an important factor, then the three storage options occupy the first three places in the "non-costs only" ranking.

The last column of Table S-1 shows unfavorable rankings for the operating costs of the storage options. This arises for two reasons: a) if storage continues for a long period, even relatively small per annum costs will add up; and b) storage is not a means for permanent retirement of bulk elemental mercury and the analysts assumed that, sooner or later, a treatment and disposal technology will be adopted, which adds to the cost. This is enough to drive the storage options out of first place in the base-case rankings. However, the analysis would support continued storage for a short period (up to a few decades) followed by a permanent retirement option. This would allow time for the treatment technologies to mature.

Table S-2 displays a sensitivity study for non-cost criteria only.[4] These sensitivity studies show that, if cost is not a concern, then storage in a hardened, RCRA-permitted structure performs favorably against all the criteria. By contrast, the landfill options do not perform as well, with public perception and environmental performance being among the criteria for which these options receive relatively low rankings.

The standard storage option ranks least favorably of all against risks (public, worker, and susceptibility to terrorism). Although the analysts consider that none of the options has a high risk, the fact that the standard storage option would have large quantities of elemental mercury in a non-hardened, aboveground structure suggested to the team that the risks are somewhat higher than those for other options.

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[4] The sensitivity studies were performed by adjusting weights so that the individual criterion receives 90% of the weighting, while the rest receive only 10% altogether while maintaining the relative weightings from the base case. The exceptions are columns 2 and 3 of the results in Table S-1 where only benefits or only costs were considered, respectively.

The options that include selenium treatment also rank less favorably with respect to risk because they were assigned a higher worker risk than were the other retirement options due to the relatively high temperature of operation and the presence of an additional toxic substance (selenium). They also (unsurprisingly) perform relatively unfavorably with respect to technological maturity.

The last row of Table S-2 shows the ratio between the scores for the alternatives that are ranked highest and lowest. Table S-2 shows that, if high importance is assigned to them, compliance with laws and regulations (ratio 7.1), implementation considerations (ratio 6.8) and the maturity of the technology (ratio 5.0) are the most significant discriminators between the retirement options. By contrast, the ratio for sensitivity to risks is only 1.6. This is because the analysts concluded that none of the retirement options has a high risk and that any variations are between low and very low risk.

Finally, a limited number of analyses were performed to address uncertainties in the assignment of the retirement options to each intensity. These analyses are discussed in Section 4.3 of the main report. Examples include increasing implementation costs for storage in a mine from medium to high, decreasing operating costs for storage of elemental mercury in a hardened, RCRA-permitted structure from high to low, and looking forward to when selenide treatment followed by storage in a mined cavity can be considered as a fully mature technology. Altogether twelve such analyses were performed by changing just one intensity assignment from the base case. These analyses showed expected trends, with scores and rankings improving if a more favorable assignment was made and decreasing if a less favorable assignment was made. In no case did the score increase or decrease by more than 40% and in most cases the change was less than 10%. These analyses are only uncertainty analyses in a very limited sense because (due to funding limitations) only one parameter at a time could be varied. A future study could potentially perform a true uncertainty analysis using Monte Carlo techniques.

S.7 Conclusions and Recommendations

A limited scope decision-analysis has been performed to compare options for the retirement of surplus mercury. The analysis has demonstrated that such a study can provide useful insights for decision-makers. Future work could include:

1. Involve additional experts or stakeholders in the process of assigning weights to the various criteria. The individuals involved in producing the current report were exclusively from SAIC. They are listed at the beginning of Section 2.0. This would ensure that a wider range of expertise and interests is incorporated into the analysis. For example, working groups within EPA, involving a cross-section of EPA offices, would provide additional perspectives. Other examples would involve the inclusion of other Federal agencies, States, nongovernmental organizations, foreign governments, industry, and academia. Such participation could be performed in stages. As discussed above, differences in the importance of the criteria relative to one another can change the results.
2. The alternatives considered in this report were limited to elemental mercury. Additional alternatives could be considered for mercury-containing wastes.
3. Additional Expert Choice analyses could be conducted in which certain alternatives are optimized. For example, within the general alternative of stabilization/ amalgamation treatment followed by landfill disposal are potential sub-alternatives addressing individual treatment technologies or landfill locations.
4. Revisit the available information periodically to determine if changes in criteria, or changes in intensities, are required. For example, some candidate criteria were not considered because insufficient information was available. One example is volatilization of mercury

during long-term management. Very little data are available at this time to adequately address this as a possible criterion.

5. Consider performing a formal uncertainty analysis utilizing Monte-Carlo-based techniques.

Table S-1 Summary of Results for 11 Evaluated Alternatives

Alternative	Ranking (as fraction of 1,000[a])					
	Overall		Non-Costs Only		Costs Only[b]	
	Score	Rank	Score	Rank	Score	Rank
Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill	137	1	99	5	217	1
Selenide treatment followed by disposal in a RCRA- permitted landfill	123	2	66	9	217	1
Storage of elemental mercury in a standard RCRA-permitted storage building	110	3	152	2	126	5
Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill	103	4	92	7	135	3
Storage of elemental mercury in a hardened RCRA-permitted storage structure	95	5	173	1	44	6
Selenide treatment followed by disposal in a RCRA- permitted monofill	94	6	74	8	135	3
Storage in a mine	81	7	140	3	44	6
Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker	70	8	108	4	42	8
Stabilization/amalgamation followed by disposal in a mined cavity	63	9	97	6	42	8
Selenide treatment followed by disposal in an earth-mounded concrete bunker	62	10	c	c	c	c
Selenide treatment followed by disposal in a mined cavity	61	11	c	c	c	c
Number of alternatives evaluated	11	—	9	—	9	—
Total	1,000	—	1,000	—	1,000	—
Average score (total divided by number of alternatives, either 9 or 11)	91	—	111	—	111	—

Shading indicates the highest ranking alternative.

[a] Scores normalized to total 1,000.

[b] Costs for storage options include both the storage costs as well as end-of-storage costs for subsequent treatment and disposal.

[c] These options were evaluated for the overall goal but were not evaluated at the lower levels of cost and non-cost items separately, due to the low score from the overall evaluation.

Table S-2 Sensitivity Analysis of Non-Cost Criteria[a]

Alternative	Ranking (as fraction of 1,000[b]; average score 111)													
	Non-Cost Baseline		Sensitivity: Env Perf		Sensitivity: Risks		Sensitivity: Implement		Sensitivity: Public		Sensitivity: Maturity		Sensitivity: Compliance	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Storage of elemental mercury in a hardened RCRA-permitted structure	173	1	176	1	142	1	172	2	197	1	226	1	263	1
Storage of elemental mercury in a standard RCRA-permitted building	152	2	173	2	87	9	259	1	52	5	224	2	261	2
Storage in a mine	140	3	145	3	101	5	168	3	193	2	223	3	78	3
Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker	108	4	94	5	132	2	57	5	190	3	52	6	74	4
Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill	99	5	71	8	131	3	146	4	46	6	67	4	73	5
Stabilization/amalgamation followed by disposal in a mined cavity	97	6	110	4	95	6	38	9	189	4	51	7	37	9
Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill	92	7	92	6	130	4	55	6	46	6	66	5	73	5
Selenide treatment followed by disposal in a RCRA- permitted monofill	74	8	81	7	92	7	53	7	44	8	46	8	71	7
Selenide treatment followed by disposal in a RCRA- permitted landfill	66	9	58	9	91	8	52	8	43	9	45	9	70	8
Total	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—
Range: highest to lowest alternative	2.6 times		3.0 times		1.6 times		6.8 times		4.6 times		5.0 times		7.1 times	

Shading indicates the two, three, or four highest-ranking alternatives. Cut-off is determined by where a large drop in the score occurs.

In the sensitivity analysis for each criterion, the importance of the criterion is set at 90 percent. The five other criteria comprise the remaining ten percent, proportional to their original contributions.

[a] Two options were not evaluated for the sensitivity analysis: selenide treatment followed by disposal in a mined cavity, and selenide treatment followed by disposal in an earth-mounded concrete bunker. This is because of the low score from the overall evaluation and because the version of Expert Choice used for this analysis only allowed the use of nine alternatives for the sensitivity analysis.

[b] Scores normalized to total 1,000.

PRELIMINARY ANALYSIS OF ALTERNATIVES FOR THE LONG TERM MANAGEMENT OF EXCESS MERCURY

1.0 INTRODUCTION

This report is intended to describe the use of a systematic method for comparing options for the retirement of excess mercury. The method chosen is the Analytical Hierarchy Procedure (AHP) as embodied in the Expert Choice software.

In this introduction, Section 1.1 provides background on why such a procedure is potentially helpful in the decision-making process. Section 1.2 describes the approach and summarizes the AHP. AHP and Expert Choice are described in more detail in Appendix A. Section 1.3 describes how the scope of the present work was limited to manageable proportions by judicious choice of retirement options for which there is reasonable information and which are representative of a wide range of technologies. Section 1.4 describes sources of information used for the work.

Section 2.0 describes the choice of a goal, criteria, and intensities for the Expert Choice software. These terms are defined in Appendix A. The criteria and intensities are the foundation of the model for mercury retirement.

Section 3.0 contains discussion and evaluation of the retirement options. The purpose of the section is to assign each technology to an intensity under each criterion. These assignments constitute the basic activity from which numerical scores emerge for each option.

Section 4.1 presents the numerical results of the Expert Choice analysis. The meaning of these results and their potential usefulness as an aid to decision making are discussed in Section 4.2 by presenting the results of some sensitivity studies. Section 4.3 contains a discussion of uncertainty.

Section 5 contains suggestions for future work. As noted above, Appendix A describes the AHP and Expert Choice. Appendix B reviews an earlier study from Environment Canada. This was a comprehensive review of many potential mercury treatment and retirement options. In the Appendix, those options are reviewed one-by-one and reasons are given why they were or were not chosen for the AHP analysis. Appendix C summarizes available environmental performance data for the treatment technologies identified in the present work. Appendix D details of the values assigned to each intensity for each of the retirement options other than those simply involving storage of bulk elemental mercury. Finally, Appendix E addresses the disposition of comments that were received on an earlier draft report.

1.1 Background

Over the past decade, the Environmental Protection Agency (EPA) has promoted the use of alternatives to mercury because it is a persistent, bio-accumulative, and toxic (PBT) chemical. The Agency's long-term goal for mercury is the elimination of mercury released to the air, water, and land from anthropogenic sources. The use of mercury in products and processes has decreased. The Department of Defense (DoD) and the Department of Energy (DOE) have excess mercury stockpiles that are no longer needed. Mercury cell chlor-alkali plants, although still the largest worldwide users of mercury, are discontinuing the use of mercury in favor of alternative technologies. Therefore, there is a need to consider possible retirement options for excess mercury.

In the USEPA, the Office of Solid Waste(OSW), working with the Office of Research and Development (ORD) and DOE, is evaluating technologies to permanently stabilize and dispose of wastes containing mercury. Furthermore, OSW is considering revisions to the Land Disposal restrictions (LDRs) for mercury. These revisions will address the Hg Stockpile and retirement issue. However, the regulatory system currently strongly supports all recycling initiatives and the concept of retirement is in its infancy as far as conceptualization is concerned. Indeed, EPA has yet to define exactly what is meant by the "retirement" of mercury.

As noted above, the Agency has focused its efforts on the reduction of current uses of mercury and future releases of mercury to the environment. The agency has focused on recycling (retorting) for mercury-containing hazardous wastes and has only performed preliminary investigations of other management options. Analysis has not been performed at the level of detail necessary to make decisions on retirement options and, in any case, data is not presently available on many of the commercially available technologies. However, despite the unavailability of information, there is a need to examine potential scenarios for the long-term management of mercury.

1.2 Approach

The approach chosen for the present work is the Analytical Hierarchy Process (AHP) as embodied in the Expert Choice software. AHP was developed at the Wharton School of Business by Dr. Thomas Saaty and continues to be a highly regarded and widely used decision-making tool. The AHP engages decision-makers in breaking down a decision into smaller parts, proceeding from the goal to criteria to sub-criteria down to the alternative courses of action. Decision-makers then make simple pairwise comparison judgments throughout the hierarchy to arrive at overall priorities for the alternatives. The decision problem may involve social, political, technical, and economic factors. The AHP helps people cope with the intuitive, the rational and the irrational, and with risk and uncertainty in complex situations. It can be used to; a) predict likely outcomes; b) plan projected and desired futures; c) facilitate group decision making; d) exercise control over changes in the decision making system; e) allocate resources; f) select alternatives; and g) do cost/benefit comparisons.

The Expert Choice software package incorporates the principles of AHP in an intuitive, graphically based and structured manner that is valuable for conceptual and analytical thinkers, novices and subject matter experts. Because the criteria are presented in a hierarchical structure, decision-makers are able drill down to their level of expertise, and apply judgments to the criteria deemed important to their objectives. At the end of the process, decision-makers are fully cognizant of how and why the decision was made, with results that are meaningful and actionable.

In summary, Expert Choice was chosen for the present work for the following reasons:

- It is based on the well-established and widely-used Analytical Hierarchy Process
- It allows the user to incorporate both data and qualitative judgements
- It can be used even in the presence of uncertainties, because it allows users to make subjective judgments
- Once the basic model for a particular decision has been set up, it is easy to perform sensitivity studies
- The model can readily be adjusted as better data become available, or if more alternatives need to be added

Appendix A contains information on the AHP and on how the inputs to the Expert Choice software were specifically developed for the comparison of mercury retirement options.

1.3 Defining the Boundaries of the Problem

This section describes the overall mercury use and disposition cycle, and then summarizes what was done to limit the scope to manageable proportions for the purposes of the present work.

1.3.1 Mercury Use and Disposition Cycle

Figure 1-1 is a simplified summary of the total mercury use and disposal cycle.

Industrial Applications

There are numerous industrial uses of mercury. These include: a) flowing mercury electrodes in the chlor-alkali industry (still the largest worldwide use of mercury); b) thermometers; c) fluorescent lights and fixtures; d) switching devices and relays; e) environmental manometers; and f) etc. Many of these uses are being phased out, so there is a growing surplus of mercury.

Sources of Elemental Mercury for Industrial Applications

In principal, stockpiled mercury is a source for use in industrial applications, although because many uses of mercury are being phased out, stockpiles are in practice growing rather than shrinking. Fresh mercury can be obtained from mining, although there is no longer mining of mercury in the USA or Canada. Some mercury is obtained by recycling techniques such as retorting. Other mercury may be imported. Finally, mercury may be recovered from waste streams and/or from contaminated media.

Surplus Elemental Mercury

As noted above, mercury is being phased out of many industrial applications so that, increasingly, there is mercury that is surplus to requirements. The principal focus of the present work is to consider options for disposal of this surplus.

Storage of Elemental Mercury

Currently, considerable amounts of surplus elemental mercury are stored. For example, in the USA the Defense Logistics Agency has nearly 5,000 MT stored in warehouses. One option is to continue to store it, in which case there are a number of possibilities: three representative ones are shown on Figure 1-1.

- Store it in aboveground, RCRA-permitted facilities, such as warehouses.
- Store it in a RCRA-permitted hardened structure.
- Store it underground in a mined cavity.

Treatment of Elemental Mercury

There exist a number of processes for the chemical treatment of mercury, the purpose being to produce mercury in a form that is suitable for long-term, unsupervised disposition. Figure 1-1 lists four of these, the DeHg Amalgamation Process, the Sulfur Polymer

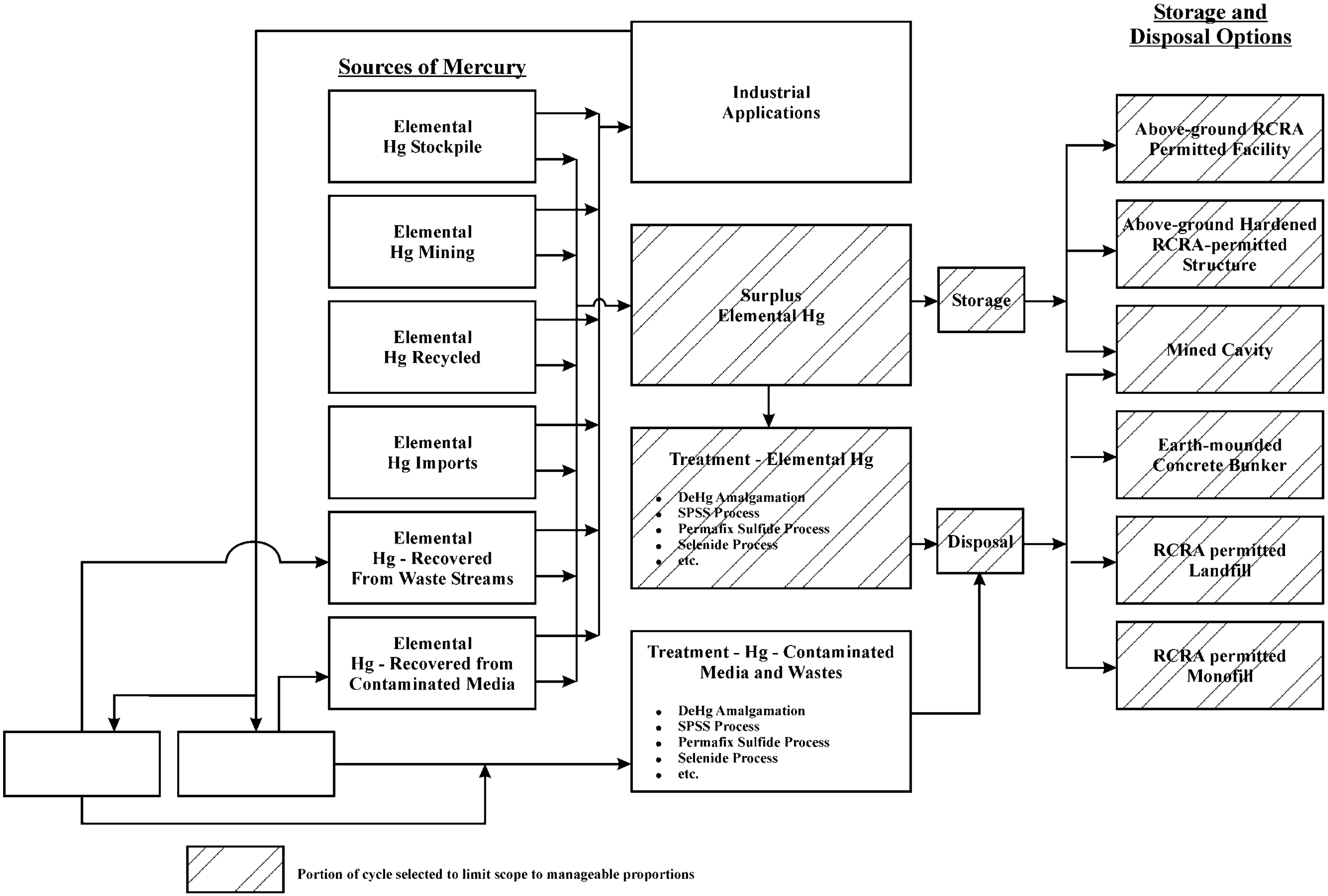

Figure 1-1 Simplified Schematic of the Mercury use and Disposal Cycle

Stabilization/Solidification Process, the Permafix Process and the mercury selenide process. The fact that these processes are mentioned here does not mean that they are favored: they should be regarded as representative of various processes such as forming a metal amalgam, producing a sulfide, or producing a selenide.

Treatment of Waste Streams and Contaminated Media

Waste streams and contaminated media can be directly treated (bypassing the mercury recovery step) to produce wastes that are suitable for disposition. Some processes that can treat elemental mercury are also able to treat wastes and contaminated media. It was decided early on that, to limit the scope of the present study to manageable proportions, technologies examined would be limited to those that can potentially treat all of elemental mercury, waste streams, and contaminated media.

Disposition of Treated Mercury

Figure 1-1 displays four representative options for disposing of treated mercury. One is by sending the waste to an independently operated, RCRA-permitted landfill. Another would be disposition to a customized, RCRA-permitted monofill. Third, there is disposal in an earth-mounded concrete bunker. Finally, there is an option that overlaps with the storage of elemental mercury, namely disposal in a mined cavity.

1.3.2 Limitation of Scope

It would be an enormous task to consider all of the treatment and disposal options that are implicit in Figure 1-1. The resources available for the present work necessitated a limitation of the scope to manageable proportions. Brainstorming among the project team led to the following decisions:

- Industry-specific technologies are excluded on the grounds that they can only manage a small fraction of the total mercury problem and in any case should be regarded as an integral part of that specific industry's waste management practices
- The study focuses on options for retirement of surplus bulk elemental mercury on the grounds that: a) this alone is a large enough project to consume the resources that are available for the present work; b) that it anyway addresses a large fraction of the problem; and c) that it will provide an adequate demonstration of the decision-making technique that can readily be expanded in the future. Thus, for example, the treatment of wastewater streams is excluded.
- The chemical treatment options are limited in number and are chosen to be representative of major classes of treatment options, such as metal amalgams, sulfides, or selenides. The choice is to some extent be driven by available information. If the decision tool favors any one class of options, then in principal it will be possible later to focus on individual technologies within that class and perform a further decision analysis to choose between individual technologies.
- Only technologies that can in principal treat contaminated media as well as elemental mercury are considered. This compensates to some extent for the decision to focus on elemental mercury.
- Retorting is excluded as merely being a well-established prior step for producing elemental mercury, some of which may end up in the pool of surplus mercury
- Deep-sea disposal is excluded because obtaining the necessary modifications to international laws and treaties is regarded as too onerous a task

- Storage in pipelines is excluded because the project team could not find information about it.

As a result of the above-described brainstorming, four treatment technologies were chosen:

- DeHg® amalgamation
- SPSS process
- Permafix sulfide process
- Selenide process

In practice, three of the treatment options have very similar characteristics when compared against the Expert Choice evaluation criteria (see Section 3.2.6 for further discussion). These are the DeHg® amalgamation process, the SPSS process, and the Permafix sulfide process. They are grouped together into one class titled Sulfide/Amalgamation (S/A). Thus, two treatment options remain, S/A and Selenide. These were combined with the four disposal options shown on Figure 1-1: disposal in a RCRA-permitted landfill; disposal in a RCRA-permitted monofill; disposal in an engineered belowground structure; and disposal in a mined cavity. In addition, there are the three storage options discussed above: storage in an aboveground RCRA- permitted facility; storage in a hardened RCRA-permitted structure; and storage in a mined cavity. Altogether, eleven options were chosen for examination with the decision-making tool (note that SAIC's proposal stated that only ten options would be considered because of the limited funding available):

- Storage of elemental mercury in a standard RCRA-permitted storage building
- Storage of elemental mercury in a hardened RCRA-permitted storage structure
- Storage of elemental mercury in a mined cavity
- Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill
- Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill
- Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker
- Stabilization/amalgamation followed by disposal in a mined cavity
- Selenide treatment followed by disposal in a RCRA- permitted landfill
- Selenide treatment followed by disposal in a RCRA- permitted monofill
- Selenide treatment followed by disposal in an earth-mounded concrete bunker
- Selenide treatment followed by disposal in a mined cavity

1.4 Sources of Information

In preparing this report, information was obtained from a variety of government sources and the general literature. All of the information used is publicly available; no proprietary information or data was used in preparing the report. All information is cited throughout the report with full citations presented in the bibliography. While there were many data sources used for this report, some of the principal sources of information that were consulted to obtain data for this study are as follows:

Canadian Study: SENES Consultants (SENES, 2001) has produced a draft report for Environment Canada on the development of retirement and long-term storage options for mercury. SENES evaluated 67 technologies using the Kepner-Tregoe ranking technique and reviewed a further 9 technologies but did not rank them because there was insufficient information. This report provides comprehensive identification regarding the range of technologies that are potentially available for mercury storage or retirement, together with a wealth of references.

Mercury Management Environmental Impact Statement: The Defense Logistics Agency (DLA) is currently preparing a Mercury Management Environmental Impact Statement (MMEIS). Information used in developing the EIS has been used in this report (e.g., DNSC 2002a). In particular, DLA published the following announcement in the Commerce Business Daily (CBD) on May 24, 2001: *Commercial Sector Provision of Elemental Mercury Processing Services – Request for Expressions of Interest*, to solicit expressions of interest in providing treatment technologies for the permanent retirement of 4,890 tons of elemental mercury from the national stockpile. Expressions of interest were received from five companies (or teams of companies). To the extent that this information is non-proprietary, it has been used in the present work. In fact, these expressions of interest generally constitute the best available sources of information and drove the choice of technologies. SAIC is currently supporting the Defense Logistics Agency (DLA) and DNSC in preparing the Mercury Management Environmental Impact Statement (MMEIS).

2000 Mercury Workshop: EPA has prepared the proceedings of the mercury workshop that was held in March 2000, in Baltimore, Maryland covering the following issues:

- State of the science of treatment options for mercury waste
- State of the science of disposal options for mercury waste such as landfill disposal, sub-seabed emplacement, stabilization, surface and deep geological repositories for mercury waste storage.

A summary of the workshop is available in the proceedings (US EPA 2001). Additional information from individual presentations held at the workshop was used throughout this report as well.

US EPA and US DOE Activities: Both EPA and DOE have been evaluating the performance and feasibility of mercury treatment technologies for several years. DOE has published various Innovative Technology Summary Reports that evaluate the treatment technologies applicable to mercury containing mixed wastes (i.e., wastes that are both hazardous and radioactive). The reports include environmental performance testing, cost information, and other operations information.

In addition, EPA has conducted performance testing of mercury-containing wastes processed by various treatment technologies. Performance testing in these studies has involved both comprehensive analytical testing and standard Toxicity Characteristics Leaching Procedure (TCLP) tests.

2.0 CHOICE OF CRITERIA AND INTENSITIES

Use of the Expert Choice computer model requires that a goal and criteria be chosen and that intensities be assigned to each criterion. The meaning of these terms will become clear in the following discussion. The criteria are then compared pairwise to obtain relative weightings, as described in Appendix A Some criteria are further reduced to sub-criteria, which are pairwise compared among themselves to obtain their relative weightings. Finally, intensities are assigned to each criterion or sub-criterion, and those intensities are themselves compared pairwise to obtain relative weightings. Development of the model, criteria, and intensities were performed by SAIC based on the review of resources identified in Section 1 and their knowledge and experience of mercury retirement, disposal, and life cycle issues.

SAIC staff primarily involved in this development included:

- John DiMarzio, with experience in mercury retirement issues and decision methodologies based on work with the Department of Defense. He is managing DLA's MMEIS project.
- John Vierow, P.E., with experience in mercury life cycle issues at various EPA offices and knowledge of EPA-sponsored treatment technology assessments;
- Geoff Kaiser, Ph.D., with experience in safety, risk assessment; and mercury issues through participation in MMEIS work.
- Linda Brown and Larry Deschaine, P.E., with experience in applying Expert Choice software to various alternative assessment problems. In addition, Larry Deschaine is experienced in the use of a variety of decision making tools to solve environmental problems.

2.1 The Goal

The goal is simply stated: "Select the best alternatives for mercury retirement." Having this goal helps the project team keep focused.

2.2 First-Level Criteria

The team developed two first-level criteria, benefits and costs. Initially, equal weights were assigned to them. Section 4.2 provides sensitivity analyses that show how weighting entirely in favor of costs or of benefits changes the rankings of the retirement options.

2.3 Benefits

Six second-level criteria were developed under the heading of benefits. These are described below. Some of the second-level benefits were further split into third-level criteria. Intensities were then assigned to each of the lowest-level criteria.

2.3.1 Benefit Criterion 1 - Compliance with Current Laws and Regulations

Clearly, a technology is more desirable if it is already compliant with existing laws and regulations. The team identified three intensities: a) already compliant; b) non-compliant with Land Disposal restrictions (LDRs) ; and c) atypical permit required. Item a) is self-explanatory. Standard storage in an existing or hardened structure would rate this intensity. The case that would require an atypical permit would be one of a type that has not been granted before, such as storage in a mined cavity. The merely non-compliant case is one in which some work has to be done to change regulations, but there is reason to believe that the cognizant agency would be supportive, such as for disposal in a landfill or a monofill.

2.3.2 Benefit Criterion 2 – Implementation Considerations

This criterion is directed at the storage or disposal option and contains two sub-criteria; a) whether there is a large increase in the volume of the waste; and b) whether new construction is necessary.

Sub-criterion 2A – Volume of Waste

The volume of waste influences the costs of disposal and possibly the necessity for new construction. Three intensity levels were used: a) zero or minimal increase; b) increase up to ten times, and c) increase greater than ten times. Clearly, there is zero increase for all three storage options. From the information available to the team, it appears that all treatment technologies generate a factor of ten or more increase in the volume of the waste

Sub-criterion 2B – Engineering Requirements

Three self-explanatory intensities have been chosen: a) no new construction required or at most minor modifications; b) new construction; c) construction of a mined cavity.

2.3.3 Benefit Criterion 3 – Maturity of the Technology

This criterion attempts to assess whether it is expected to be easy to implement a technology that will operate reliably at full scale. There are two sub-criteria, the state of maturity of the technology, and how reliably it operates.

Sub-criterion 3A – State of Maturity of the Technology

The confidence with which a technology can be accepted clearly depends on how much experience there has been with its operation. Three intensities were chosen: a) experience with full-scale operation; b) pilot treatment with full-scale disposal; and c) pilot treatment with untested disposal. Thus, the team considered that all three storage options (including the mined cavity) have had experience with full-scale operation. All of the treatment technologies are considered to be at the pilot plant stage, and disposal of treated mercury wastes into a bunker or a mined cavity is considered to be untested.

Sub-criterion 3B – Expected Reliability of the Treatment Technology

Here reliability is assigned three intensities: a) no treatment; b) simple; and c) complex. Thus, the three storage options are assigned to the no treatment intensity. The S/A options are considered to be simple and therefore likely to be reliable. The selenium technology is somewhat more complex and, as a general rule, the more complex the technology, the less reliable it is apt to be.

2.3.4 Benefit Criterion 4 – Risks

This criterion addresses risks and is divided into three sub-criteria: public risk; worker risk; and terrorism/sabotage.

Sub-Criterion 4A – Public Risk

This sub-criterion is intended to assess whether there are any potential catastrophic accident scenarios that can affect the public or the environment. The team did not consider that any of the technologies poses a high risk to the public. For storage in a standard building, there is a large quantity of elemental mercury that would cause large consequences if released to the environment. However, the team considered that the frequency of such an accident would be very low, so that the overall risk is low. All of the other retirement options were assessed as having a very low public risk, either because there are no large quantities of elemental mercury or because the elemental mercury would be in a hardened or underground structure. Thus, two intensities have been chosen: a) very low; and b) low.

Sub-Criterion 4B – Worker Risk

As for public risk, the team identified only two intensities, very low and low. Worker risk can never be totally eliminated, because someone could always fall off a ladder or be subject to some other common industrial accident. It was considered that all retirement options pose very low risk to the workers, except for storage in a mine and the selenium technology. One would expect that workers regularly accessing a mine would be more at risk than those accessing an aboveground structure. The selenium technology does involve the presence of some hazardous materials and high temperatures. Therefore, these retirement options were considered to have a low risk, rather than a very low risk.

Sub-Criterion 4C – Susceptibility to Terrorism/Sabotage

It seems necessary to include consideration of terrorism or sabotage in the wake of the events of September 11, 2001. The goal here is to assess how attractive a target each retirement option would be to a terrorist or saboteur, and to assign each option to one of two intensities: a) very low; and b) low. The goal of an international terrorist is to create maximum impact, by causing spectacular damage to a highly prestigious target, by causing a very large number of casualties and/or by strongly affecting the national economy or the national security. The goal of a saboteur motivated by local grievances may be revenge or to cause local embarrassment. Pertinent considerations here therefore whether there is potential for someone to engineer a catastrophic accident, whether this is easy, and whether it is worth wasting a precious resource (such as a hijacked plane) on this target rather than others where the effect might be more spectacular. The team considered that none of the retirement options would qualify as particularly attractive to a terrorist or saboteur. Therefore, all of the options were assigned to the very low intensity with the exception of the aboveground storage in a standard building, where it might be somewhat less difficult to engineer a serious accident.

2.3.5 Benefit Criterion 5 – Environmental Performance

There are several aspects of environmental performance, so the team deemed it necessary to develop four sub-criteria: a) discharges during treatment; b) degree of performance testing; c) stability of conditions in the long term; and d) ability to monitor conditions during storage or disposal.

Sub-Criterion 5A – Discharges during Treatment

Issues that need to be considered under this criterion include atmospheric discharges, liquid discharges, and solid waste streams. Appropriate intensities are a) no impact; and b) minimal.

The “no impact” intensity was introduced for the storage options, where there is no treatment step; the “minimal” intensity was introduced for the treatment technologies. The team considered that, while there would be some discharges during operations, there was no reason to believe that any of the technologies would lead to discharges that would not be compliant with discharge permits.

Sub-Criterion 5B – Degree of Performance Testing

This refers to the tests that have been carried out on the treatment technologies to demonstrate that the product of the technology meets requirements for leachability, etc. The three intensities are: a) adequate; b) moderate and c) low. The “adequate” intensity was introduced for the storage options. The “moderate” intensity apples to all of the S/A options, while the selenium options remain the least tested and were assigned to the “low” intensity.

Sub-Criterion 5C – Stability of Conditions in the Long Term

This sub-criterion applies to the storage or disposal options. It is expected that the selected technology will meet EPA standards for such criteria as leachability, and that any containers will meet certain requirements with respect to corrosion. However, those criteria are not valid in all environments. Therefore, it is necessary to be confident that the long-term storage or disposal conditions can be controlled so that the disposed materials remain in their repository. The intensities chosen here are: a) very good; b) good; c) fair; and d) poor. Thus, one would anticipate that conditions in a carefully engineered mined cavity would be expected to remain stable over long periods, so that the appropriate intensity would be “very good.” For a monofill or a bunker, conditions are likely to remain good. In a landfill, where many materials in addition to the mercury waste may be disposed of, conditions may be no more than fair. Finally, storage options are characterized as poor simply because they are not intended to be long-tem options.

Sub-Criterion 5D – Ability to Monitor

The ability to monitor is one of the key factors in ensuring good performance after storage or disposal. The team identified four intensities; a) easy and correctable; b) easy to monitor but not necessarily easy to correct; and c) difficult to monitor. Thus, all of the storage options are characterized as easy and correctable because they are designed to be monitored and, if conditions deteriorate, the storage containers can easily be moved. Disposal in a mine would be difficult to monitor because the intention would be to dispose of the materials and seal the mine. Other options would be easy to monitor but not necessarily easy to correct.

2.3.6 Benefit Criterion 6 – Public Perception

Clearly, any mercury retirement project will not fly if the public is strongly against it. It was decided that there are two distinct possibilities: a) public perception is positive to neutral, in which case there is no problem; b) public perception is negative, but a campaign that combines elements of public relations, marketing and the distribution of information might be sufficient to overcome it. Initially, a third intensity was considered, namely that public perception is intensely negative, so that there is a strong likelihood that the retirement project will never be accepted. However, the team did not identify any retirement options that could potentially attract such strong public opposition.

These two possibilities are the intensities that were assigned to the public perception criterion. The team then brainstormed pairwise the relative desirability of each of these intensities, as described in Appendix A. In this particular case, there is only one pair and it was decided that a positive to neutral perception is strongly preferable to a negative perception, within a scale that allows the team to choose between equally preferable, moderately preferably, strongly preferable, very strongly preferable, and extremely preferable. In Expert Choice, these correspond to multipliers on a numerical scale from 1 to 9, with strongly preferable corresponding to 5 times more preferable. This is provided as an example of pairwise comparison of intensities. Detailed discussion of all pairwise comparisons of intensities is provided in Appendix A.

The allocation of intensities to each of the retirement options is discussed in detail in Section 3. As an example, in this specific case, the team decided that all options that provided for bulk elemental mercury or treated mercury to be stored or disposed of in hardened structures or in a mine would be regarded favorably by the public. The other options that allow for storage in a regular warehouse or disposal into a landfill or monofill could potentially attract some negative public attention.

2.3.7 Pairwise Comparison of the Criteria

It is necessary to pairwise compare the six second-level criteria under the overall benefit criterion. The numerical weightings generated in this way can then be manipulated in expert choice to rank the criteria in terms of importance, as shown in the table below.

Table 2-1 Ranking of Non-Cost Criteria after Pairwise Comparisons

Criterion	Relative Numerical Ranking Index from Expert Choice
Environmental Performance	0.336
Risks	0.312
Implementation Considerations	0.154
Public Perception	0.107
Maturity of the Technology	0.047
Compliance with Current Laws and Regulations	0.045

This ranking emerged from the team's brainstorming of pairwise comparisons between each of these criteria. In other words, the team brainstormed each of the 15 pairs that can be extracted from the first column of Table 2-1 and in each case determined whether the two criteria in the pair were equally important, or whether one was extremely, very strongly, strongly, or moderately more important than the other. Table 2-1 then provides a "sanity check" – does it seem reasonable? Of course, the answer is subjective, as are the pairwise comparisons themselves. However, the team reviewed Table 2-1 carefully and decided that the ranking looks reasonable.

2.4 Costs

Costs were divided into two components – the cost of implementation and operating costs. These were assigned equal importance.

2.4.1 Cost Criterion 1 – Implementation Costs

Different implementation costs are associated with storage, treatment, and disposal. For storage and disposal, implementation costs are those associated with site development, construction, permitting, etc., which take place before any material is introduced to the unit. For treatment, implementation costs in this report are generally limited to capital expenditures. Other costs such as for research and development are not included because they are difficult to project, or because all of the alternatives considered have already been developed and used to some extent.

The intensities applied to this criterion are identified as either low, medium, or high. While no hard-and-fast dollar delineations are provided with these intensities, approximate costs are as follows: (1) low (includes the use of existing facilities or expenditures under about $5 million); (2) medium (includes the construction of new facilities projected to require expenditures between $5 million and $50 million), and (3) high (includes the construction of new facilities projected to require expenditures above $50 million).

2.4.2 Cost Criterion 2 – Operating Costs

Operating costs refer to expenditures which maintain the management option. In the case of mercury retirement, the metal is assumed to be removed from commerce on an annual basis and require subsequent management. This is different from a case where a 'one-time' quantity of waste requires management. In this context, operating costs associated with storage include the costs to maintain the storage structure, staff costs, monitoring, etc. Operating costs associated with treatment include the cost to treat the waste; in commercial waste management these are typically cited on a 'per ton' basis. Finally, operating costs associated with disposal include similar components as with storage.

One additional costs component is assessed for storage options that is not assessed for treatment and disposal options. Once stored, the material is assumed to require some type of further management (i.e., it will not be stored forever). Consequently, the costs for this future management alternative are added into the other existing operating cost components. While the ultimate alternative, and the associated costs, are unknown, the costs are expected to be similar to those reflected in the alternatives evaluated here.

The intensities applied to this criterion are also qualitatively identified as low, medium, or high. In general, operating costs for disposal are assumed to be lowest for landfills and higher for more complex disposal (where additional operating mechanisms may be required). Operating costs for storage are assumed to be highest due to the additional, end-of-life costs identified above. Therefore, these intensities were applied to operating costs more as a rank order than as representing specific dollar amounts.

2.5 Summary of Criteria and Intensities

Table 2-2 summarizes the criteria and intensities in a convenient form.

Table 2-2 Criteria Used for Evaluating Options

Criterion	Intent of Criterion	How Option is Evaluated Against Criterion
Benefit – Public perception	To assess the degree to which the public might be for or against the technology.	a) public reaction positive to neutral; or b) public reaction negative.
Benefit – Compliance with current laws and regulations	To assess whether new regulations and/or laws will be required.	a) already compliant; b) non-compliant with LDRs; or c) atypical permit required.
Benefit – Environmental performance: discharges during treatment	To assess the acceptability of atmospheric or liquid discharges, or solid waste streams during treatment.	a) no impact; or b) minimal.
Benefit – Environmental performance: degree of performance testing	To assess to what extent the product of the treatment technology meets the requirements for storage or disposal (e.g. leachability)	a) adequate; b) moderate; or c) low.
Benefit – Environmental performance: stability of conditions in the long term	To assess to what extent conditions in the long term storage or disposal repository can be controlled so that the results of performance tests remain valid (e.g. leachability)	a) very good; b) good; c) fair; or d) poor.
Benefit – Environmental performance: ability to monitor	To assess whether conditions in the long term disposal or storage repository can be easily monitored	a) easy and correctable; b) easy to monitor but not necessarily easy to correct; c) difficult to monitor.
Benefit – Risks: public risk	To assess whether the retirement option poses a risk to the public as a result of accidents.	a) very low; or b) low.
Benefits – Risks: worker risk	To assess whether a retirement option poses a risk to workers.	a) very low; or b) low.
Benefit – Risks: susceptibility to terrorism/sabotage	To assess the attractiveness of a retirement option to a terrorist or saboteur.	a) very low; or b) low.
Benefit – Maturity of the technology: state of maturity of the technology	To assess how much experience there has been with the retirement option.	a) experience with full-scale operation; b) pilot treatment with experience of full-scale disposal; or c) pilot treatment with untested disposal.
Benefit – Maturity of the technology: expected reliability of operation	To assess whether the treatment technology is likely to operate reliably and deliver reliable quality in the product.	a) no treatment; b) simple; or c) complex.
Benefit – Implementation considerations: volume of waste	To assess whether the technology causes large increases in the volume of waste for storage or disposal.	a) zero or minimal increase in volume; b) an increase in volume by less than a factor of ten; or c) an increase in volume by greater than a factor of 10.
Benefit – Implementation considerations: engineering requirements	To assess whether construction of the storage or disposal option is required.	a) no new construction needed or minor modifications; b) new above-ground construction needed; c) construction of a mined cavity needed.
Costs of Implementation	To assess the cost of developing the retirement option to the point at which it is ready to accept mercury or mercury waste	a) low; b) medium; c) high.
Operating Costs	To assess costs after the retirement option begins operation	a) low; b) medium; c) high.

3.0 DISCUSSION AND EVALUATION OF OPTIONS

3.1 Storage Information

Storage allows for certain flexibility in management. As depicted in the options below, storage has the following characteristics:

- *Temporary management*. While the materials being stored can certainly be left in one place for many years, storage should offer a means of moving the mercury to another location.
- *Ease of monitoring*. There should be a means for the materials to be monitored for releases, such as air emissions or leaks, which could affect public health and worker safety. In a related sense, there should also be a mechanism to stop or remediate any releases, if found.

Based on these criteria, three storage options have been identified for evaluation: storage in a standard RCRA-permitted storage building, storage in a hardened RCRA-permitted storage building, and storage in an underground mine.

3.1.1 Storage in a Standard RCRA-Permitted Storage Building

Hazardous waste or hazardous materials are commonly stored throughout the U.S. using a variety of methods. DNSC uses warehouses for the storage of mercury. At one site, the mercury is contained in 76 lb steel flasks within wooden pallets. At three of the sites, the steel flasks are overpacked within steel drums on wooden pallets. The warehouses are covered (as a building) and have a sealed concrete floor. Access restrictions are provided by fencing and 24-hour security personnel. (DNSC 2002a)

The DNSC sites are storing mercury that is considered an industrial commodity and therefore are not RCRA-permitted for hazardous waste storage. RCRA-permitted hazardous waste storage is required any time hazardous waste is stored for more than three months and entails detailed requirements, higher costs, greater regulatory oversight, etc. While certain mercury-containing wastes (e.g., dental amalgam) are hazardous wastes, there is uncertainty as to whether elemental mercury would be similarly designated by the regulatory authorities, if stored at other sites. One example of elemental mercury storage is the national stockpile. DLA considers its mercury to be a commodity rather than a RCRA hazardous waste. (Lynch 2002) Another example is elemental mercury from the now closed HoltraChem (Maine) site in which 80 tons of mercury stored at the facility is considered a hazardous waste by the State. (Young 2001) Therefore, the regulatory status is expected to depend on the source of mercury, State laws and regulations, and other factors.

For this evaluated alternative, it is conservatively assumed that elemental mercury storage would require a hazardous waste storage permit. Information from several sites in Utah was obtained to identify typical requirements. Security measures at facilities with RCRA-permitted storage are similar to those at the DNSC sites. DOT-acceptable containers are required, with visual inspection for integrity every year. Enclosed buildings with concrete floors, with sumps for spill control and ventilation systems, are used for storage. (Utah 2002)

Costs for the storage of 1,500 tons of elemental mercury at a single hypothetical commercial site have been estimated by SAIC as $3.8 million of initial costs and $200,000 of annual costs, if a new structure is required. (SAIC 2002) Alternatively existing sites could be used. The DNSC has also estimated the present annual costs associated with the storage of the 4,890 ton stockpile at its four sites at $750,000 per year (DNSC 2002b). In descending order of magnitude, cost components included: (1) rent, (2) labor, (3) security, (4) other expenses of utilities, groundskeeping, etc. These estimates have uncertainty because the cost components may not necessarily be applicable to a commercial site, and because they are preliminary and not based on in-depth accounting.

An additional source of cost estimates for storage is from options being considered for 82 tons of elemental mercury located at the now-closed HoltraChem chemical facility in Maine. The long-term storage costs for this quantity at an existing commercial facility were estimated to be $120,000 to $180,000 per year. The capital cost of construction of a storage structure on facility property was estimated to be $100,000 to $750,000 with no operating costs provided. A small sample of area residents favored the idea of sending the material offsite rather than storing it at the plant, even though the costs were identified as higher. (Gagnon 2001)

3.1.2 Storage in a Hardened RCRA-Permitted Storage Building

Concrete bunkers have been constructed and used for the storage of radioactive or nuclear materials. They have not been used in the U.S. for the storage of hazardous materials or hazardous wastes. Nevertheless, a similarly-designed structure can be used for the storage of mercury. One such structure was constructed in Russia in 1999. The storage bunker has double concrete walls with sand between the two concrete layers. It is 450 feet long and 240 feet wide. It is used for the storage of nuclear material from dismantled weapons. (Rizley 2000) More specific information regarding the construction is not available.

Another example of this design is associated with the storage of spent fuel at nuclear power plants. Approximately twelve U.S. nuclear power plants include areas for dry storage of nuclear waste. These areas are designed to temporarily hold the material until it can be moved and transported to a permanent disposal site, once a site is selected and constructed. The radioactive material is placed inside large containers comprised of steel, concrete, and/or lead with total thickness of 18 inches or more. The containers are stored outside on a concrete pad or are stored within a concrete vault. Costs for construction and storage of the containers were identified as an initial cost of $10 to $20 million, plus $500,000 to $1,000,000 per container. For this analysis it is assumed that a container can hold a year's supply of spent fuel. In 1998, 6,200 spent assemblies were generated from 104 generating units, or about 60 assemblies per unit on average. (DOE 2001) A single container can hold between 7 and 56 fuel rods, each 12-feet long, in an inert gas. (NEI 2001) However, these costs are in all likelihood very much higher than would be the case for similar storage of mercury because there would not be the need to design against radioactive exposures.

Because these design and storage costs are reflective of radioactive waste storage, both the upfront and continuing costs are expected to overestimate the costs of elemental mercury because the measures designed to protect against radioactivity would be unnecessary to protect against the migration of mercury.

3.1.3 Storage in a Mined Cavity

For purposes of this analysis, storage in a mined cavity is assumed to differ from disposal in a mined cavity. Like other storage options, the mercury is assumed to be stored in movable containers which can be monitored, moved, and if necessary repackaged over the lifetime of the mine. This differs from disposal, where it is expected to be difficult or impossible to move the mercury once placed in the mine. Further, for storage, it is assumed that an existing underground cavity can be used for holding the mercury. While some additional construction modifications may be needed, this eliminates high additional costs of drilling, detailed site characterization, etc.

The costs and complexities associated with mine cavity storage are likely to vary greatly depending on the suitability of currently available underground cavities. Underground cavities for hard rock minerals, coal, and other commodities exist in the U.S. It is assumed that such facilities can be used with minimal upgrades.

No examples of temporary storage in a mined cavity were identified for mercury or any other waste types. In contrast, permanent deep underground disposal has been suggested and used for various wastes. Nevertheless, the use of a mined cavity for the temporary storage of mercury will be retained as an option in this analysis.

3.1.4 Storage Options Not Considered

Storage in an Earth-Mounded Concrete Bunker

This technology is used worldwide as a method of disposing low-level and mid-level nuclear waste. As depicted in the examples identified during this review, this is a permanent disposal technology rather than a temporary or long-term storage solution (See Section 3.3.4). Therefore, this alternative is eliminated as a storage option and will be retained as a disposal option.

3.1.5 Summary of Storage Options versus Evaluation Criteria

Table 3-1 summarizes the available information regarding the above three options for storage, based on the available information. These results will be subsequently used in the evaluation process. Table 3-1 uses the specific information above for individual alternatives in conjunction with other information that is available for storage alternatives in general. Specifically, the information summarized in Table 3-1 is based on the following for each evaluated criterion:

Compliance with current laws and regulations. The aboveground storage of elemental mercury can be accomplished in the current regulatory framework, even if it is assumed that the storage of untreated elemental mercury will require hazardous waste permitting. This is because land disposal is not involved. In the case of mine storage, it is unclear whether this method would require any deviations from the procedures applicable to above-ground storage; although the mercury is not placed or disposed on the land, there is very little precedent to assess if land disposal restrictions requirements for hazardous wastes would be applicable. In a conservative case, it is assumed that there will be some additional difficulties with mine storage that would not be the case with above ground storage which would require some modifications to current regulations to allow such storage: that is, an atypical permit would be required.

Implementation Considerations. All storage options have a similar attribute in that there is no volume increase with the mercury (because there is no treatment). Additionally, it is assumed that aboveground storage could occur at an existing hazardous waste storage facility (because it is relatively common), while the other two options would require construction of new structures and/or auxiliary facilities.

Maturity of the technology. Aboveground storage is a very common and mature procedure for many hazardous materials, including elemental mercury. While the other options are not as common for storage, it is assumed that similar features of aboveground storage are applicable to all.

Table 3-1 Evaluation for Three Storage Options

Criteria	Standard RCRA-Permitted Storage Building	Hardened RCRA-Permitted Storage Structure	Underground Mine Cavity
Compliance with current laws and regulations	Already compliant	Already compliant	Atypical permit required.
Implementation considerations: volume of waste	Zero increase in volume	Zero increase in volume	Zero increase in volume
Implementation considerations: engineering requirements	Existing facilities can be used	Construction of new facilities is required	Construction of new facilities is required
Maturity of the technology: state of maturity of the technology	Experience with full-scale operation	Experience with full-scale operation (extrapolated from the warehouse case)	Experience with full-scale operation (extrapolated from the warehouse case)
Maturity of the technology: expected reliability of treatment	No treatment	No treatment	No treatment
Risks: worker risk	Very low	Very low	Low
Risks: public risk	Low (while unlikely, large quantities of mercury are present at one time and could be released)	Very low (although large quantities of mercury are present at one time, the mercury is less easily accessible than the warehouse case)	Very low (although large quantities of mercury are present at one time, the mercury is less easily accessible than the warehouse case)
Risks: susceptibility to terrorism/sabotage	Low (while unlikely, large quantities of mercury are present at one time and could be released)	Very low (although large quantities of mercury are present at one time, the mercury is less easily accessible than the warehouse case)	Very low (although large quantities of mercury are present at one time, the mercury is less easily accessible than the warehouse case)
Environmental performance: discharges during treatment	No impact (no treatment)	No impact (no treatment)	No impact (no treatment)
Environmental performance: degree of performance testing	Adequate	Adequate (extrapolated from the warehouse case)	Adequate (extrapolated from the warehouse case)
Environmental performance: stability of conditions in the long term	Poor	Poor	Poor
Environmental performance: ability to monitor	Easy (monitoring)	Easy (monitoring)	Easy (monitoring)
Public perception	Somewhat negative	Positive to neutral (probably)	Positive to neutral
Costs: implementation	Low (about $4 million, or zero if existing facilities are used)	Medium (up to $10 to $20 million)	Medium (expected to be similar to hardened storage case)
Costs: operating	High	High	High

Worker risks. Potential risks to workers from routine handling or accidental release are expected to be very low for the aboveground options. Potential risks for mine storage may be slightly higher due to the increased hazards posed from belowground work (i.e., unrelated to mercury).

Public Risks and Risk Susceptibility to Terrorism or Sabotage. The most significant potential risks are due to the presence of large quantities of mercury at a site. In above ground storage, a fire or explosion, while extremely unlikely, could result in a widespread distribution of the toxic element. A principal advantage of the other options is the ability to prevent, control, or contain such an unlikely occurrence.

Environmental performance. The results of the DNSC's experience with aboveground storage of elemental mercury indicate that mercury can be effectively monitored and safely managed with little or no release to the environment. These results have been extrapolated to the other storage options. One drawback of storage that is reflected in Table 3-1 is that while storage is expected to be effective for the short term (e.g., 10 to 100 years) with active monitoring and maintenance, its performance for the long term (hundreds or thousands of years) if simply left in place is unknown. In this case it is assumed to be poor because elemental mercury may be released from the containers if left unattended.

Public perception. Public perception to any alternative is likely different at the local level (e.g., city or county) than at the national level. In almost any action involving mercury, a negative local perception is likely in the same way that most citizens would oppose a landfill close to their homes. At the national level, a different perception may result. Reaction can be neutral or even positive for an action identified as a suitable and defensible alternative for mercury management. This is assumed to be the case for the hardened storage and mine storage, which are designed to mitigate some of the potential risks posed by a more simple aboveground storage. Of course, forecasting the potential public perception of any alternative is uncertain.

Costs of Implementation. As identified above, the cost of construction of a standard storage unit is estimated to be up to $4 million. Alternatively, an existing commercial site could be used which would require no additional costs. Such is the case for the DLA mercury stockpile in which existing warehouses or munition bunkers could be used. (DLA 2002) Standard storage is expected to have the lowest initial cost for any of the storage alternatives. In contrast, the estimated initial cost of $10 to $20 million for concrete-hardened storage, while expected to be overstated since it is based on radioactive containment, is nonetheless higher than for standard storage. There are no cost estimates for mine storage but it is assumed that costs are similar to those estimated for hardened storage.

Operating Costs. As identified above, the costs for operating the 4,890 ton mercury stockpile by DLA are estimated to be about $750,000 per year, and costs for storing 80 tons of mercury at a commercial facility are estimated to be $120,000 to $180,000 per year. Costs for other storage options are assumed to be similar. A key additional component considered in this analysis is eventual disposal costs. While it is possible to continue the practice of storage for the short term, sooner or later treatment and disposal will be required and additional costs for such management will result. Therefore, operating costs include both the costs of maintaining storage integrity and the additional costs of eventual implementation of a long-term retirement option.

3.2 Treatment Information

Treatment reduces the mobility of mercury in the environment to the air (i.e., from volatilization) and groundwater (i.e., from leaching). Mercury is typically treated through chemical and/or physical methods through the addition of additives to convert the mercury into a less mobile form, such as mercury compounds or amalgams. In addition, physical methods such as stabilization reduce the exposure of mercury to environmental media such as leachant within a landfill.

Four treatment options have been identified for evaluation. These are: a) ADA / Permafix treatment; b) BNL sulfur polymer solidification; c) IT/NFS DeHg® process; and d) the selenide process. More detailed information is presented below to the extent information is publicly available.

The environmental performance of the treatment technologies has been evaluated by EPA and DOE, in addition to data collected by the vendors themselves. In the past several years EPA and DOE have evaluated various treatment technologies for wastes containing a wide range of mercury, from 'low mercury' solid wastes of less than 260 mg/kg to elemental mercury. The tests and programs conducted by EPA and DOE are summarized in Table 3-2. In some cases, the vendor names were not provided in the reports. To retain consistency, the vendor names in such cases are not included here. More detailed results from the studies are provided in Appendix C.

Mercury mobility is influenced by many factors, and only some of the factors have been evaluated in the tests summarized in Table 3-2. Factors affecting the mobility of mercury, or any other metal, include the following:

- Liquid/solid ratio of test or in disposal environment.
- Redox potential (which influences whether the conditions are more likely to oxidize or to reduce mercury)
- Co-contaminants such as other ionic species.
- pH
- Particle size
- Exposure duration.

Table 3-2 Summary of Available Environmental Performance Data

Reference	Participating Vendors/ Wastes Evaluated	Major Tests Conducted
Sanchez (2001). Evaluated mercury-contaminated soil, ~ 4,500 ppm	ATG BNL Unnamed vendor	Evaluate mercury leaching with respect to pH and liquid-to-solid ratio
DOE (1999a and 1999b). Elemental mercury	NFS ADA	TCLP
DOE (1999c, 1999d, 1999e). Mercury-contaminated waste, <260 ppm)	NFS GTS Duratek ATG	TCLP
USEPA (2002a). Evaluated mercury waste, ~ 5,000 ppm	Four vendors	Evaluate mercury leaching with respect to pH
USEPA (2002b). Evaluated elemental mercury	Three vendors. In addition, there was limited testing of simulated mercury selenide	Evaluate mercury leaching with respect to pH

Cost information is provided in this section of the report for the treatment of 1,500 tons of elemental mercury. This is done to provide a constant basis of comparison between the different data. The estimate of 1,500 tons was selected as representative of approximately a ten-year supply at current use rates. Based on estimates from Bethlehem Apparatus Company (2000), a company specializing in recycling mercury and mercury bearing wastes, the United States produces between 2,000 to 4,000 76-lb. flasks, or 152,000 to 304,000 pounds, of mercury per year from recovery operations. Therefore, this is an upper bound on the rate of increase of surplus mercury.

3.2.1 ADA / Permafix Treatment

Perma-Fix Environmental Services and ADA Technologies Inc. have submitted an expression of interest for treatment of the U.S. DoD mercury stockpile. Perma-Fix operates waste treatment facilities for a variety of materials, while ADA Technologies have developed technology specific to mercury treatment. ADA's technology converts mercury to mercuric sulfide, and is capable of treating elemental mercury or mercury in waste material.

Raw materials for the ADA process include a sulfur-based reagent. The treated material can be a granular material or a monolithic material. Permafix proposed to treat 880 flasks of mercury per week (66,800 lb) and generate 150 55-gallon drums. This represents a volume increase of 14 times. The vendor estimates it would take three years to process the 4,890 tons of mercury stockpile.

The ADA amalgamation process, a batch process, consists of combining liquid mercury with a proprietary sulfur mixture in a pug mill; in one application a 60-liter capacity pug mill was used for treatment of an elemental mercury waste. Treatment of the liquid mercury was conducted by adding powdered sulfur to the pug mill, while a preweighed amount of mercury was poured into the mill. As the mill continued to mix and the reaction took place, additional chemicals were added. While the processing of mercury in the pug mill was performed without the addition of heat, the reaction of mercury with sulfur is exothermic at room temperature, and the mixture increases in temperature during processing. Reaction products include water vapor. Off-gas is passed through a HEPA filter and then passed through a sulfur-impregnated carbon filter. Mercury vapor concentrations above the pug mill were below the Threshold Limit Value (TLV) of 50 mg/m^3. All operators wore respirators fitted with cartridges designed to remove mercury vapor. (DOE 1999b).

Costs for this treatment process were estimated by DOE as $300 per kg, exclusive of disposal costs, when treating more than 1,500 kg of elemental mercury. (DOE 1999a) It is not known if such costs are representative of treatment on a much larger scale. For example, using this unit cost estimate, costs for the treatment of 1,500 tons of elemental mercury would equate to more than $400 million for treatment alone.

3.2.2 BNL Sulfur Polymer Solidification

The sulfur polymer solidification/ stabilization process (SPSS) is a batch process. In this process, elemental mercury is combined with an excess of powdered sulfur polymer cement and sulfide additives and heated to 40^oC to 70^oC for several hours. This converts mercury to the mercuric sulfide form. Additional sulfur polymer cement is added and heated to 135^oC. The molten mixture is poured into a mold to cool and solidify. (Fuhrmann 2002) The system is currently operated at pilot scale, using a one cubic foot conical mixer. The process has been demonstrated for both elemental mercury and for mercury-containing soil. (Kalb, 2001) The vendor has projected it can scale up by a factor of 350 for treatment of the DLA stockpile of 4,890 tons and complete treatment in 60 days. Currently, BNL is attempting to license the technology for different applications to be installed at customer sites. BNL estimates that commercial scale implementation would take one year or less. (BNL Response, 2001)

Volume and weight changes for the treatment of elemental mercury are estimated from several case studies. In one test, a total of 140 lb was treated using the process. (Kalb, 2001) Each batch of mercury, about 25 pounds, generated about 4 gallons of molten product, which solidified in a container. This represents a volume increase from about 0.22 gallons (assuming pure elemental mercury) to 4 gallons, or 18 times. In another study, a volume increase of 15 times was identified. (USEPA, 2002b) The treated waste had a waste loading of 33 percent (i.e., 100 pounds of treated waste contained 33 pounds mercury). Mass balance measurements show an estimated 0.3 percent mercury is released from the process vessel and captured in the air control system.

Additives used include the sulfur polymer cement and sulfide additives. Sulfur polymer cement consists of 95 weight percent elemental sulfur and 5 percent organic binders. Sulfide additives which have been examined include sodium sulfide monohydrate and triisobutyl phosphine sulfide.

During operation, 1 to 2 personnel are expected to operate the equipment, exclusive of additional workers for waste handling, etc. Typical protective equipment is expected to be required (e.g., gloves and lab coat).

Costs for treatment of the 4,890 metric ton mercury stockpile were estimated by BNL to be approximately $2.4 million for materials, additives, and process unit capital. This represents $250,000 in capital costs for a single 350-cubic foot treatment vessel, $2 million for additives, and $150,000 for other materials. Costs for other components (e.g., treatment facility, disposal) were not included. Based on this information, the costs for the treatment of 1,500 tons of elemental mercury would equate to less than $1 million for treatment alone.

3.2.3 IT/NFS DeHg® Process

This is a batch metal amalgamation process conducted at ambient temperature. The final product is monolithic. The first step is an amalgamation process using proprietary powdered reagents. In a second step, the waste is stabilized using liquid reagents. The process generates hydrogen gas as a byproduct, which is vented following control equipment. The quantity of hydrogen gas produced was not identified, and the chemical reactions are proprietary. However, conservatively assuming that hydrogen is generated from mercury treatment at a stoichiometric ratio of 4 to 1 (hydrogen to mercury), the batch treatment of 75 kg of mercury (the quantity to be used at production scale) would generate about 600 standard cubic feet of hydrogen gas. (IT/NFS 2001) This is not expected to represent a significant additional hazard to personnel or the process in general.

The process has been used to treat 50 cubic meters of mixed radioactive hazardous waste containing mercury at the NFS site in Erwin TN. For larger scale treatment, construction of a new additional site would be required. (IT/NFS 2001)

Releases of mercury from the process are estimated at 0.05 percent. Ambient air measurements have been taken during processing and have been less than regulatory and nongovernmental standards. (IT/NFS 2001)

The processing of mercury-containing wastes can generate a waste liquid. Following stabilization, the material is a presscake. Any filtrate from this processing is recycled to the reactor for further treatment, or is discharged. (DOE 1999a) For elemental mercury treatment using small quantities of mercury (about 10 kg of treated material per batch), the treated product is reported to consist of moist amalgam in polyethylene bottles with no free liquid. No discussion is available concerning whether the treatment of elemental mercury by itself would be expected to generate a wastewater stream.

As with the ADA process discussed above, costs for the DeHg® treatment process were estimated by DOE at $300 per kg, exclusive of disposal costs, when treating more than 1,500 kg of elemental mercury. (DOE 1999a) It is unknown if such costs are representative of treatment on a much larger scale. For example, using this unit cost estimate, costs for the treatment of 1,500 tons of elemental mercury would equate to more than $400 million for treatment alone.

3.2.4 Selenide Process

Bjästa Återvinning, a Swedish firm, uses a full-scale commercial process for the treatment of mercury in fluorescent lights. Unlike the previously described treatment processes, this is a continuous process. In this process, the lamps are crushed and melted in a 1400°C electric furnace. The molten glass is tapped and selenium is added to the hot gas to form mercury selenide in a vapor phase reaction. The mercury selenide, a less mobile compound than elemental mercury, is condensed by refrigeration. (Bjästa 2002)

The quantity of mercury demonstrated to have been treated by this process is relatively small. The process has been used for fluorescent lamps. In the U.S., an estimated 17 tons of mercury in lamps was disposed of in 1999 (NEMA 2000), which is a good indication of the upper bound of mercury that can be managed by this treatment method. The process has also been patented for treatment of batteries, which in Sweden (the company's base) are expected to contain no more than about 3 tons of mercury.[5] In treating wastes such as batteries, a rotary kiln is used to provide agitation of the material; selenium is added to the furnace under inert conditions and other components of the process are similar to those used for lamps. In a lab scale test using a feed rate of 100 grams of batteries per hour, 0.9 percent of the mercury remained in the solid residue and 3 percent in the vapor phase was not precipitated as mercury selenide. This unreacted quantity was captured in a downstream filter, which would potentially require further processing for adequate treatment. (Lindgren 1996)

The process has not been applied to elemental mercury, although lamps do contain elemental mercury. The quantities of mercury in batteries and lamps, as identified above, are much less than the quantities of elemental mercury available in commerce. This is another limitation to applying the process to relatively large quantities of elemental mercury.

The company claims that less than 20 grams of mercury escapes for every million kg of lamps processed. (Bjästa 2002) This corresponds to a release rate of 0.03 percent.[6] Reagent-grade mercury selenide (i.e., not produced from a treatment step) was part of the EPA elemental mercury treatment study that evaluated the mobility of mercury subject to a treatment method that generates such a product. EPA data are available for the constant leaching test at two pHs, 7 and 10, and two simulated environmental conditions, with and without chloride in the leaching solution. (USEPA 2002b)

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[5] Lindgren (1996) identifies that the mercury composition of batteries can vary widely, from less than one percent to 35 percent. About 11 tons of batteries are generated in Sweden each year as of the mid-1990's (Lindgren 1996). Using the annual battery generation rate and the mercury composition data gives an upper bound estimate of about three to four tons.

[6] Data from Phillips Lighting (Phillips 2002) indicates that about 26,000 four-foot lamps weigh 5,000 kg. The lighting and electrical trade association, NEMA, estimates that the average mercury composition of a four-foot lamp is 12 mg in 1999, the latest year available (NEMA 2000). Thus, one million kg of lamps contain about 60 kg of mercury.

No cost estimates are available for this process.

3.2.5 Treatment Technologies Not Considered

ATG

The ATG process has been demonstrated for mercury-containing wastes (DOE, 1999c; USEPA, 2002a), but not for elemental mercury itself. ATG demonstrated its process at full-scale for the treatment of a process waste stream with a total mercury content less than 260 mg/kg. The full-scale demonstration was a batch set-up capable of treating 165-kg of waste at one time, although it was demonstrated at 33-kg batches. The process used raw materials that included a dithiocarbamate formulation, phosphate and polymeric reagents, magnesium oxide, calcium carbonate, sodium metasulfite, sodium hydrosulfide, and activated carbon. The volume of the treated waste was reported to be 16 percent greater than that of the untreated waste. The treated waste was in the form of a damp paste. Additional wastes generated include PPE, containers, etc.

Costs of treatment were estimated as $1.73/kg waste. This includes both capital costs ($30,000) and operating costs ($95/hr). (DOE 1999c)

GTS/Duratek

The GTS/Duratek process has been demonstrated for mercury-containing wastes (DOE, 1999d), but not for elemental mercury itself. In this process, water and cement are added to sludge, and then blended with sodium metasilicate, a stabilization agent. The process was demonstrated at pilot scale in treating four 55-gallon drums containing approximately 570 kg of waste sludge. The materials are mixed in the 55-gallon drum using a vertical mixer, and then allowed to harden (cure).

Phosphate Ceramics

This is a stabilization technique, which has been demonstrated at bench scale for mercury-containing waste. It is an ambient temperature process that combines chemical stabilization of mercury within a ceramic encapsulation. Raw materials include magnesium oxide and potassium phosphate, as well as a sulfur compound such as sodium sulfide or potassium sulfide. The treated waste forms a dense ceramic. The process has been demonstrated on wastes containing up to 0.5 percent mercury. (Wagh, 2000)

Mercury Recovery

Several U.S. facilities currently recover elemental mercury from mercury-containing wastes for subsequent reuse. While this is a treatment method, it does not, by itself, serve to reduce the mobility of elemental mercury. Information on mercury recovery facilities, nevertheless, is useful for projecting the characteristics of other treatment methods, which are not as widespread.

Bethlehem Apparatus, a mercury recovery facility, has operated commercial scale mercury recovery facilities in the Bethlehem Pennsylvania area for many years. The facilities are also permitted for mercury waste storage with additional permitting for limited treatment prior to recovery. Presently, they principally conduct recovery from mercury wastes and while changes to existing equipment would be necessary for conducting more extensive treatment operations, many capital expenditures (e.g., containment, ventilation) are already in place. The facility uses 30 workers in the production area for various activities. (Bethlehem 2001)

3.2.6 Summary of Treatment Options versus Evaluation Criteria

Table 3-3 summarizes the available information regarding the above four options for treatment. These will be subsequently used in the evaluation process. In Table 3-3, three of the treatment processes (the ADA / Permafix treatment, BNL sulfur polymer solidification, and IT/NFS DeHg® process) are grouped together and termed 'stabilization/ amalgamation.' This is done for several reasons: (1) they have very similar characteristics when compared against the evaluation criteria, (2) environmental performance data in available reports do not always identify the vendors associated with the data, although information is available regarding the general process type, and (3) differentiating between individual treatment processes is anticipated to be a required decision only after it is decided that treatment is an appropriate decision. Note that, in Table 3-3, the selenide process is evaluated separately due to significant differences between this process and the other three technologies.

Table 3-3 summarizes the available information regarding the above four treatment options, based on the available information. These results are subsequently used in the evaluation process. Table 3-3 uses the specific information above for individual alternatives in conjunction with more general information that is available for treatment alternatives in general. Specifically, the information summarized in Table 3-3 is based on the following for each evaluated criterion:

Compliance with current laws and regulations. Each of the treatment options would likely require hazardous waste permitting, which can be accomplished in the current regulatory framework with no special difficulties anticipated. The subsequent disposal of the treated waste would be prohibited based on current regulations, as discussed in a subsequent section of this report.

Implementation Considerations. Data and calculations for the ADA and BNL processes show that the treatment process results in a volume increase of at least 14 times. Data for the other two processes are not available. Due to the lack of data, it is assumed that the volume increase for all treatment options is approximately the same. In addition, each of the three stabilization/ amalgamation processes use simple 'off-the shelf' equipment while the selenide process may require additional construction considerations.

Maturity of the technology. In all cases the treatment technologies have been demonstrated for elemental mercury or related wastes. However, the projected scale of retirement options is much larger than the more limited capability already demonstrated.

Worker risks. Potential risks to workers from routine handling or accidental release are expected to be very low for the stabilization/ amalgamation options because of the simple, ambient temperature characteristics. Potential risks may be slightly higher for the selenide process due to the additional components of heat and selenium (a toxic metal).

Public Risks and Risk Susceptibility to Terrorism or Sabotage. Risks are anticipated to be very low because small quantities of mercury are anticipated to be present at the treatment site at any one time.

Table 3-3 Evaluation for Treatment Options

Criteria	Amalgamation/Stabilization Options				Selenide Process
	ADA / Permafix Treatment	**BNL Sulfur Polymer Solidification**	**IT/NFS DeHg® Process**	**Overall for 3 Stabilization/ Amalgamation Options**	
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Would require permitting through existing regulatory structure	Would require permitting through existing regulatory structure	Would require permitting through existing regulatory structure	Would require permitting through existing regulatory structure
Implementation considerations: volume of waste	Volume increase of 14x	Volume increase of 18x	Volume increase not known	Volume increase about 15x	Volume increase not known, assumed similar to others
Implementation considerations: engineering requirements	Simple components	Simple components	Simple components	Simple components	More capital requirements and relatively complex
Maturity of the technology: state of maturity of the technology	Not commercial scale	Not commercial scale	Not commercial scale	Not commercial scale	Commercial scale for mercury wastes but not for elemental mercury. Quantities of wastes treated are likely much less than quantities of elemental mercury.
Maturity of the technology: expected reliability of treatment operation	Simple components and batch processing	Simple components and batch processing	Simple components and batch processing	Simple components and batch processing	Relatively complex and continuous processing
Risks: worker risk	Very low	Very low	Very low	Very low	Higher than other alternatives due to high temperatures and additional toxic chemical
Risks: public risk	Very low because large quantities of mercury will not be present	Very low because large quantities of mercury will not be present	Very low because large quantities of mercury will not be present	Very low because large quantities of mercury will not be present	Very low because large quantities of mercury will not be present

Table 3-3 Evaluation for Treatment Options (Continued)

Criteria	Amalgamation/Stabilization Options				Selenide Process
	ADA / Permafix Treatment	**BNL Sulfur Polymer Solidification**	**IT/NFS DeHg® Process**	**Overall for 3 Stabilization/ Amalgamation Options**	
Risks: susceptibility to terrorism/sabotage	Very low because large quantities of mercury will not be present	Very low because large quantities of mercury will not be present	Very low because large quantities of mercury will not be present	Very low because large quantities of mercury will not be present	Very low because large quantities of mercury will not be present
Environmental performance: discharges during treatment	Minimal discharges expected	Minimal discharges expected	Minimal discharges expected	Minimal discharges expected	Minimal discharges expected
Environmental performance: degree of performance testing	Moderate: TCLP and additional testing performed	Moderate: TCLP and additional testing performed	Moderate: TCLP and additional testing performed	Moderate: TCLP and additional testing performed	Low: limited testing performed by EPA
Environmental performance: stability of conditions in the long term	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Environmental performance: ability to monitor	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Public perception	Neutral	Neutral	Neutral	Neutral	Neutral
Implementation costs	Extremely variable estimates				
Operating costs	Mainly operating costs from the initial treatment				

Environmental performance. Discharges of mercury potentially occur during treatment. Based on the above information, the estimated releases for each treatment process are 0.3 percent for the BNL process, 0.05 percent for the DeHg® process, 0.03 percent for the selenide process, and no data for the ADA process. In each case, the mercury may continue to be collected in filters, etc. prior to discharge to the atmosphere.

Based on Table 3-2, there is a moderate amount of data regarding the mobility of mercury in treated wastes for the stabilization/ amalgamation technologies. Fewer data were identified for the selenide process.

Public perception. The principal 'driver' of public perception of a treatment and disposal train likely results from the disposal method used, rather than specific concerns regarding the treatment. Therefore, the public perception of disposal options is used for this analysis.

Costs. The identified costs for these treatment options vary widely. In one case (BNL), the cost of treatment of 1,500 tons of elemental mercury is estimated as less than $1 million. Using DOE data for two other cases (ADA and NFS) results in estimates exceeding $400 million. No cost data are available for the selenide process. This wide range in costs represent a significant uncertainty.

3.3 Disposal Information

Disposal provides a permanent method of managing mercury. Unlike storage, elemental mercury once disposed of is very difficult, or impossible, to move again. While it is certainly possible to remediate a site if the disposal site is causing environmental concerns, this is clearly not an intended outcome.

Four disposal options have been identified for evaluation: disposal in a mined cavity, disposal in a RCRA-permitted landfill, disposal in a RCRA-permitted monofill and disposal in an earth-mounded concrete bunker.

3.3.1 Disposal in a Mined Cavity

There are several examples of deep underground storage for the long-term disposal of wastes. The Swedish EPA decided in December 1997 to dispose of waste mercury in deep rock mine sites. This involves treating the waste and then storing it 200 to 400 meters below the surface at one or more locations. The rock would serve as a buffer to emissions and would provide stability in disposal. Reasons given by the Swedish EPA for selecting this alternative include the following: (1) leaching is estimated at less than 10 grams of mercury per year; and (2) the method provides protection against unforeseen occurrences such as inadvertent human entry or breach of containment. Barriers noted by the Swedish EPA to implementation include the following: (1) changes in regulations would be required along with a timeline for when the new regulations would be effective; and (2) it could take 5 to 10 years until the proposal becomes effective due to reasons such as selecting a site, technical site analysis, and permit procedure. Wastes with one percent or more mercury would be priority candidates for storage. The Swedish EPA also investigated other options including surface storage and shallow storage in rock (Sweden, 1997)

Sweden has not actually selected any site(s) for a disposal location. One potential location for such a disposal site is Stripa Mine, an existing hard rock mine located about 180 km west of Stockholm. This site has only been identified as a candidate, and has not been selected by any government agency for waste disposal. (Stripa 1999).

In the U.S., deep underground storage/disposal is an option for radioactive materials. The Carlsbad, New Mexico Waste Isolation Pilot Plant (WIPP) is an up-and-running site. This site has been characterized by long periods of study and development: the WIPP began operation in 1999 following a 20+ year period of study, public input, and regulatory changes and compliance. Disposal at the WIPP occurs in a salt formation 2,000 feet below the surface. (WIPP 2002) In this facility, drummed waste is placed in larger macroencapsulation containers consisting of polyurethane foam and a relatively thin steel exterior. Congress requires that WIPP be used solely for noncommercial U.S. defense related transuranic waste. Therefore, WIPP itself is unlikely to be used as a disposal site for mercury (because authorization from Congress would be required). However, this could serve as an example for the design of a future disposal site for mercury.

The Swedish EPA provides data with which to estimate the costs for this alternative. A storage capacity of 13,000 cubic meters is required for Sweden's needs. No upfront costs are provided (such costs may be integrated with the ongoing disposal costs). For every kilogram of mercury, the estimated disposal cost is SEK 240 to 650 (about $10 to $30/lb). The Swedish EPA estimates that, in 50 years, the country will generate 1,100 metric tons of mercury and estimates the total cost as about SEK 260 million ($25 million, or $10 per pound and in the lower range of the previously cited estimate). These costs do not include costs for treatment which are estimated to be an additional SEK 10 to 80/kg ($0.43 to $3.50/lb). Applying these costs to a hypothetical 1,500 ton quantity of mercury results in costs ranging from $30 million to 90 million for disposal.

An additional example of mine disposal is available for arsenic-containing mining wastes. At the Giant mine in Yellowknife Canada, 265,000 tons of dust from ore roasting was placed in underground storage chambers from the early 1950s to the 1990s. Most of these chambers were specially constructed for storage of the dust, which was stored without treatment or other containment, in areas intended to be dry. (Thompson 2001) This example can be applied to the disposal of treated mercury; it is less applicable to mercury storage because it is assumed that mercury would be contained prior to storage. Options for future management of this material are being considered; leaving the dust 'as is' is expected to require pumping and treating of underground water to prevent flooding of the chambers, and inclusion of barriers such as grouting or reestablishing the permafrost. (Thompson 2001) Cost of an option to reestablish permafrost is estimated to be $50 million. (O'Reilly 2000) This example shows that additional, and unanticipated, complexities from mine disposal of mercury may be encountered, which would affect costs, environmental impact, and implementation considerations.

3.3.2 Disposal in a RCRA-permitted Landfill

Landfills are a common management method for many types of hazardous wastes, with several commercial hazardous waste landfills currently in operation. Landfills typically dispose of hazardous wastes treated to remove organics and immobilize metals; such immobilization methods typically involve stabilization with alkaline agents. Presently, the disposal of hazardous waste containing more than 260 mg/kg mercury is prohibited, even if treated. Requirements for landfills vary with the year that they were constructed, but current regulations require design criteria such as double synthetic liners, leachate collection, and ground water monitoring.

Costs for commercial landfill disposal vary according to the waste complexity, quantity, and disposal site. However, industry averages are compiled by Environmental Technology Council, a trade association representing the disposal industry. The industry average costs for 2001 without treatment ranged from $66 per ton (for bulk soil) to $220 per ton (for drummed waste). Industry average costs with treatment ranged from $130 per ton (for bulk soil) to $400 per ton (for drummed waste). Costs do not include transportation. (ETC 2001) Applying these costs to a hypothetical 1,500 ton quantity of mercury results in an overall range of $100,000 for bulk solids (without treatment) to $600,000 for drummed waste with treatment.

3.3.3 Disposal in a RCRA-permitted Monofill

Monofills are constructed to hold only one type of waste or wastes with very similar characteristics. For example, a company may construct a landfill to dispose of large quantities of waste generated from onsite processes rather than sending the waste to a commercial facility. Design requirements are required to follow those for any other hazardous waste landfill (if the monofill is used for hazardous waste). A monofill provides certain environmental advantages over conventional, commercial co-disposal. First, the disposal conditions may be more closely controlled to minimize incompatibility with treated mercury. Second, monitoring and risk reduction may be more focused towards mercury.

As identified above, land disposal of elemental mercury is prohibited under current U.S. regulations and therefore this alternative is only applicable with a regulatory change. A monofill for mercury disposal would be relatively small. For example, a hypothetical 1,500 tons of mercury (a ten year supply as discussed above) corresponds to 130 cubic yards. Even assuming a significant volume increase during treatment and the use of a single disposal location, this would require relatively little space. In contrast, a typical landfill cell at one commercial landfill facility is 500,000 cubic yards. (Utah 2002)

A monofill would require construction of a new unit or cell. Construction costs are not available. Ongoing disposal costs would likely be comparable to the costs identified above for commercial landfills.

3.3.4 Disposal in an Earth-Mounded Concrete Bunker

Earth-mounded concrete bunker technology is used in France as means for disposing of low-level and mid-level nuclear waste. This technique has been used since 1969. The newest site is the Centre de l'Aube. At this site, drummed waste is taken to aboveground, concrete vaults with one-foot think concrete and underground drainage. The structure is protected with a removable (temporary) roof; when filled, a three-foot thick roof is poured and overlain with earth to form a mound. In addition, within the vault the containers are covered in grout. As depicted in this example, this is a permanent disposal technology rather than a temporary or long-term storage solution. Materials managed in this manner would be very difficult or impossible to remove at a later time.

Development costs for the site are estimated at $240 million and disposal costs are estimated at $1,600 per cubic meter (1997 prices). (USACE 1997) A hypothetical 1,500 tons of mercury (corresponding to 130 cubic yards untreated) may result in about 1,300 to 2,600 cubic yards of treated material (a volume increase of ten to twenty times), and therefore cost $1.6 to $3.2 million for disposal in addition to the initial capital costs. Costs for radioactive waste disposal (as cited here) are expected to be higher than costs for mercury disposal because of the additional protection required for radioactive wastes. Nevertheless, the capital costs for this alternative are expected to be higher than the costs for landfilling or monofilling.

3.3.5 Other Disposal Options not Evaluated

Sub-Seabed Emplacement

Sub-seabed emplacement was originally developed as a disposal alternative for nuclear waste. In this plan, solidified and packaged waste is buried in containers tens of meters below the ocean floor. The multiple layers of the waste container, in addition to the ocean sediments and the ocean water, would serve to delay migration of any contaminants. Research and models developed in the 1970s and 1980s for nuclear waste could be applied to mercury. However, such research specific to mercury has not resumed and therefore this represents a very preliminary option. (Gomez, 2000) Sub-seabed emplacement is not considered further as an option because (1) it is very preliminary with a correspondingly small amount of available information, and (2) significant, onerous changes in international treaties will be required.

3.3.6 Summary of Disposal Options versus Evaluation Criteria

Table 3-4 summarizes the available information regarding the above four disposal options, based on the available information. These results are subsequently used in the evaluation process. Table 3-4 uses the specific information above for individual alternatives in conjunction with more general information that is available for disposal alternatives in general. Specifically, the information summarized in Table 3-4 is based on the following for each evaluated criterion.

Compliance with current laws and regulations. The land disposal of mercury-containing waste (above 260 mg/kg) is prohibited under current regulations. Any of the disposal alternatives would require changes in EPA regulations. Additional difficulties may be encountered for the mine disposal option because local permitting authorities would have less experience with this alternative and a longer approval process may occur.

Implementation Considerations. The complexities of the above land disposal alternatives cover a wide range. Existing commercial landfills can be used with little or no modifications, as one alternative. A monofill or bunker would require new construction. Finally, a mined cavity (in hard rock or in material such as salt) would likely be more complex than any of the other options.

Maturity of the technology. Landfills (both co-disposal units and monofills) are very common for hazardous and industrial wastes. In contrast, bunker and mine alternatives are present as only isolated examples.

Worker risks. Potential risks to workers from routine handling or accidental release are expected to be very low for all of the alternatives, although additional potential hazards are present in any alternative where underground activity is required.

Public Risks and Susceptibility to Terrorism or Sabotage. Risks are anticipated to be very low for all alternatives because the mercury is present in the ground and cannot be widely dispersed.

Table 3-4 Evaluation for Four Disposal Options

Criteria	RCRA Permitted Landfill	RCRA Permitted Monofill	Earth-Mounded Concrete Bunker	Mined Cavity
Compliance with current laws and regulations	Non-compliant with LDRs	Non-compliant with LDRs	Non-compliant with LDRs	Non-compliant with LDRs and unusual permitting may be required
Implementation considerations: volume of waste	Not applicable (affected by treatment, not disposal)	Not applicable (affected by treatment, not disposal)	Not applicable (affected by treatment, not disposal)	Not applicable (affected by treatment, not disposal)
Implementation considerations: engineering requirements	An existing commercial landfill can be used	New in-ground construction is required	New in-ground construction is required	Construction would be more complex than other alternatives
Maturity of the technology: state of maturity of the technology	Very mature in U.S.	Very mature in U.S.	Technology has been applied but not widely used	Technology has been applied but not widely used
Maturity of the technology: expected reliability of treatment operation	Not applicable	Not applicable	Not applicable	Not applicable
Risks: worker risk	Very low	Very low	Very low	Low
Risks: public risk	Very low (because no bulk elemental mercury)	Very low (because no bulk elemental mercury)	Very low (because no bulk elemental mercury)	Very low (because underground and no bulk elemental mercury)
Risks: susceptibility to terrorism/sabotage	Very low (because no bulk elemental mercury)	Very low (because no bulk elemental mercury)	Very low (because no bulk elemental mercury)	Very low (because underground and no bulk elemental mercury)
Environmental performance: discharges during treatment	Not applicable	Not applicable	Not applicable	Not applicable
Environmental performance: degree of performance testing	Not applicable	Not applicable	Not applicable	Not applicable
Environmental performance: stability of conditions in the long term	Fair	Good	Good	Very good
Environmental performance: ability to monitor	Easy	Easy	Easy	Difficult
Public perception	Negative	Negative	Positive to neutral	Positive to neutral
Costs: implementation	Low (existing unit can be used)	Medium (requires new construction)	High (costs are likely higher than monofill)	High (costs are likely higher than monofill)
Costs: operating	Low	Low	Medium	Medium

Environmental performance. A significant difference among the alternatives involves the projected stability of the disposal site over the long term. Of course, this performance can only be imperfectly projected or modeled. Deep underground or mine storage is expected to offer the greatest stability of conditions, and the presence deep underground offers additional protection from other environmental media to help mitigate any release (although the Yellowknife example presents some uncertainty). The monofill alternative, because it is only used for one type of waste, can be designed to encourage conditions promoting the stability of mercury (e.g., conditions involving pH, oxygen availability). The bunker alternative provides a means of limiting rainfall and providing additional containment, in addition to the potential advantages of the monofill. Finally, conditions in the commercial landfill alternative are subject to the properties of the co-disposed, non-mercury wastes and represent the least stable conditions.

The alternatives also differ in the ability to monitor releases, if any. Deep underground disposal is expected to be the most difficult to monitor. The other alternatives, representing shallow disposal, are easier to monitor using conventional technologies. In these alternatives, however, if releases are identified it is very difficult to change or adjust the disposal conditions to prevent such occurrences in the future.

Public perception. As stated previously, it is extremely difficult to forecast the potential public perception of any alternative. Reaction can be neutral or even positive for an action identified as a suitable and defensible alternative for mercury management. This is assumed to be the case for the bunker and mine disposal alternatives, which are designed to mitigate some of the potential risks posed by conventional landfill disposal.

Costs. As discussed above, each of these alternatives have different cost components. These are summarized as follows:

- Commercial landfill: no upfront costs, estimated disposal costs of $100,000 to $600,000 for 1,500 tons of mercury.
- Monofill: upfront costs are unknown, estimated disposal costs similar to those for commercial landfill.
- Bunker: upfront costs are unknown with $240 million the only available estimate, for radioactive waste. Estimated disposal costs are $1.6 million to $3.2 million for 1,500 tons of mercury.
- Mine: upfront costs are unknown and may be included in the unit disposal costs. Disposal costs for 1,500 tons of mercury are estimated to range from $30 million to $90 million.

Each of the alternatives would require ongoing costs such as testing, monitoring, and operational costs.

3.4 <u>Evaluation of Options</u>

In this section, the various options are evaluated against the intensities associates with each criterion or sub-criterion. For storage, it is assumed that no pretreatment occurs and any post storage management (e.g., disposal) will not be planned until much later in the future. This results in three storage options: storage in a standard building, storage in a hardened building, and storage in a mine. This differs from the evaluation for treatment and disposal, in which each treatment option is evaluated with each disposal option. Specifically, the two treatment options and the four disposal options result in a total of eight (four multiplied by two) alternatives. As identified above, the two treatment options are as follows:

- One of the following three stabilization/amalgamation technologies:
  - DeHg amalgamation
  - SPSS process
  - Permafix sulfide process
- Selenide process

Altogether, 11 options for treatment, storage, and disposal were evaluated. These options are identified as follows:

- Storage of elemental mercury in a standard RCRA-permitted storage building
- Storage of elemental mercury in a hardened RCRA-permitted storage structure
- Storage of elemental mercury in a mine
- Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill
- Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill
- Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker
- Stabilization/amalgamation followed by disposal in a mined cavity
- Selenide treatment followed by disposal in a RCRA- permitted landfill
- Selenide treatment followed by disposal in a RCRA- permitted monofill
- Selenide treatment followed by disposal in an earth-mounded concrete bunker
- Selenide treatment followed by disposal in a mined cavity

The evaluation of each of the 11 alternatives against the various criteria, which is input to Expert Choice, is summarized in Tables 3-5 and 3-6. Table 3-5 includes half of the criteria for all of the options, and Table 3-6 includes the remaining criteria (all information could not be included in a single table). This table was generated using the data previously presented in Tables 3-1, 3-3, and 3-4. For example, data for the storage options are identical in Table 3-1 and Tables 3-5/3-6. For the treatment and disposal alternatives, information was integrated between Table 3-3 (for treatment) and Table 3-4 (for disposal). In most cases this integration was straightforward; Appendix D provides more detailed tables for each of the eight treatment and disposal alternatives to better show how this was conducted.

Table 3-5 Summary of Criteria Values Assigned to Each Evaluated Alternative

Alternative	Compliance with current laws and regulations	Implementation considerations		Maturity of the technology	
		Volume change of waste	Engineering requirements	State of maturity of the technology	Expected reliability of treatment step
Standard storage	Compliant	Zero or minimal	Existing facilities	Full-scale operation	No treatment
Hardened storage	Compliant	Zero or minimal	New facilities	Full-scale operation	No treatment
Mine storage	Non-compliant w/LDRs	Zero or minimal	New facilities	Full-scale operation	No treatment
S/A + landfill	Non-compliant w/LDRs	Increase > 10x	Existing facilities	Pilot trt/ full-scale disposal	Simple
S/A + monofill	Non-compliant w/LDRs	Increase > 10x	New facilities	Pilot trt/ full-scale disposal	Simple
S/A + bunker	Non-compliant w/LDRs	Increase > 10x	New facilities	Pilot trt/ untested disposal	Simple
S/A + mine	Atypical permit required	Increase > 10x	Mine cavity construction req'd	Pilot trt/ untested disposal	Simple
Se + landfill	Non-compliant w/LDRs	Increase > 10x	New facilities	Pilot trt/ full-scale disposal	Complex
Se + monofill	Non-compliant w/LDRs	Increase > 10x	New facilities	Pilot trt/ full-scale disposal	Complex
Se + bunker	Non-compliant w/LDRs	Increase > 10x	New facilities	Pilot trt/ untested disposal	Complex
Se + mine	Atypical permit required	Increase > 10x	Mine cavity construction req'd	Pilot trt/ untested disposal	Complex

Table 3-6 Continuation of Summary of Criteria Values Assigned to Each Evaluated Alternative

Alternative	Risks			Environmental Performance				Public perception	Cost	
	Worker Risk	Public Risk	Susceptibility to Terrorism/ Sabotage	Discharges During Treatment	Degree of Treatment Performance Testing	Stability of Conditions in the Long Term	Ability to Monitor		Implementation	Operating
Standard storage	Very low	Low	Low	No impact	Adequate	Poor	Easy and correctible	Negative	Low	High
Hardened storage	Very low	Very low	Very low	No impact	Adequate	Poor	Easy and correctible	Positive to neutral	Medium	High
Mine storage	Low	Very low	Very low	No impact	Adequate	Poor	Easy and correctible	Positive to neutral	Medium	High
S/A + landfill	Very low	Very low	Very low	Minimal	Moderate	Fair	Easy	Negative	Low	Low
S/A + monofill	Very low	Very low	Very low	Minimal	Moderate	Good	Easy	Negative	Medium	Low
S/A + bunker	Very low	Very low	Very low	Minimal	Moderate	Good	Easy	Positive to neutral	High	Medium
S/A + mine	Low	Very low	Very low	Minimal	Moderate	Very good	Difficult	Positive to neutral	High	Medium
Se + landfill	Low	Very low	Very low	Minimal	Low	Fair	Easy	Negative	Low	Low
Se + monofill	Low	Very low	Very low	Minimal	Low	Good	Easy	Negative	Medium	Low
Se + bunker	Low	Very low	Very low	Minimal	Low	Good	Easy	Positive to neutral	High	Medium
Se + mine	Low	Very low	Very low	Minimal	Low	Very good	Difficult	Positive to neutral	High	Medium

4.0 RESULTS

This section presents base-case results (Section 4.1), a sensitivity analysis (Section 4.2), and a discussion of uncertainty (Section 4.3).

4.1 Initial Results

The 11 options identified in the previous section of this report were evaluated using the Expert Choice software. The data from Tables 3-5 and 3-6 are used as inputs to the model. The model outputs provide results based on comparisons to the criteria and to the other alternatives. While the input to the model is somewhat narrative (based on Tables 3-5 and 3-6), the output provides a single numerical result for each alternative.

To interpret the results, it is important to note that no alternative will achieve a 'perfect score,' however defined. This is because the options are evaluated partially against each other, so that the total score will always equal unity no matter how many options are evaluated. In addition, as the number of options increases or decreases, the score of each option will change to maintain the same sum of scores of all options (i.e., unity). In this manner, the results are best interpreted as scores *relative* to each other, rather than the *absolute* value of an option's score.

Table 4-1 presents the Expert Choice results for each of the eleven alternatives discussed in the previous section of this report. Three columns of results are presented. The first result represents the overall score when considering all criteria. The second result represents only those criteria comprising the six non-cost items (i.e., compliance with current laws and regulations, implementation considerations, maturity of the technology, risks, environmental performance, and public perception). The third result represents only the cost criteria. As described in Section 3, cost criteria and non-cost criteria each comprise 50 percent of the overall goal. The results from the model were multiplied by 1,000 for convenience to provide a score as a whole number, rather than as a decimal.

The three columns show the strong effect that cost criteria can have upon the results. For example, each of the two options involving treatment followed by commercial landfilling are clearly the lowest cost alternatives, based on these results, and contribute heavily towards a high overall score even though the results for the non-cost criteria are not as high. Similarly, the option of storage in a hardened building provides the best result when only non-cost criteria are considered. Because of its relatively low result for cost criteria, its overall result is only slightly better than average. Of course, putting more or less emphasis on cost factors would change the results.

Table 4-1 shows that the general order of the option scores are as follows when considering both cost and non-cost criteria: treatment and commercial landfill disposal options, storage options, treatment and monofill disposal options, treatment and concrete bunker disposal options, and treatment and mine disposal options. When cost criteria are not considered, the general order changes to the following: storage options, concrete bunker disposal options, commercial landfill disposal options, mine disposal options, and monofill disposal options. Section 4.2 helps explain how contributions from individual criteria influence the results.

Table 4-1 Summary of Results for 11 Evaluated Alternatives

Alternative	Ranking (as fraction of 1,000)					
	Overall		Non-Costs Only		Costs Only	
	Score	Rank	Score	Rank	Score	Rank
Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill	137	1	99	5	217	1
Selenide treatment followed by disposal in a RCRA- permitted landfill	123	2	66	9	217	1
Storage of elemental mercury in a standard RCRA-permitted storage building	110	3	152	2	126	5
Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill	103	4	92	7	135	3
Storage of elemental mercury in a hardened RCRA-permitted storage structure	95	5	173	1	44	6
Selenide treatment followed by disposal in a RCRA- permitted monofill	94	6	74	8	135	3
Storage in a mine	81	7	140	3	44	6
Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker	70	8	108	4	42	8
Stabilization/amalgamation followed by disposal in a mined cavity	63	9	97	6	42	8
Selenide treatment followed by disposal in an earth-mounded concrete bunker	62	10	a	a	a	a
Selenide treatment followed by disposal in a mined cavity	61	11	a	a	a	a
Number of alternatives evaluated	11	—	9	—	9	—
Total	1,000	—	1,000	—	1,000	—
Average score (total divided by number of alternatives, either 9 or 11)	91	—	111	—	111	—

Shading indicates the highest-ranking alternative.

a These options were evaluated for the overall goal but were not evaluated at the lower levels of cost and non-cost items separately, due to the low score from the overall evaluation.

Because storage options rank high in this analysis, storage appears to be a viable option for the long-term management of mercury. Storage is generally only a temporary solution, however, because the ultimate disposition of mercury would not be achieved. Nevertheless, during the time that decisions take place regarding more permanent solutions, storage can be a good alternative while longer-term mercury disposition solutions are formatted.

Another important consideration is the relative difference between the results for each alternative. Given that each alternative will result in a different numerical score, it must be determined if the magnitude of these differences are large enough to be significant, or whether the results indicate that the numerical results are similar. In general, small differences between one option and another indicate that no discernible difference exists between the two. A determination of what is ‘small’ can be addressed in several ways. One is through examination of the sensitivity analysis, as identified in Section 4.2. A second is by conducting an uncertainty analysis, as described in Section 4.3.

Another method is by assessing the range in potential results. By evaluating two extreme, hypothetical options where one option receives the highest intensities for each criteria and the second option receives the lowest intensities for each criteria, such a range can be determined. When this is conducted using the data for weightings and intensities presented in Appendix A, the range between an option which scores the 'highest' for all criteria and that which scores the 'lowest' for all criteria is a factor of 7.2 (i.e., the result for one option is 7.2 times greater than the other). This overall, hypothetical range should be kept in mind when interpreting results of these analyses. For the results in Table 4-1, the difference between the highest option and the lowest option results in a difference of a factor of 2.2, when considering the results for the overall analysis in the first column. This indicates that, even when comparing the highest-ranking alternative to the lowest ranking alternative in Table 4-1, the difference between the two is not extreme.

4.2 Sensitivity Analysis

Sensitivity analyses were conducted within Expert Choice. These analyses served two functions: (1) to provide insight into how the overall scores were generated, and (2) to identify how greater emphasis on different criteria would influence the results. In the baseline analysis, each alternative was evaluated according to the following non-cost and cost criteria. The percentages in parentheses represent the value of each criterion in developing the overall score:

- Non-cost criteria (50% of total)
    - Environmental performance (33.1% of non-cost criteria)
    - Potential for accidents or risks to public safety (31.1% of non-cost criteria)
    - Implementation considerations (13.8% of non-cost criteria)
    - Public perception (11.4% of non-cost criteria)
    - Maturity of technology (6.1% of non-cost criteria)
    - Compliance with current laws and regulations (4.5% of non-cost criteria)
- Cost criteria (50 % of total)
    - Implementation cost (50% of cost criteria)
    - Operating cost (50% of cost criteria)

The results from Table 4-1 show how the different alternatives are affected by changes in the importance of cost criteria. The sensitivity analyses similarly identify how changes in the importance of different criteria affect the results, although at a more detailed level. For example, in the initial results presented in Table 4-1, environmental performance criteria contributed to 33.1% of all non-cost criteria. A sensitivity analysis is a type of 'what-if?' analysis where the contribution of this criterion is made extremely important, contributing 90% (+/- 1%) of all non-cost criteria, with the remaining five criteria contributing a combined importance of only 10%. A similar type of analysis is conducted for all six non-cost criteria, and the two cost criteria, analyzing the results as each criterion is alternately made the most important.

4.2.1 Sensitivity Analyses for Non-Cost Criteria

The sensitivity analysis results are summarized in Table 4-2 for non-cost criteria. Note that Table 4-2 does not consider cost criteria at all to better understand the effects of non-cost objectives. The first column of results in Table 4-2, labeled 'baseline,' corresponds to the results in Table 4-1 when cost criteria are not considered. In this column, the importance of each of the six criteria is equal to the above percentages (e.g., environmental performance is 33.1%). The next columns list the sensitivity results for each of the six non-cost criteria. For example, for the environmental performance sensitivity analysis, the contribution of this criterion to the importance of all non-cost criteria was moved from 33.1% (i.e., the 'baseline' reflected in the first results column) to 90% (+/- 1%). The importance of each of the other five criteria was reduced proportionally so that the contributions from all six criteria add to 100 percent.

Some of the data in Table 4-2 are highlighted to emphasize results. The top two, three, or four ranking alternatives are highlighted (i.e., to account for the highest scoring alternatives, taking into account small or large differences in scores).

Some of the significant findings from the sensitivity analysis are as follows:

- Identifying the importance of criteria: the last row of Table 4-2 shows the ratio between the highest scoring alternative and the lowest scoring alternative. The higher the ratio, the more sensitive the criterion. For example, the ratio between the highest and lowest score from the catastrophic risks criterion is 1.6. This is due, in part, to the fact that each of the alternatives were assigned similar or identical values for this criterion. In contrast, compliance with the current regulatory climate resulted in the highest differences between the highest and lowest ranked alternative, a factor of 7.1. This indicates that this criterion can significantly impact results, if a high importance is placed on this criterion for evaluating the objective.
- Isolating how alternatives perform against individual criteria: this analysis demonstrates how an alternative performs when overriding, but not absolute, importance is placed on one criteria. Other criteria continue to influence the result. Nevertheless, the results are useful to show potential flaws in particular alternatives (e.g., ranks of 8s and 9s) as well as bright spots (e.g., ranks of 1s and 2s). Further discussion is provided below for individual criteria.
- Alternatives impacted by environmental performance criterion: the alternatives scoring the highest in this portion of the sensitivity analysis are the storage alternatives. Of the disposal options, the highest-ranking alternative is stabilization/ amalgamation treatment with mine disposal. As detailed in Section 2 of this report, environmental performance includes a number of sub-criteria including testing adequacy and disposal conditions, and therefore is not limited to performance in leaching tests.
- Alternatives impacted by catastrophic risk criterion: this portion of the sensitivity analysis demonstrates one drawback of standard aboveground storage, which is ranked last in this portion of the sensitivity analysis. However, as noted above, the ratio between the highest and lowest scores from catastrophic risks is only 1.6, so this should not be regarded as a severe disadvantage of the standard storage option.
- Alternatives impacted by implementation issues: a wide range between the highest ranking alternative and the lowest ranking alternative (a factor of 6.8) shows this criterion can significantly affect results for some alternatives. Disposal in a mined cavity is ranked last in this portion of the sensitivity analysis, while an ‘easy to implement’ option, storage in a standard building, ranks first.
- Alternatives impacted by public perception: vaues for this criteria have the greatest uncertainty, but the wide range in results suggests that it can impact results. Therefore, attempts to better gauge public perception issues would improve the selection of an appropriate alternative.
- Alternatives impacted by technology maturity: the results of this portion of the analysis are similar to the results for implementation issues.
- Alternatives impacted by current regulatory compliance: as expected, the only two alternatives that could be implemented without change to federal laws or regulations score the highest in this portion of the sensitivity analysis.

The sensitivity analysis demonstrates that if greater (or less) emphasis is placed on one particular criterion, then the results of the overall analysis will change. The general trend of the results in response to these changes can be predicted from Table 4-2.

Table 4-2 Sensitivity Analysis of Non-Cost Criteria[a]

Alternative	Ranking (as fraction of 1,000[b]; average score 111)													
	Non-Cost Baseline		Sensitivity: Env Perf		Sensitivity: Risks		Sensitivity: Implement		Sensitivity: Public		Sensitivity: Maturity		Sensitivity: Compliance	
	Score	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
Storage of elemental mercury in a hardened RCRA-permitted structure	173	1	176	1	142	1	172	2	197	1	226	1	263	1
Storage of elemental mercury in a standard RCRA-permitted building	152	2	173	2	87	9	259	1	52	5	224	2	261	2
Storage in a mine	140	3	145	3	101	5	168	3	193	2	223	3	78	3
Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker	108	4	94	5	132	2	57	5	190	3	52	6	74	4
Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill	99	5	71	8	131	3	146	4	46	6	67	4	73	5
Stabilization/amalgamation followed by disposal in a mined cavity	97	6	110	4	95	6	38	9	189	4	51	7	37	9
Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill	92	7	92	6	130	4	55	6	46	6	66	5	73	5
Selenide treatment followed by disposal in a RCRA- permitted monofill	74	8	81	7	92	7	53	7	44	8	46	8	71	7
Selenide treatment followed by disposal in a RCRA- permitted landfill	66	9	58	9	91	8	52	8	43	9	45	9	70	8
Total	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—
Range: highest to lowest alternative	2.6 times		3.0 times		1.6 times		6.8 times		4.6 times		5.0 times		7.1 times	

Shading indicates the two, three, or four highest-ranking alternatives. Cut-off determined by where there is a big drop in the score.

In the sensitivity analysis for each criterion, the importance of the criterion is set at 90 percent. The five other criteria comprise the remaining ten percent, proportional to their original contributions.

[a] Two options were not evaluated for the sensitivity analysis: selenide treatment followed by disposal in a mined cavity, and selenide treatment followed by disposal in an earth-mounded concrete bunker. This is because of the low score from the overall evaluation and the version of Expert Choice used for this analysis only allowed the use of nine alternatives for the sensitivity analysis.

[b] Scores normalized to total 1,000.

4.2.2 Sensitivity Analyses for Cost Criteria

The sensitivity analysis results are summarized in Table 4-3 for cost criteria. Note that Table 4-3 only includes two criteria as identified in Section 2 of this report. The format of Table 4-3 is very similar to that for Table 4-2. The first column of results in Table 4-3, labeled 'baseline,' corresponds to the results in Table 4-1 when only cost criteria are considered. In this column, the importance of each criterion is equal (i.e., both implementation and operating costs contribute equally to the total 'cost scores. The next columns list the sensitivity of the results of each of these two cost criteria. For example, for the implementation cost sensitivity analysis, the contribution of this criterion to the importance of both non-cost criteria was moved from 50% (i.e., the 'baseline' reflected in the first results column) to 90% (+/- 1%). The importance of the other criterion was reduced proportionally (to 10%), so that the contributions from both criteria add to 100 percent.

Some of the data in Table 4-3 are highlighted to emphasize results. The top two, three, or four ranking alternatives are highlighted (i.e., to account for the highest scoring alternatives, taking into account small or large differences in scores).

Some of the significant findings from the sensitivity analysis are as follows:

- Identifying the importance of criteria: The last row of the Table 4-3 shows the ratio between the highest scoring alternative and the lowest scoring alternative. The higher the ratio, the more sensitive the criterion. The ratio is relatively high for each of the two criteria indicating that each can significantly affect results for the overall objective.
- Differences between implementation costs and operating costs: In the 'baseline' results presented in Table 4-1, equal weight was given for each of implementation and operating costs. Table 4-3 helps demonstrate how results for alternatives would be impacted if one or the other criterion was given more importance. In most cases, alternatives which score high in the implementation cost sensitivity analysis also score well in the operating cost sensitivity analysis. However, for some cases there appear to be greater differences. For example, the sensitivity analysis for implementation costs for standard aboveground storage results in a high score for this alternative. The sensitivity analysis for operating cost gives a low score for this alternative. Therefore, placing a different level of importance on these two criteria would result in significant differences in results.

The sensitivity analysis demonstrates that if greater (or less) emphasis is placed on one particular criterion, then the results of the overall analysis will change. The general trend of the results in response to these changes can be predicted from Table 4-3.

4.3 Discussion of Uncertainty

Uncertainty identifies the extent to which variation in the information and data influences appropriate conclusions. An uncertainty analysis is conducted to assess confidence in the results. In this section of the report, uncertainty is incorporated into the analysis by using (1) ranges of available information and data, and (2) 'what-if' analyses for cases in which the true range is unknown or not well defined. For example, a different calculation, or assessment, is generated for values associated with the extreme of a range.

Table 4-3 Sensitivity Analysis of Cost Criteria to Results for 9 Evaluated Alternatives[a]

Alternative	Ranking (as fraction of 1,000; average score 111)					
	Cost Baseline		Sensitivity: Implementation Cost		Sensitivity: Operating Costs	
	Score	Rank	Score	Rank	Score	Rank
Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill	217	1	227	1	207	1
Selenide treatment followed by disposal in a RCRA- permitted landfill	217	1	227	1	207	1
Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill	135	3	79	4	190	3
Selenide treatment followed by disposal in a RCRA- permitted monofill	135	3	79	4	190	3
Storage of elemental mercury in a standard RCRA-permitted storage building	126	5	209	3	43	7
Storage of elemental mercury in a hardened RCRA-permitted storage structure	44	6	61	6	27	8
Storage in a mine	44	6	61	6	27	8
Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker	42	8	28	8	55	5
Stabilization/amalgamation followed by disposal in a mined cavity	42	8	28	8	55	5
Total	1,000	—	1,000	—	1,000	—
Range: highest to lowest alternative	5.2 times		8.1 times		7.7 times	

Shading indicates the two, three, or four highest-ranking alternatives.

[a] Two options were not evaluated for the sensitivity analysis: selenide treatment followed by disposal in a mined cavity, and selenide treatment followed by disposal in an earth-mounded concrete bunker. This is because of the low score from the overall evaluation and the version of Expert Choice used for this analysis only allowed the use of nine alternatives for the sensitivity analysis.

Section 3 of this report identifies the values used in the analysis. It also discusses the certainty, or confidence, associated with some of the data. Rather than identify all the areas of uncertainty and attempt to address each of them for every alternative, this section of the analysis will identify the sources of uncertainty identified in Section 3 that are expected to impact the results and demonstrate their effect for selected alternatives. These areas of uncertainty include the following:

- Environmental performance - long term stability: it is difficult or impossible to predict future conditions impacting environmental releases in a disposal environment. Therefore, this represents an obvious area of uncertainty.
- Public perception: again, it is difficult to assess what local and national attitudes will be towards any of the alternatives.
- Cost data: the publicly available cost data for treatment alternatives showed an extremely wide range. In addition, the operating costs for storage options include projected costs for future treatment and disposal. Future management practices and their costs, as well as whether additional management would be needed, are also uncertain. Finally,

implementation cost estimates for mine storage could potentially vary between those estimated for more typical storage (i.e., generally low costs) to those for mine disposal (i.e., generally high costs).

- Technology maturity of treatment and storage alternatives. Each of the treatment alternatives has been demonstrated for limited quantities of mercury or mercury-containing wastes. There is uncertainty as to whether treatment of additional quantities would raise any unforeseen difficulties. Some of the storage alternatives may present similar uncertainties.
- Waste volume increase: No data were available for the increase in waste volume during the treatment of elemental mercury in the selenide process.

The analysis described in this section takes into account the uncertainty of the above parameters for some of the evaluated alternatives. A series of different analyses were conducted using Expert Choice, for several of the selected alternatives to better identify the impact that uncertainty has on the results. These analyses and results are described in Table 4-4. Each row of the table represents an instance where data are changed for just one of the alternatives. Table 4-4 presents results when compared against both cost and non-cost objectives. As shown, a total of 12 different uncertainty analyses were conducted.

The 12 sets of uncertainty analysis results in Table 4-4 show how the overall ranking of each alternative is affected as the intensities of individual criteria are changed. These uncertainty analyses show that results change most significantly in the case of costs, which may cover the wide range of available information. The uncertainty analysis can be used to identify important parameters in which further research may be required. That is, particular attention could be placed on uncertain data, which significantly affect the results.

In general, Table 4-4 shows that changes in a single criterion produce relatively small effects in the overall rankings, except in certain cases involving costs. For example, if the operating costs for storage in a hardened structure were changed from high to low, the overall rank of the alternative is greatly improved. This change in the intensity of the criterion would correspond to a case where only the maintenance costs of storage are considered, rather than any subsequent long-term disposal costs following storage.

A true uncertainty analysis should take into account potential simultaneous variations in all of the values that are input to the Expert Choice calculation. This can in principle be done by using Monte-Carlo-based techniques. However, the limited funding available meant that this was not feasible in the course of the present work.

Table 4-4 Uncertainty Analysis for Mercury Management Alternatives

Ref. No.	Alternative	Criteria	Change in Intensity for Uncertainty Analysis		Initial Result (Table 4-1)		Uncertainty Analysis Result	
			Baseline	Change	Score	Rank	Score	Rank
0	All	Baseline for comparison: Same results as Table 4-1			—	—	—	—
1	Storage in a mine	Stability of disposal conditions	Poor	Very good	81	7	87	7
2	Stabilization/ amalgamation followed by disposal in a RCRA- permitted monofill	Stability of disposal conditions	Good	Poor	103	4	100	4
3	Storage of elemental mercury in a standard RCRA-permitted building	Public perception	Negative	Positive to neutral	110	3	117	3
4	Storage of elemental mercury in a hardened RCRA-permitted building	Public perception	Positive to neutral	Negative	95	5	88	6
5	Storage in a mine	Implementation costs	Medium	High	81	7	74	7
6	Selenide treatment followed by disposal in an earth mounded concrete bunker	Implementation costs	High	Medium	62	10	69	9
7	Stabilization/ amalgamation followed by disposal in a RCRA- permitted landfill	Operating Costs	Low	High	137	1	101	4
8	Stabilization/ amalgamation followed by disposal in a RCRA- permitted landfill	Operating Costs	Low	Medium	137	1	110	3
9	Storage of elemental mercury in a hardened RCRA-permitted structure	Operating Costs	High	Low	95	5	130	2
10	Selenide treatment followed by disposal in a mined cavity	State of Technology Maturity	Pilot treatment/ untested disposal	Full scale operation	61	11	63	9
11	Storage of elemental mercury in a hardened RCRA-permitted building	State of Technology Maturity	Full scale operation	Pilot treatment/ untested disposal	95	5	93	6
12	Selenide treatment followed by disposal in a RCRA- permitted landfill	Volume of waste increase	Increase greater than 10 times	Increase up to 10 times	123	2	124	2

5.0 CONCLUSIONS AND RECOMMENDATIONS

A limited scope decision-analysis has been performed to compare options for the retirement of surplus mercury. The analysis has demonstrated that such a study can provide useful insights for decision-makers. Future work could include:

1. Involve additional experts in the process of assigning weights to the various criteria. The individuals involved in producing the current report were exclusively from SAIC. They are listed at the beginning of Section 2.0. This would ensure that a wide range of expertise is incorporated into the analysis. For example, working groups within EPA, involving a cross-section of EPA offices, would provide additional perspectives. Other examples would involve the inclusion of other Federal agencies, States, nongovernmental organizations, foreign governments, industry, and academia. Such participation could be performed in stages. As shown in the sensitivity analysis in Section 4.2 of this report, differences in the importance of the criteria relative to one another can strongly affect the results.

2. The alternatives considered in this report were limited to elemental mercury. Additional alternatives could be considered for mercury-containing wastes.

3. Additional Expert Choice analyses could be conducted in which certain alternatives are optimized. For example, within the general alternative of stabilization/ amalgamation treatment followed by landfill disposal are sub-alternatives addressing individual treatment technologies or landfill locations. Such optimization, however, is unlikely to be necessary until a general alternative is selected or more detailed criteria are established to assess the more detailed alternatives.

4. Revisit the available information periodically to determine if changes in criteria, or changes in intensities, are required. For example, some candidate criteria were not considered because insufficient information was available. One example is volatilization of mercury during long-term management. Very little data are available at this time to adequately address this as a possible criterion.

5. Consider performing a formal uncertainty analysis utilizing Monte-Carlo-based techniques.

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APPENDIX A
THE ANALYTICAL PROCESS AND THE EXPERT CHOICE MERCURY RETIREMENT MODEL

THE ANALYTIC HIERARCHY PROCESS

The analytic hierarchy process (AHP), developed at the Wharton School of Business by Thomas Saaty, allows decision makers to model a complex problem in a hierarchical structure showing the relationships of the goal, objectives (criteria), sub-objectives, and alternatives as show in Figure A-1. Uncertainties and other influencing factors can also be included.

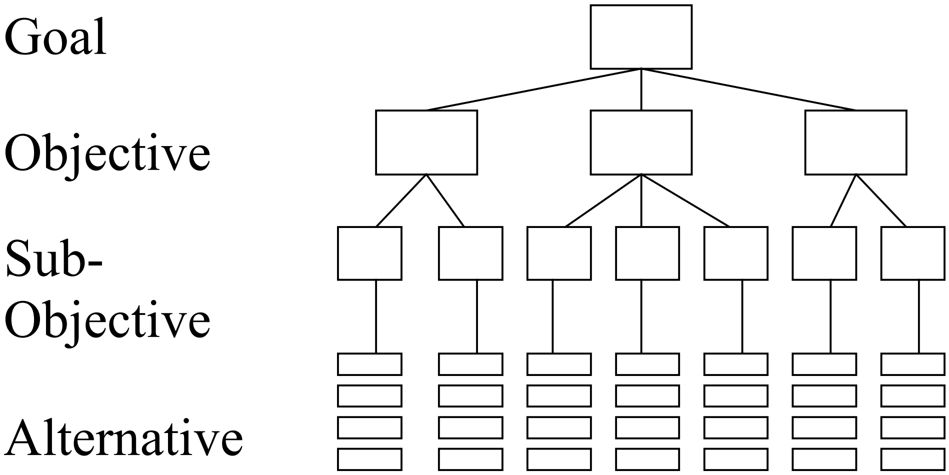


Figure A-1 Decision Hierarchy

AHP allows for the application of data, experience, insight, and intuition in a logical and thorough way. AHP enables decision-makers to derive ratio scale priorities or weights as opposed to arbitrarily assigning them. In doing so, AHP not only supports decision-makers by enabling them to structure complexity and exercise judgment, but also allows them to incorporate both objective and subjective considerations in the decision process. AHP is a compensatory decision methodology because alternatives that are deficient with respect to one or more objectives can compensate by their performance with respect to other objectives. AHP is composed of several previously existing, but unassociated concepts and techniques such as hierarchical structuring of complexity, pairwise comparisons, redundant judgments, and the Eigenvector method for deriving weights, and consistency considerations. Although each of these concepts and techniques were useful in and of themselves, Saaty's synergistic combination of the concepts and techniques along with some new developments produced a process whose power is indeed far more than the sum of its parts (Formar and Selly, Undated).

One of the major benefits of AHP is that the theory does not demand perfect consistency. AHP allows inconsistency, but provides a measure of the inconsistency in each set of judgments. This inconsistency measure is an important by-product of the process of deriving priorities based on pairwise comparisons. Being consistent is often thought of as a prerequisite to clear thinking. However, the real world is hardly ever perfectly consistent. Another reason for inconsistency is lack of information about the factors being compared. An inconsistency ratio of about 10% or less is usually considered acceptable. With the model developed for mercury retirement options, consistency ratios of 0-6% were achieved.

AHP is built on a solid yet simple theoretical foundation based on three basic principles: decomposition, comparative judgments, and hierarchic composition or synthesis of priorities. The decomposition principle is applied to structure a complex problem into a hierarchy of clusters, sub-clusters, and so on. The principle of comparative judgments is applied to construct pairwise comparisons of all combinations of elements in a cluster with respect to the parent of the cluster. These pairwise comparisons are used to derive "local" priorities of the elements in a cluster with respect to their parent. The principle of hierarchic composition of synthesis is applied to multiply the local priorities of elements in a cluster by the "global" priority of the parent element, producing global priorities for the lowest level elements (the alternatives) (Saaty, 1980).

All theories are based on axioms. The simpler and fewer the axioms, the more general and applicable is the theory. Originally, AHP was based on three relatively simple axioms. The first axiom, the reciprocal axiom, requires that if $P_C(E_A, E_B)$ is a paired comparison of elements A and B with respect to their parent, element C, representing how many times more element A possesses a property than does element B, then $P_C(E_B, E_A) = 1/P_C(E_A, E_B)$. For example, if A is 5 times larger than B, then B is one fifth as large as A.

The second, or homogeneity axiom, states that the elements being compared should not differ by too much, else there will tend to be larger errors in judgment. When constructing a hierarchy of objectives, one should attempt to arrange elements in a cluster so that they do not differ by more than an order of magnitude. (The AHP verbal scale ranges from 1 to 9, or about an order of magnitude. The numerical and graphical modes of Expert Choice accommodate almost two orders of magnitude, allowing a relaxation of this axiom. Judgments beyond an order of magnitude generally result in a decrease in accuracy and increase in inconsistency).

The third axiom states that those judgments about, or the priorities of, the elements in a hierarchy do not depend on lower level elements. This axiom is required for the principle of hierarchic composition to apply. While the first two axioms are always consonant with real work applications, this axiom requires careful examination, as it is not uncommon for it to be violated.

A fourth axiom, introduced later by Saaty, says that individuals who have reasons for their beliefs should make sure that their ideas are adequately represented for the outcome to match these expectations. While this axiom might sound a bit vague, it is very important because the generality of AHP makes it possible to apply AHP in a variety of ways and adherence to this axiom ensures the application AHP in appropriate ways.

Most mathematicians will agree that the simplest of two or more competing theories is preferable. As discussed above, the axioms behind AHP are simple. This simplicity and the ratio scale measures that AHP produces make it a powerful decision theory.

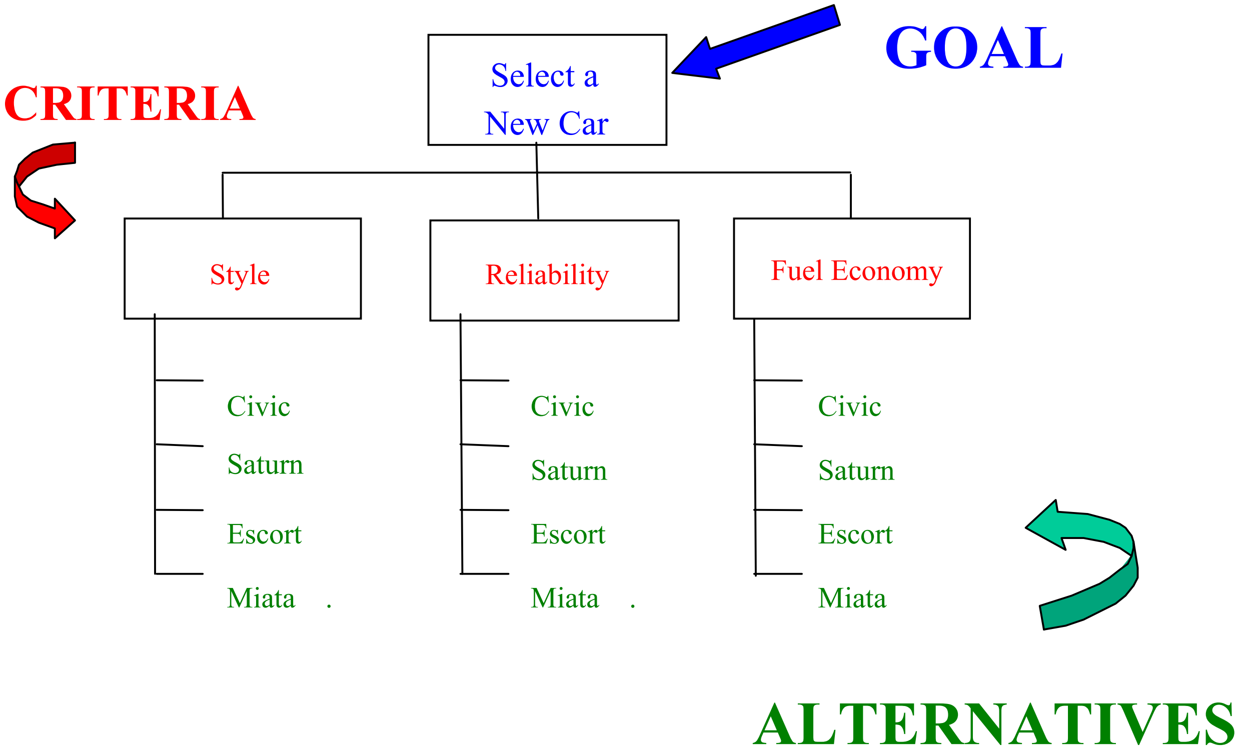
MATHEMATICS OF AHP

The following example of the decision making process behind buying a new car illustrates AHP and the associated mathematics used to derive weights and priorities (TASC, Undated). An approximation to the Eignevector method suitable for hand calculations is used. While this approximation is reasonable when the judgements are consistent, it may not be so for inconsistent judgements and is therefore not recommended unless a computer and software are available.

The first three steps are to:

- State the Goal:
  - Select a New Car
- Define the Criteria (or Objectives)
  - Style (i.e., want a good looking car)
  - Reliability (i.e., want a reliable car)
  - Fuel Economy (i.e., want a fuel efficient car)
- Identify the Alternatives:
  - Civic Coupe
  - Saturn Coupe
  - Ford Escort
  - Mazda Miata

This information is then arranged in a hierarchical tree as follows:



To determine the relative importance or ranking of the criteria or objectives by making judgements using the established scale below:

1 Equal	3 Moderate	5 Strong	7 Very Strong	9 Extreme

Thus, one possible outcome of a brainstorming sessions would be that:

1. Reliability is 2 times as important as style
2. Style is 3 times as important as fuel economy

3. Reliability is 4 times as important as fuel economy

This can be expressed as a matrix

$$
\begin{array}{l}
 \\
\text{Style} \\
\text{Reliability} \\
\text{Fuel Economy}
\end{array}
\begin{array}{ccc}
\text{Style} & \text{Reliability} & \text{Fuel Economy} \\
\end{array}
$$

$$
\begin{array}{l|ccc}
 & \text{Style} & \text{Reliability} & \text{Fuel Economy} \\
\hline
\text{Style} & 1/1 & 1/2 & 3/1 \\
\text{Reliability} & 2/1 & 1/1 & 4/1 \\
\text{Fuel Economy} & 1/3 & 1/4 & 1/1
\end{array}
$$

To get a ranking of priorities from a pair wise matrix, Eigenvectors are used. The Eigenvector solution was demonstrated mathematically as the best approach by Dr. Saaty. To solve for the Eigenvector:

1. In successive calculations, square the matrix.
2. The row sums are then calculated and normalized
3. Stop when the difference between these sums in two consecutive calculations is smaller than a prescribed value

First convert the fractions to decimals so that standard matrix algebra can be used:

$$
\begin{array}{l|ccc}
 & \text{Style} & \text{Reliability} & \text{Fuel Economy} \\
\hline
\text{Style} & 1.0000 & 0.5000 & 3.0000 \\
\text{Reliability} & 2.0000 & 1.0000 & 4.0000 \\
\text{Fuel Economy} & 3.0000 & 0.2500 & 1.0000
\end{array}
$$

Step 1. Square the matrix, using standard rules of matrix

$$
\begin{bmatrix}
1.0000 & 0.5000 & 3.0000 \\
2.0000 & 1.0000 & 4.0000 \\
3.0000 & 0.2500 & 1.0000
\end{bmatrix}
\quad \text{times} \quad
\begin{bmatrix}
1.0000 & 0.5000 & 3.0000 \\
2.0000 & 1.0000 & 4.0000 \\
3.0000 & 0.2500 & 1.0000
\end{bmatrix}
$$

so that, for example, (1.0000 * 1.0000) + (0.50000 * 2.0000) + (3.0000* 0.3333) = 3.0000 gives the first entry in the squared matrix, which is as follows:

$$
\begin{bmatrix}
3.0000 & 1.7500 & 8.0000 \\
5.3332 & 3.0000 & 14.0000 \\
1.1666 & 0.6667 & 3.0000
\end{bmatrix}
$$

Step 2. Compute the first Eigenvector

First, sum the rows,

$$
\begin{bmatrix}
3.0000 & + & 1.7500 & + & 8.0000 \\
5.3332 & + & 3.0000 & + & 14.0000 \\
1.1666 & + & 0.6667 & + & 3.0000
\end{bmatrix}
\begin{array}{cr}
= & 12.7500 \\
= & 22.3332 \\
= & 4.8333
\end{array}
$$

Next sum the row totals (i.e., 12.7500 + 22.3332, + 4.8333 = 39.9165), and then normalize by dividing the row sum by the row totals.

$$\begin{array}{lcr} 12.7500/39.9165 & = & 0.3194 \\ 22.3332/39.9165 & = & 0.5595 \\ 4.8333/39.9165 & = & \underline{0.1211} \\ & & 1.0000 \end{array}$$

The result is our Eigenvector:

$$\begin{bmatrix} 0.3194 \\ 0.5595 \\ 0.1211 \end{bmatrix}$$

This process must be iterated until the Eigenvector solution does not change from the previous iteration. Therefore, continuing the example, again we square our resulting matrix from the first iteration (step 1).

$$\begin{bmatrix} 3.0000 & + & 1.7500 & + & 8.0000 \\ 5.3332 & + & 3.0000 & + & 14.0000 \\ 1.1666 & + & 0.6667 & + & 3.0000 \end{bmatrix}$$

which results in

$$\begin{bmatrix} 27.6653 & + & 15.8330 & + & 72.4984 \\ 48.3311 & + & 27.6662 & + & 126.6642 \\ 10.5547 & + & 6.0414 & + & 27.6653 \end{bmatrix}$$

Next compute the Eigenvector (step 2):

$$\begin{bmatrix} 27.6653 & + & 15.8330 & + & 72.4984 \\ 48.3311 & + & 27.6662 & + & 126.6642 \\ 10.5547 & + & 6.0414 & + & 27.6653 \end{bmatrix} \begin{array}{crr} = & 115.9967 & 0.3196 \\ = & 202.6615 & 0.5584 \\ = & \underline{44.2612} & \underline{0.1220} \\ & 362.9196 & 1.0000 \end{array}$$

Finally, compute the difference between the previously computed Eigenvector and this one:

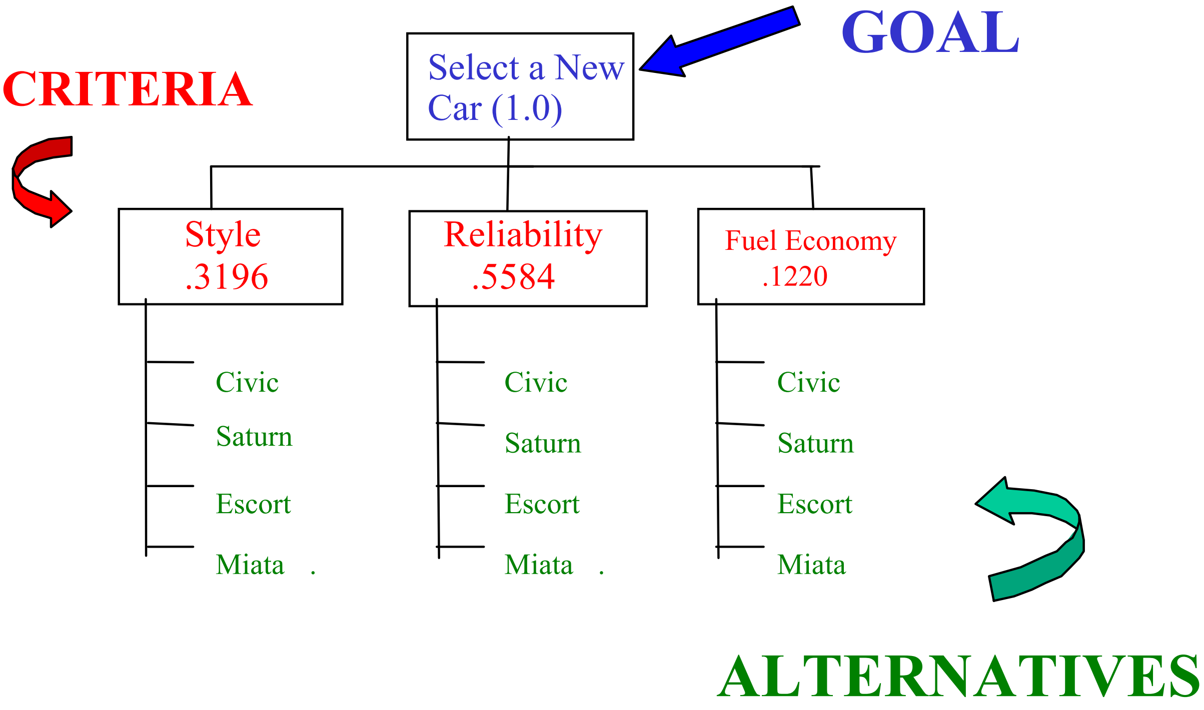
$$\begin{bmatrix} 0.3194 \\ 0.5595 \\ 0.1211 \end{bmatrix} \begin{array}{c} - \\ - \\ - \end{array} \begin{bmatrix} 0.3196 \\ 0.5584 \\ 0.1220 \end{bmatrix} \begin{array}{c} = \\ = \\ = \end{array} \begin{bmatrix} -0.0002 \\ 0.0011 \\ -0.0009 \end{bmatrix}$$

This process should be continued until there is no difference to four decimal places. Although it is helpful to understand the mathematics behind the decision theory, it is not necessary to know how to do the calculations as Expert Choice, does all the calculations automatically.

The computed Eigenvector provides us the relative ranking of our criteria or objectives. Using the second computed Eigenvector as an example,

$$\begin{array}{l} \text{Style} \\ \text{Reliability} \\ \text{Fuel Economy} \end{array} \begin{bmatrix} 0.3196 \\ 0.5584 \\ 0.1220 \end{bmatrix} \begin{array}{l} \longleftarrow \text{The second most important criterion} \\ \longleftarrow \text{The most important criterion} \\ \longleftarrow \text{The least important criterion} \end{array}$$

Going back to our hierarchical tree, our weights would be shown as follows:



Next, the same type of pairwise comparisons would be performed for each of the alternatives. For example, in terms of style, pairwise comparisons determines the preferences of each alternative over another:

	Civic	Saturn	Escort	Miata
Civic	1/1	1/4	4/1	1/6
Saturn	4/1	1/1	4/1	1/4
Escort	1/4	1/4	1/1	1/5
Miata	6/1	4/1	5/1	1/1

Following the above steps, the Eigenvector would be computed to determine the relative ranking of alternatives, namely:

$$\begin{array}{l} \text{Civic} \\ \text{Saturn} \\ \text{Escort} \\ \text{Miata} \end{array} \begin{bmatrix} .1160 \\ .2470 \\ .0600 \\ .5770 \end{bmatrix}$$

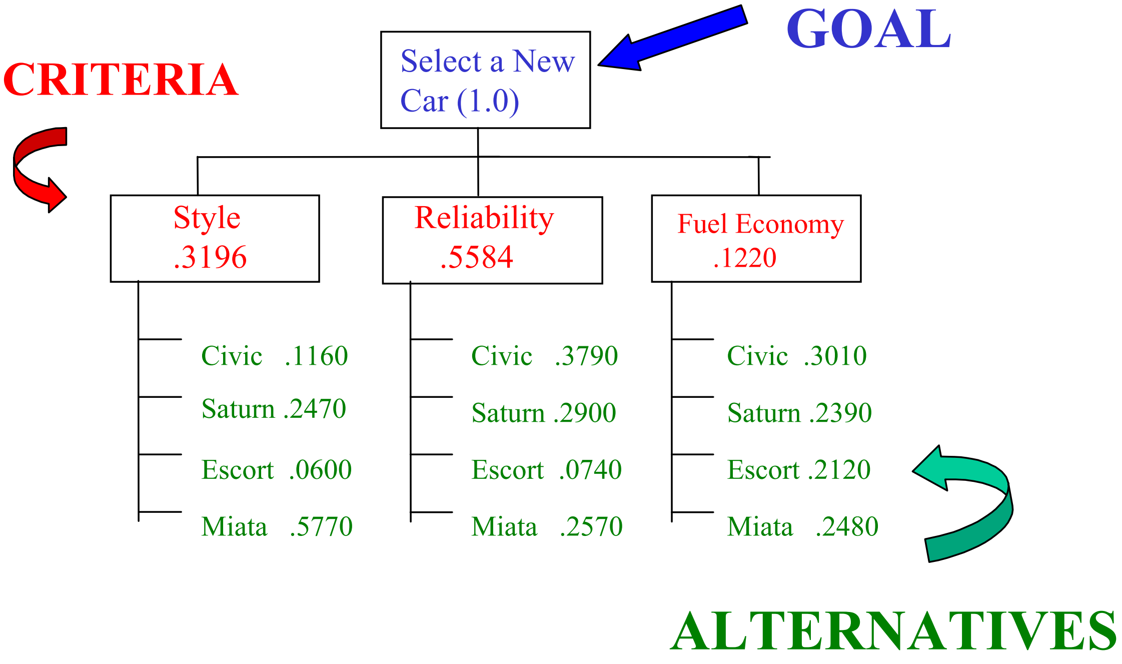
The Eigenvector and ranking of alternatives for reliability would be accomplished the same way. Since AHP can combine both qualitative and quantitative information, fuel economy information in miles per gallon for each alternative would be obtained and normalized to allow it to be used with the other rankings as shown below.

Civic	34	34/113	=	.3010
Saturn	27	27/113	=	.2390
Escort	24	24/113	=	.2120
Miata	28	28/113	=	.2480
	113			1.0000

The populated hierarchical tree with all the weights is shown on the following page. To derive the solution, matrix algebra is used one more time to multiply the alternative weights by the criteria weights.

$$\begin{array}{l|ccc|} & \text{Style} & \text{Reliability} & \text{Fuel Economy} \\ \text{Civic} & .1160 & .3790 & .3010 \\ \text{Saturn} & .2470 & .2900 & .2390 \\ \text{Escort} & .0600 & .0740 & .2120 \\ \text{Miata} & .5770 & .2570 & .2480 \end{array} * \begin{array}{|c|l} \text{Criterion} & \\ .3196 & \text{Style} \\ .5584 & \text{Reliability} \\ .1220 & \text{Fuel Economy} \\ & \end{array}$$

$$= \begin{array}{l|c|} \text{Civic} & .3060 \\ \text{Saturn} & .2720 \\ \text{Escort} & .0940 \\ \text{Miata} & .3280 \end{array}$$



The end results show that the Miata is the best choice for the stated criteria based on the highest ranking of .3280. Of course costs were not included. Although costs could have been included, in many complex decisions, costs should be set aside until the benefits of the alternatives are evaluated. Discussing costs together with benefits can sometimes bring forth many political and emotional responses. There are several ways to handle benefits and costs to include:

1. Graphing benefits and costs of each alternative and chose the alternative with the lowest cost and highest benefit.

2. Benefit to cost ratios
3. Linear programming
4. Separate benefit and cost hierarchical trees and then combine the results

Using the benefits to cost ratios for the simple car example, the Civic would then become the best choice.

	Cost	Normalized Costs	Benefit to Cost Ratios		
1. Miata	$18,000	.3333	.3280/.3333	=	.9840
2. Civic	$12,000	.2222	.3060/.2222	=	1.332
3. Saturn	$15,000	.2778	.2720/.2778	=	.9791
4. Escort	$9,000	.1667	.0940/.1667	=	.5639
	$54,000	1.000			

EXPERT CHOICE

Expert Choice was developed in 1983 and as of 1995, was being used by major Fortune 100 companies such as IBM, Ford, General Electric and Rockwell; numerous government agencies to include the FAA, VA, GSA, the U.S. Navy, and the U.S. Air Force; and in 57 countries throughout the world. The list of commercial and government users and sponsors continues to grow today as AHP gains wider understanding and acceptance. Expert Choice automates the analytic hierarchy process and calculates all of the mathematical computations detailed in the earlier section. It provides an easy to use graphical interface for structuring the decision problem as a hierarchy and deriving ratio scales measures through pairwise relative comparisons.

The pairwise comparison process can be performed in Expert Choice using words, numbers, or graphical bars, and typically incorporates redundancy, which results in a reduction of measurement error as well as producing a measure of consistency of the comparison judgments. Humans are much more capable of making relative rather than absolute judgments. The use of redundancy permits accurate priorities to be derived from verbal judgments even though the words themselves are not very accurate. Therefore, words can be used to compare qualitative factors and derive ratio scale priorities that can be combined with quantitative factors. In addition, Expert Choice allows the conduct of sensitivity analysis. Sensitivity analysis allows the investigation of the effect on the optimal solution or ranking if the objectives or criteria take on other possible values or weights. Usually there are some parameters that can be assigned any reasonable value without affecting the optimality of the solution. However, there may also be parameters with likely values that would yield a new optimal solution. Therefore, the basic objective of sensitivity analysis is to identify these particularly sensitive parameters so that special care can then be taken in estimating them more closely and in selecting a solution which performs well for most of their likely values.

The steps in applying AHP and Expert Choice to a decision problem include:

Step 1: Problem identification and research

1a) Problem identification
1b) Identify objectives and alternatives. A list of the pros and cons of each alternative is often helpful in identifying the objectives

1c) Research the alternatives

Step 2: Eliminate infeasible alternatives

2a) Determine the "musts"
2b) Eliminate alternatives that do not meet the "musts"

Step 3: Structure a decision model in the form of a hierarchy to include goal, objectives (and sub objectives), and alternatives. Add other relevant factors (such as scenarios) as required.

Step 4: Evaluate the factors in the model by making pairwise relative comparisons

4a) Use as much factual data as is available, but interpret the data as it relates to to satisfying the objectives (i.e., do not assume a linear utility curve without thinking about whether it is a reasonable assumption)
4b) Use knowledge, experience, and intuition for these qualitative aspects of the problem or when no hard data is available

Step 5: Synthesize to identify the "best" alternative. Once judgments are entered for each part of the model, the information is synthesized to achieve an overall preference. The synthesis ranks the alternatives in relation to the goal.

Step 6: Examine and verify decision, iterate as required.

6a) Examine the solution and perform sensitivity analyses. If the solution is sensitive to factors in the model for which accurate data are not available, consider spending the resources to collect the necessary data and iterate back to step 4.
6b) Check the decision against intuition. If they do not agree, ask why intuition suggests that a different alternative is best. See if the reason is already in the model. If not, revise the model (and or judgements). Iterate as required. In general both model and intuition may change as more information about the problem becomes available.

Step 7: Document the decision for justification and control.

MERCURY RETIREMENT MODEL

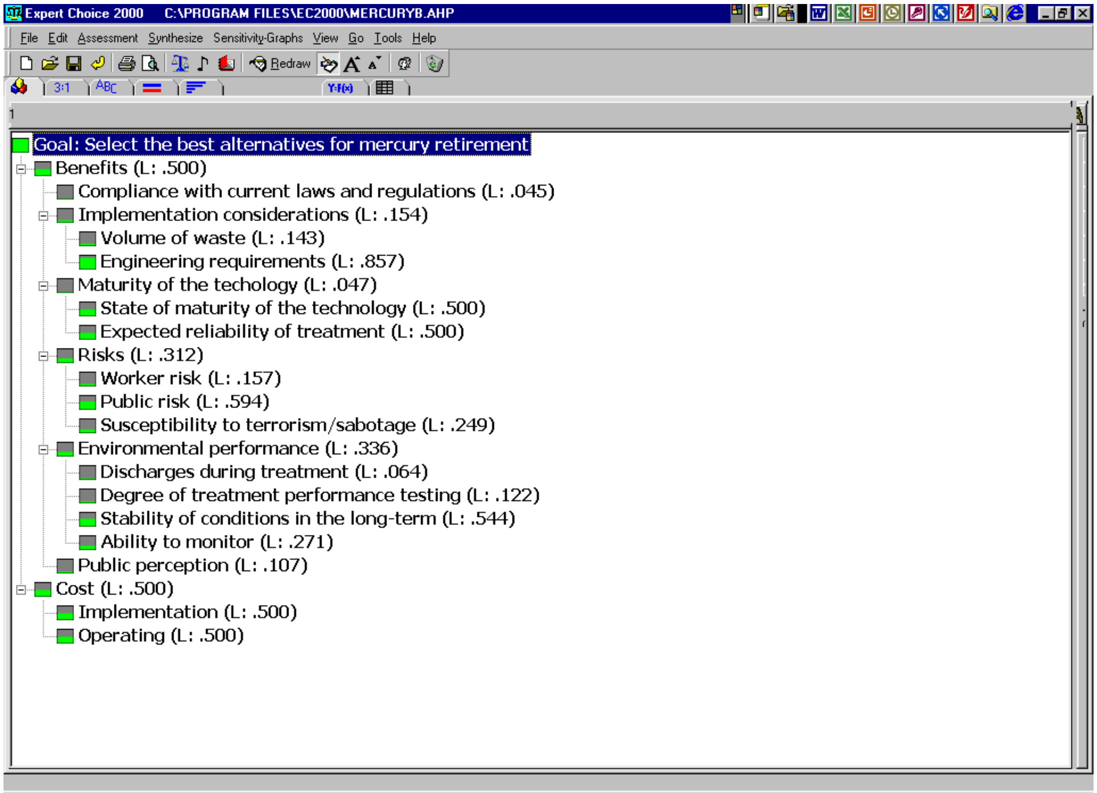
The model was developed using the Expert Choice software following the steps identified above and using the expertise of SAIC engineers and analysts. The hierarchical model is comprised of a goal, several levels of objectives (or criteria), and rating intensities or scales for the alternatives that were identified. Two modes are available within Expert Choice for prioritizing alternatives: relative measurement and absolute measurement. When a model is created based on relative measurement, the priorities of the objectives, sub-objectives and alternatives are computed by comparing the elements to each other. If there is a large number of alternatives (from 10 to thousands), which is the case with this specific mercury refinement problem, the pairwise comparison process can become overwhelming.

In contrast, absolute measurement gauges elements against an established scale, thereby reducing the volume of comparisons. In Expert Choice, absolute measurement is performed in a Ratings spreadsheet that is incorporated into the software. The objectives and sub-objectives are pairwise compared against one another, but the alternatives are compared against a pre-established scale.

While some scales such as cost (e.g. dollars) and measurement (e.g., tons, milligrams, etc.) are well established and widely recognized, other scales can be customized for the particular model. The scale of intensities for each objective appears as a group of nodes under that objective. The intensities are prioritized through the usual pairwise comparison process. Alternatives do not appear within the main structure of the tree, but instead are maintained in the Ratings spreadsheet. Each alternative is then rated against the established scale of intensities defined for each criterion. The scores for each alternative are weighted according to the priorities derived from the pairwise comparison process and then summed to determine the overall score. When alternatives are rated in this way, the alternatives are not compared against each other, but against the standard scales that have been derived for each criterion.

Model Structure

Figure A-2 below depicts the tree structure for the preliminary model. The goal as shown on the top of the screen is to "Select the best alternatives for mercury retirement".



Goal: Select the best alternatives for mercury retirement
- Benefits (L: .500)
  - Compliance with current laws and regulations (L: .045)
  - Implementation considerations (L: .154)
    - Volume of waste (L: .143)
    - Engineering requirements (L: .857)
  - Maturity of the techology (L: .047)
    - State of maturity of the technology (L: .500)
    - Expected reliability of treatment (L: .500)
  - Risks (L: .312)
    - Worker risk (L: .157)
    - Public risk (L: .594)
    - Susceptibility to terrorism/sabotage (L: .249)
  - Environmental performance (L: .336)
    - Discharges during treatment (L: .064)
    - Degree of treatment performance testing (L: .122)
    - Stability of conditions in the long-term (L: .544)
    - Ability to monitor (L: .271)
  - Public perception (L: .107)
- Cost (L: .500)
  - Implementation (L: .500)
  - Operating (L: .500)

Figure A-2 Decision Model Tree Structure

The top level criteria are Benefits and Cost. The associated objectives obviously are to maximize the benefits and to minimize the costs. Equal weightings were assigned to each of these top level objectives. Each of these objectives include one level or more sub-objectives as seen in Figure A-2. Six sub-objectives were defined for the covering Benefits objective, four of which was further broken down into additional sub-objectives. Two objectives were defined for the covering Cost objective. These are detailed below:

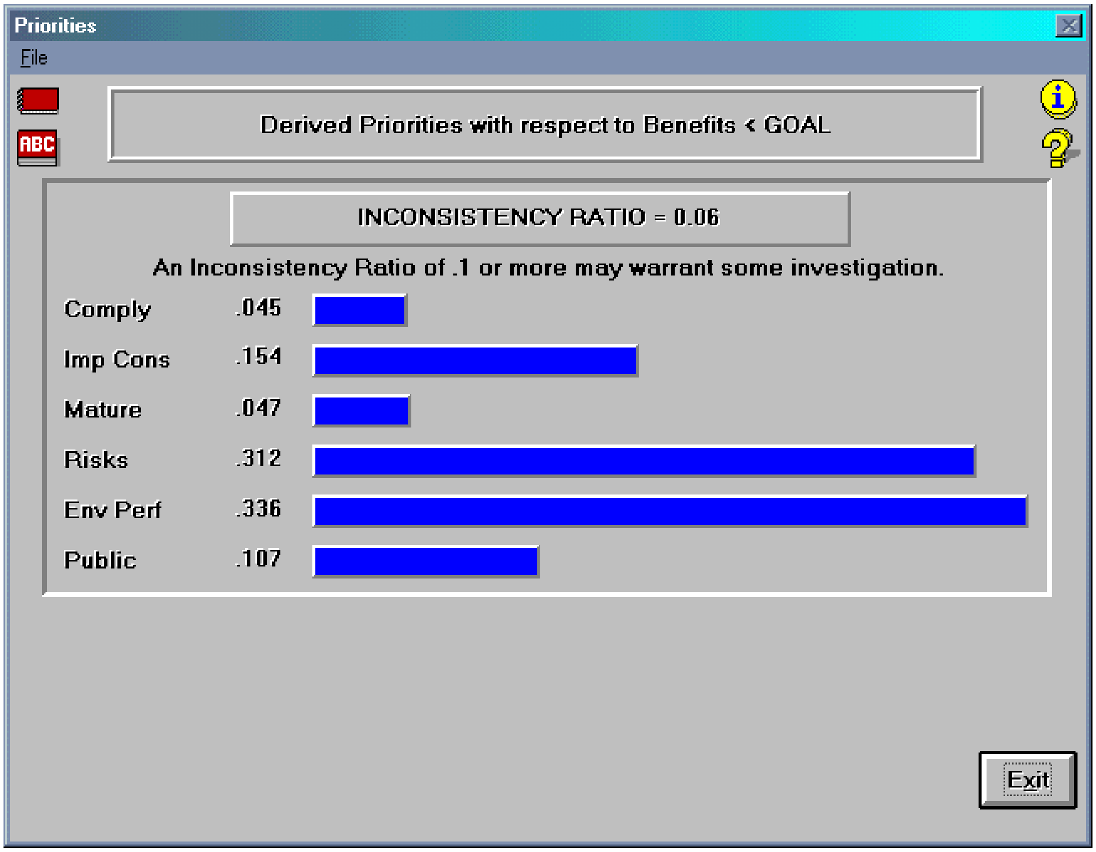
Benefits

- Compliance with current laws and regulations (maximize)
- Implementation considerations
  - Volume of waste (minimize)
  - Engineering requirements (minimize)
- Maturity of the technology
  - State of the maturity of the technology (maximize)
  - Expected reliability of treatment (maximize)
- Risks (minimize)
  - Risks to worker (minimize)
  - Risks to public (minimize)
  - Susceptibility to terrorist attack or sabotage (minimize)
- Environmental performance
  - Discharges during treatment (minimize)
  - Degree of treatment performance testing (maximize)
  - Stability of conditions in the long term (maximize)
  - Ability to monitor (maximize)
- Public perception (maximize positive reaction)

Cost

- Implementation costs (minimize)
- Operating costs (minimize)

The derived priorities for the Benefits sub-objectives from the pairwise comparison by the team's scientists can be seen in Figure A-3. Equal priorities were given to the two Cost sub-objectives.



Derived Priorities with respect to Benefits < GOAL

INCONSISTENCY RATIO = 0.06

An Inconsistency Ratio of .1 or more may warrant some investigation.

Comply .045
Imp Cons .154
Mature .047
Risks .312
Env Perf .336
Public .107

Figure A-3 Derived Benefits Sub-objectives Priorities

The resulting priorities shown are normalized and indicate that the environmental performance and the potential for catastrophic accidents are the most significant criteria when evaluating options for retirement of mercury.

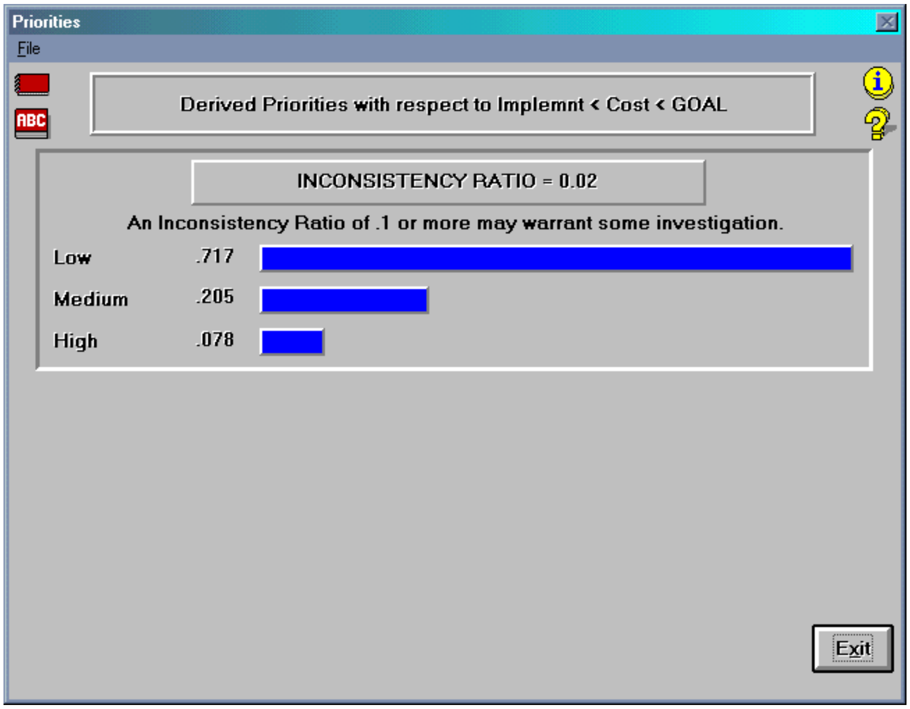
The rating intensity scales defined for each objective/criterion are shown in Table A-1.

Table A-1. Rating Intensities Scale

Covering Objective	Criteria	Rating Scale Parameters
Cost	Implementation cost	Low (0.717)[a] Medium (0.205) High (0.078)
	Operating cost	Low (0.717) Medium (0.205) High (0.078)
Benefits	Compliance with current laws and regulations	Compliant (0.731) Non-complaint with LDRs (0.188) Atypical permit required (0.081)
	Public perception	Positive to neutral (0.833) Negative (0.167)
Benefits: Implementation Considerations	Volume of waste	Zero or minimal (0.731) Increase up to 10 times (0.188) Increase greater than 10 times (0.081)
	Engineering requirements	Existing or minor modifications (0.731) New facilities (0.188) Construction of a mined cavity (0.081)
Benefits: Maturity of the technology	State of the maturity of the technology	Full-scale operation (0.731) Pilot treatment/full-scale disposal (0.188) Pilot treatment/untested disposal (0.081)
	Expected reliability of treatment	No treatment (0.717) Simple (0.205) Complex (0.078)
Benefits: Risk	Worker risk	Very Low (0.800) Low (0.200)
	Public risk	Very Low (0.800) Low (0.200)
	Susceptibility to terrorist attack or sabotage	Very Low (0.800) Low (0.200)
Benefits: Environmental Performance	Discharges during treatment	No impact (0.833) Minimal (0.167)
	Degree of treatment performance testing	Adequate (0.705) Moderate (0.211) Low (0.084)
	Stability of conditions in the long term	Very good (0.554) Good (0.289) Fair (0.106) Poor (0.051)
	Ability to monitor	Easy and correctable (0.649) Easy (0.279) Difficult (0.072)

[a] The figures in parentheses are the relative weights given to each intensity.

The corresponding weights determined from comparison of the intensities are shown in Figures A-4 through A-27.



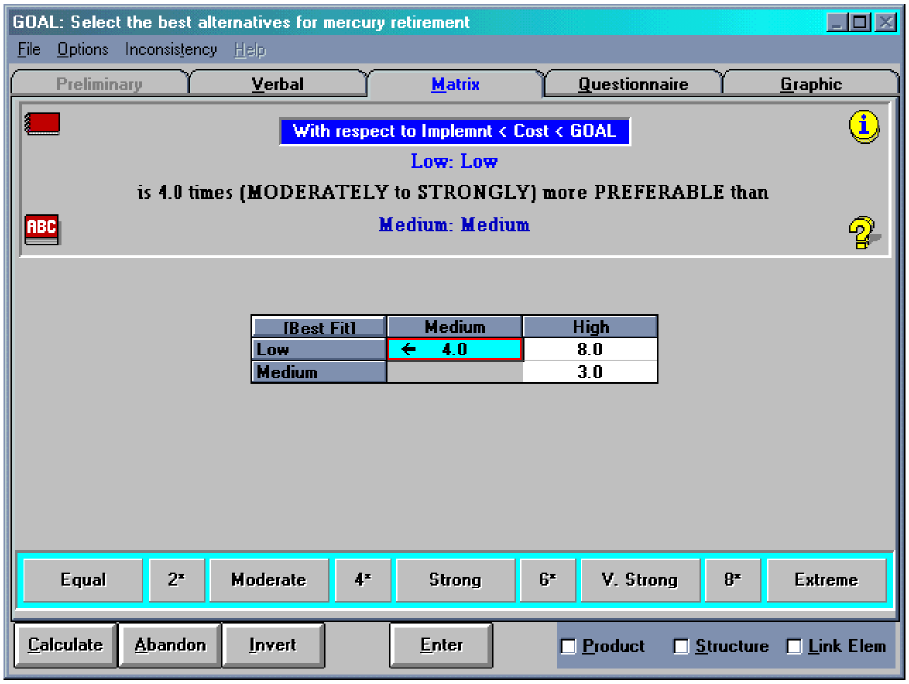
Derived Priorities with respect to Implemnt < Cost < GOAL

INCONSISTENCY RATIO = 0.02

An Inconsistency Ratio of .1 or more may warrant some investigation.

Low	.717
Medium	.205
High	.078

Figure A-4 Derived Priorities for Implementation Costs and Operating Costs with Respect to Cost



With respect to Implemnt < Cost < GOAL

Low: Low

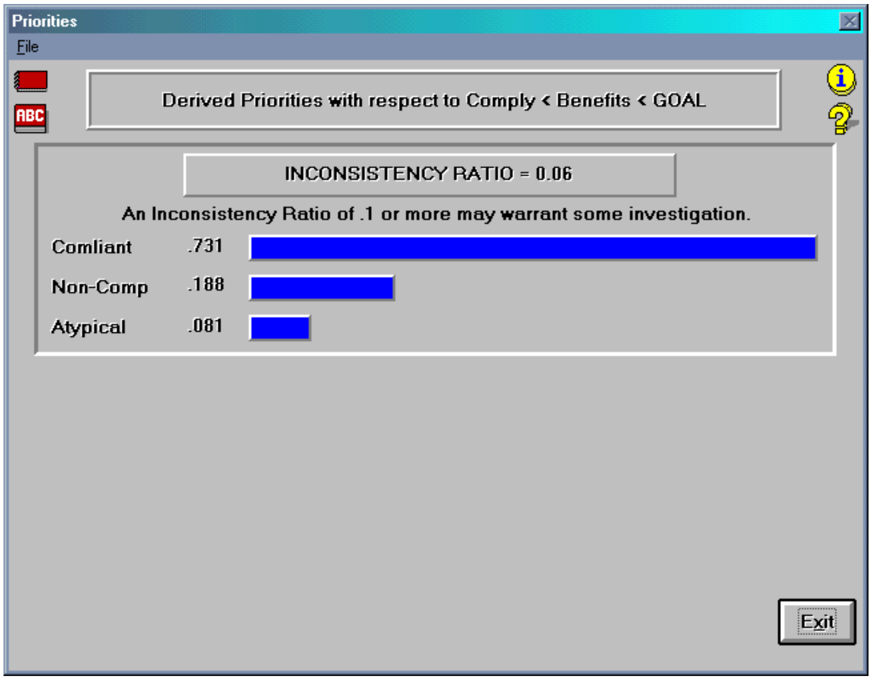
is 4.0 times (MODERATELY to STRONGLY) more PREFERABLE than

Medium: Medium

[Best Fit]	Medium	High
Low	← 4.0	8.0
Medium		3.0

Figure A-5 Pairwise Judgements of Implementation Cost Rating Scale Parameters

The pairwise judgements for the Operating cost rating scale parameters were identical to that of the implementation costs.



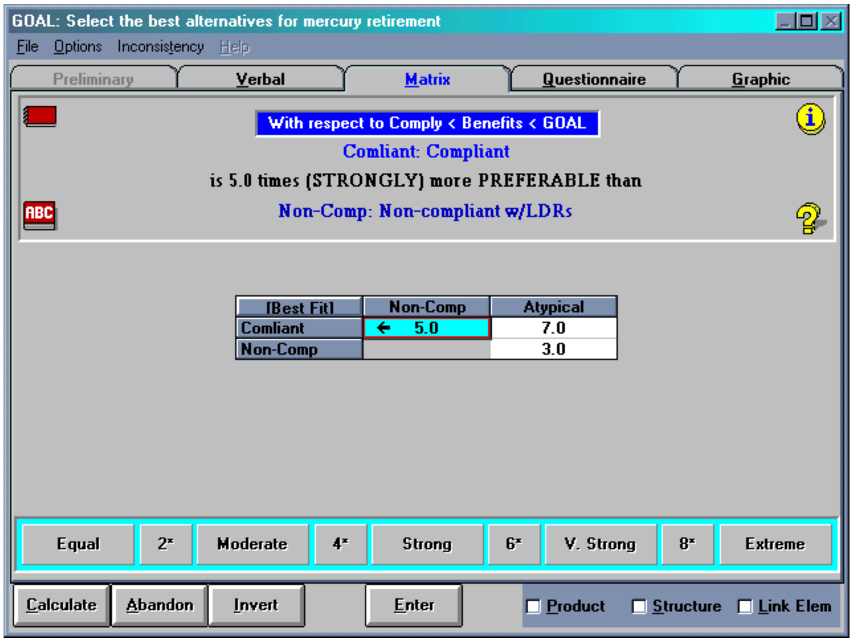
Derived Priorities with respect to Comply < Benefits < GOAL

INCONSISTENCY RATIO = 0.06

An Inconsistency Ratio of .1 or more may warrant some investigation.

Comliant	.731
Non-Comp	.188
Atypical	.081

Figure A-6 Derived Priorities for Compliance with Current Laws and Regulations with Respect to Benefits



With respect to Comply < Benefits < GOAL

Comliant: Compliant

is 5.0 times (STRONGLY) more PREFERABLE than

Non-Comp: Non-compliant w/LDRs

[Best Fit]	Non-Comp	Atypical
Comliant	← 5.0	7.0
Non-Comp		3.0

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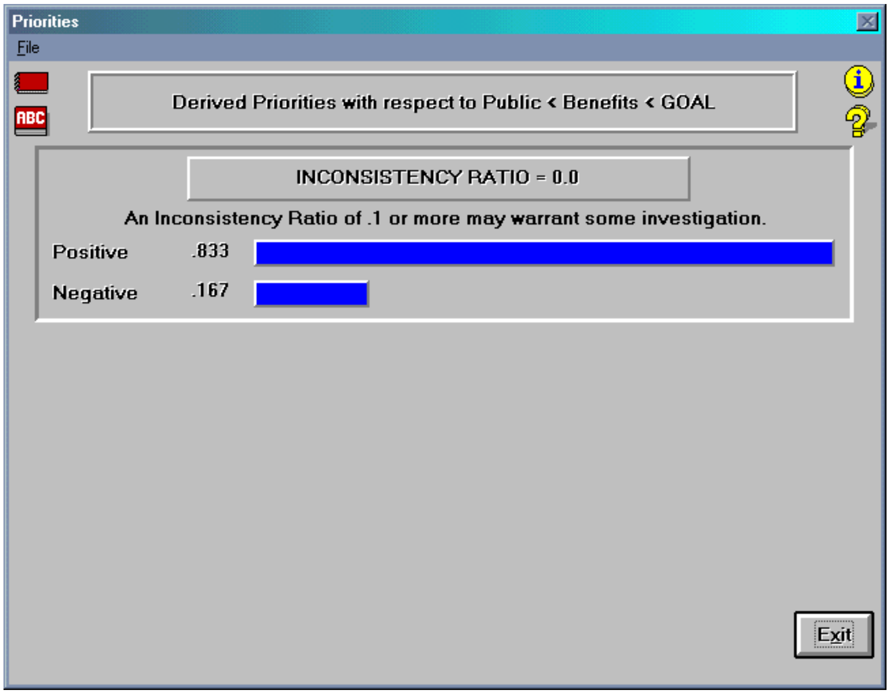
Figure A-7 Pairwise Judgements of Compliance with Current Laws and Regulations Rating Scale Parameters



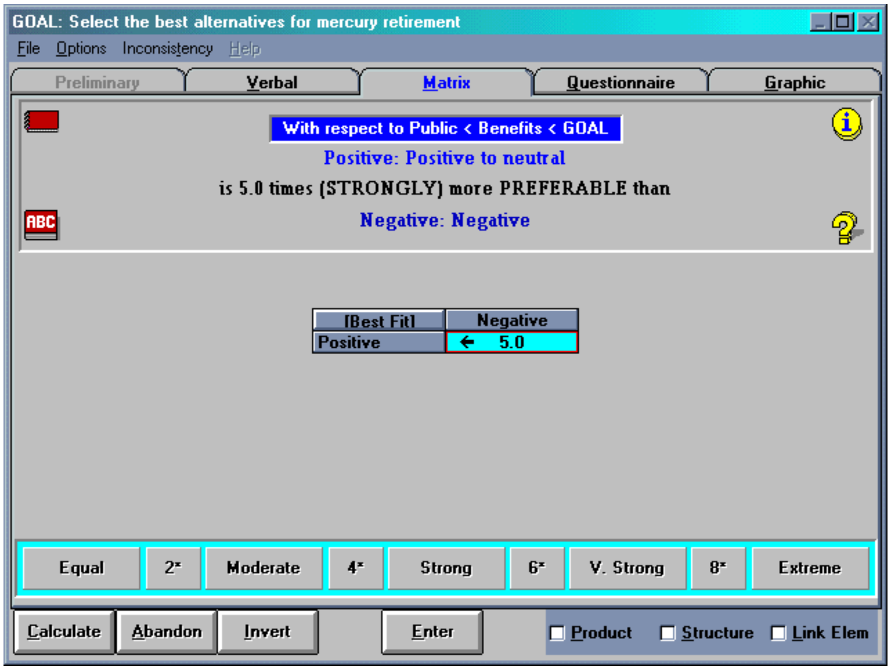
Derived Priorities with respect to Public < Benefits < GOAL

INCONSISTENCY RATIO = 0.0

An Inconsistency Ratio of .1 or more may warrant some investigation.

Positive	.833
Negative	.167

Figure A-8 Derived Priorities for Public Perception with Respect to Benefits



With respect to Public < Benefits < GOAL

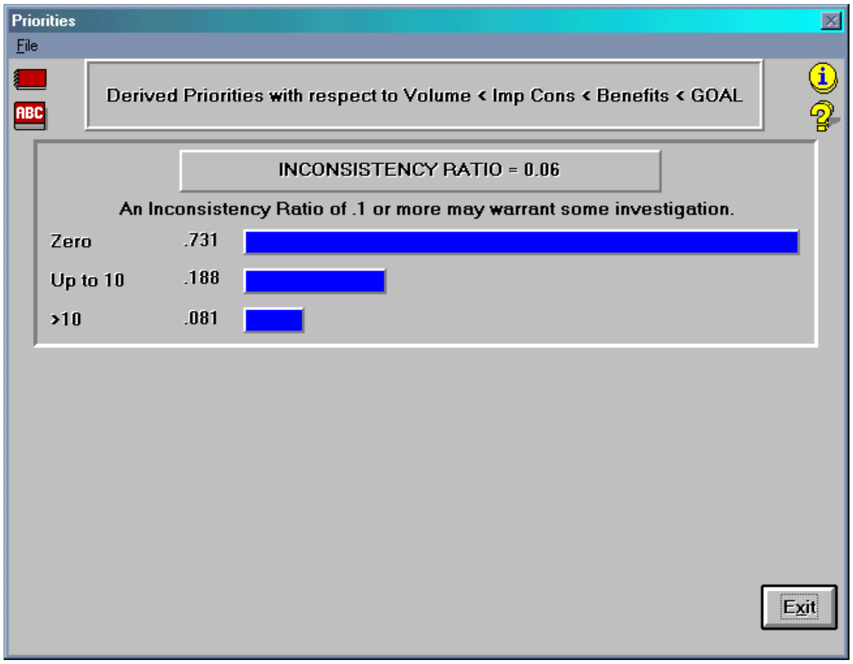
Positive: Positive to neutral

is 5.0 times (STRONGLY) more PREFERABLE than

Negative: Negative

[Best Fit]	Negative
Positive	← 5.0

Figure A-9 Pairwise Judgements of Public Perception Rating Scale Parameters



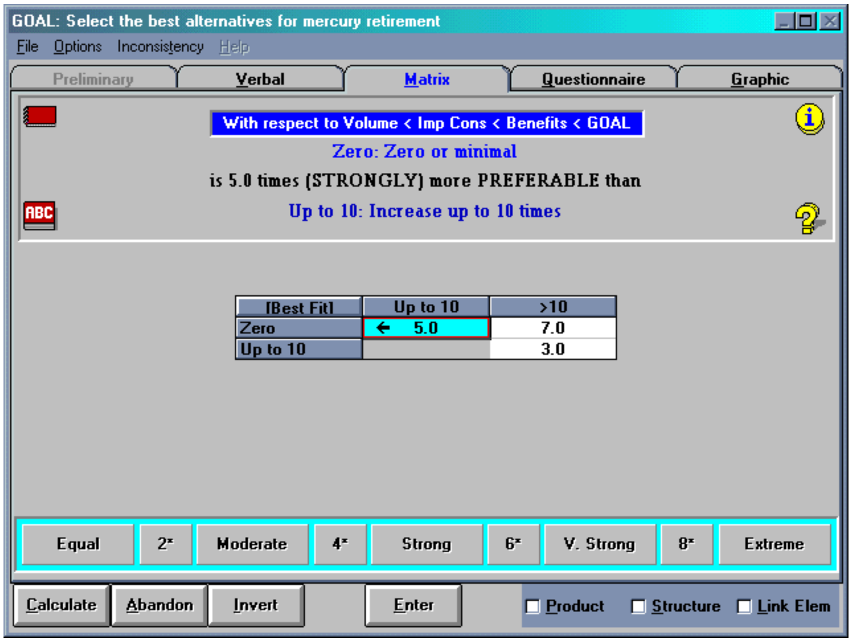
Derived Priorities with respect to Volume < Imp Cons < Benefits < GOAL

INCONSISTENCY RATIO = 0.06

An Inconsistency Ratio of .1 or more may warrant some investigation.

Zero	.731
Up to 10	.188
>10	.081

Figure A-10 Derived Priorities for Volume of Waste with Respect to Implementation Considerations



With respect to Volume < Imp Cons < Benefits < GOAL

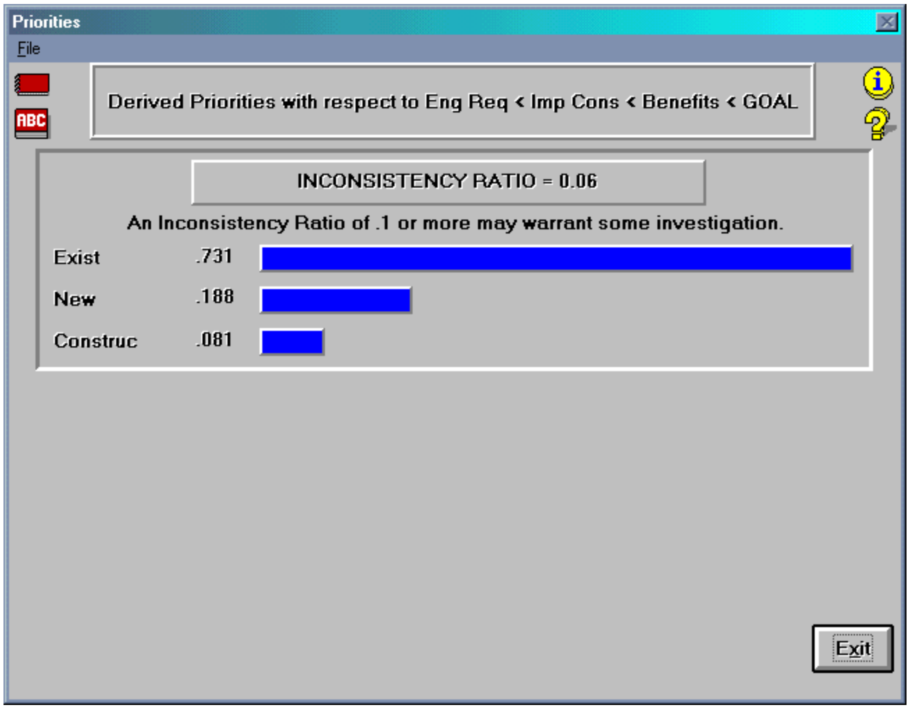
Zero: Zero or minimal

is 5.0 times (STRONGLY) more PREFERABLE than

Up to 10: Increase up to 10 times

[Best Fit]	Up to 10	>10
Zero	← 5.0	7.0
Up to 10		3.0

Figure A-11 Pairwise Judgements of Volume of Waste Rating Scale Parameters



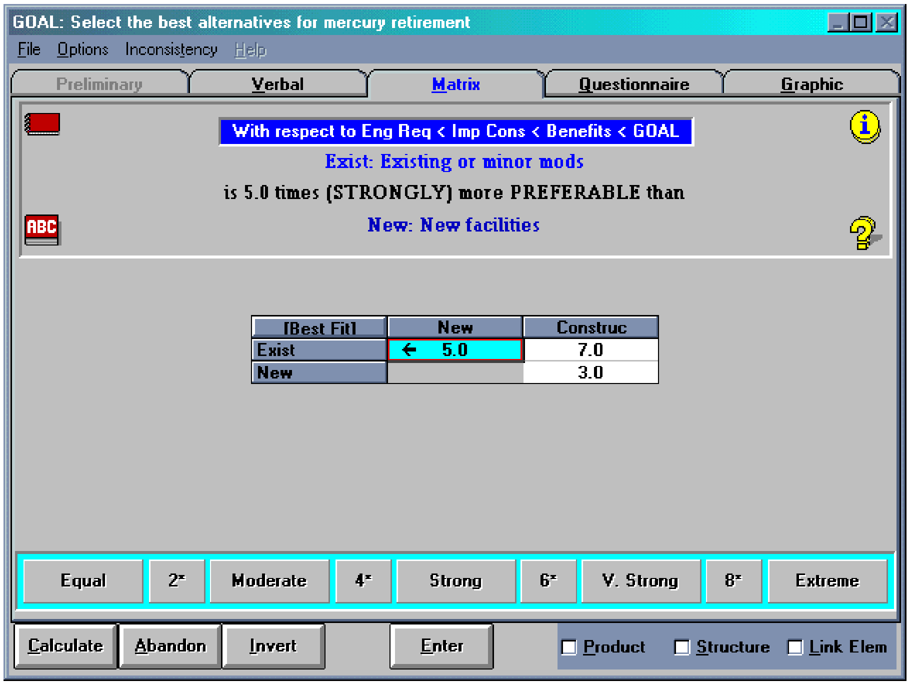
Derived Priorities with respect to Eng Req < Imp Cons < Benefits < GOAL

INCONSISTENCY RATIO = 0.06

An Inconsistency Ratio of .1 or more may warrant some investigation.

Exist	.731
New	.188
Construc	.081

Figure A-12 Derived Priorities for Engineering Requirements with Respect to Implementation Considerations



GOAL: Select the best alternatives for mercury retirement

With respect to Eng Req < Imp Cons < Benefits < GOAL

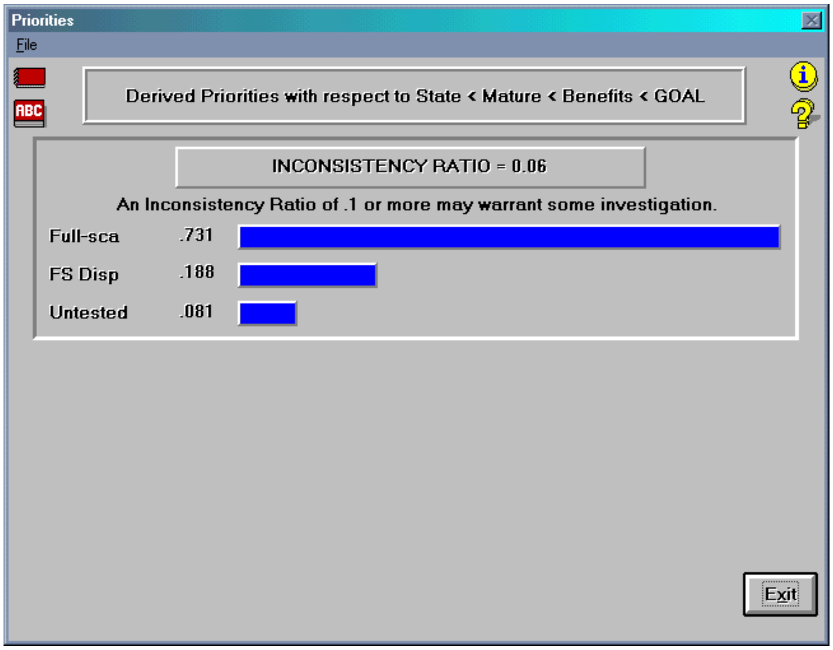
Exist: Existing or minor mods

is 5.0 times (STRONGLY) more PREFERABLE than

New: New facilities

[Best Fit]	New	Construc
Exist	← 5.0	7.0
New		3.0

Figure A-13 Pairwise Judgements of Engineering Requirements Rating Scale Parameters



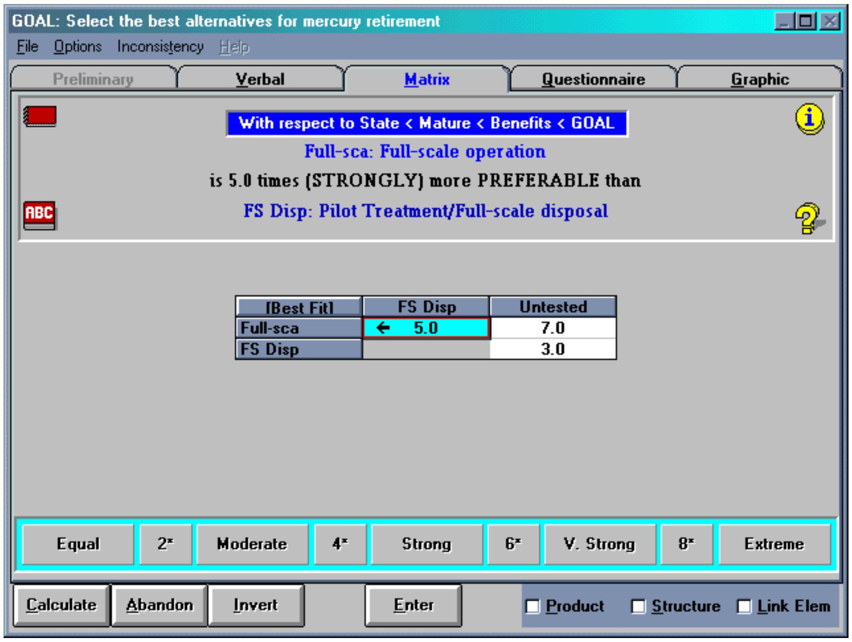
Derived Priorities with respect to State < Mature < Benefits < GOAL

INCONSISTENCY RATIO = 0.06

An Inconsistency Ratio of .1 or more may warrant some investigation.

Full-sca	.731
FS Disp	.188
Untested	.081

Figure A-14 Derived Priorities for State of Maturity of the Technology with Respect to Maturity of the Technology



With respect to State < Mature < Benefits < GOAL

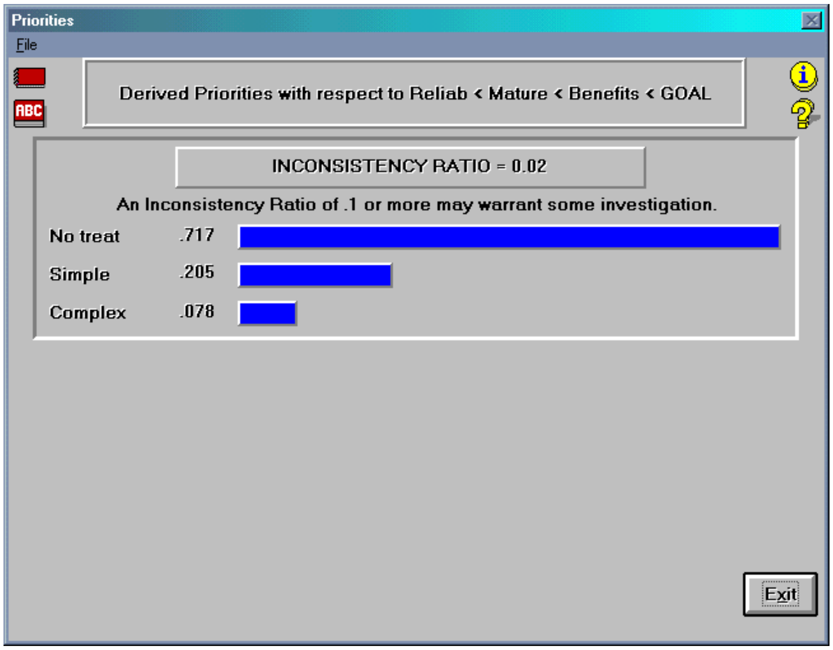
Full-sca: Full-scale operation

is 5.0 times (STRONGLY) more PREFERABLE than

FS Disp: Pilot Treatment/Full-scale disposal

[Best Fit]	FS Disp	Untested
Full-sca	← 5.0	7.0
FS Disp		3.0

Figure A-15 Pairwise Judgements of State of Maturity of the Technology Rating Scale Parameters



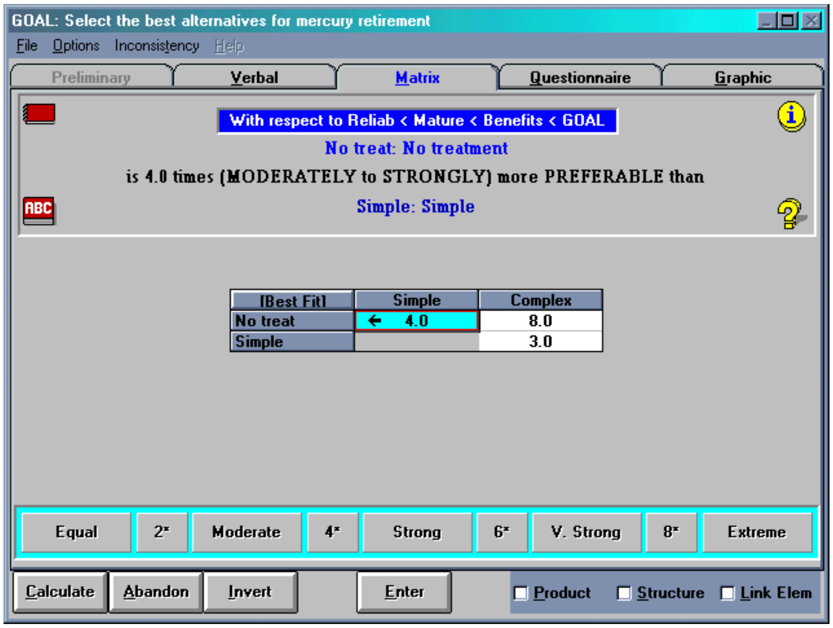
Derived Priorities with respect to Reliab < Mature < Benefits < GOAL

INCONSISTENCY RATIO = 0.02

An Inconsistency Ratio of .1 or more may warrant some investigation.

No treat	.717
Simple	.205
Complex	.078

Figure A-16 Derived Priorities for Expected Reliability of Treatment with Respect to Maturity of the Technology



With respect to Reliab < Mature < Benefits < GOAL

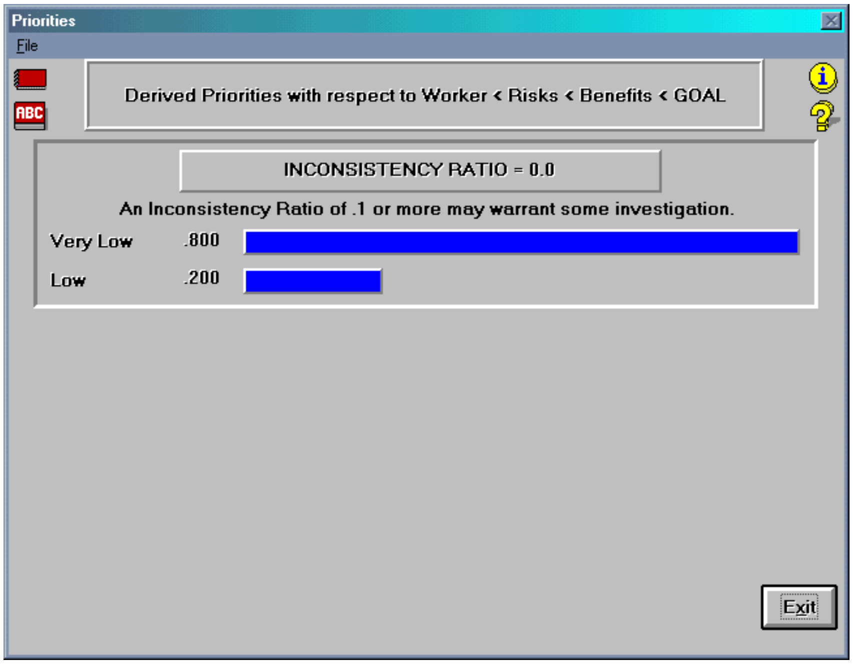
No treat: No treatment

is 4.0 times (MODERATELY to STRONGLY) more PREFERABLE than

Simple: Simple

[Best Fit]	Simple	Complex
No treat	← 4.0	8.0
Simple		3.0

Figure A-17 Pairwise Judgements of Expected Reliability of Treatment Rating Scale Parameters



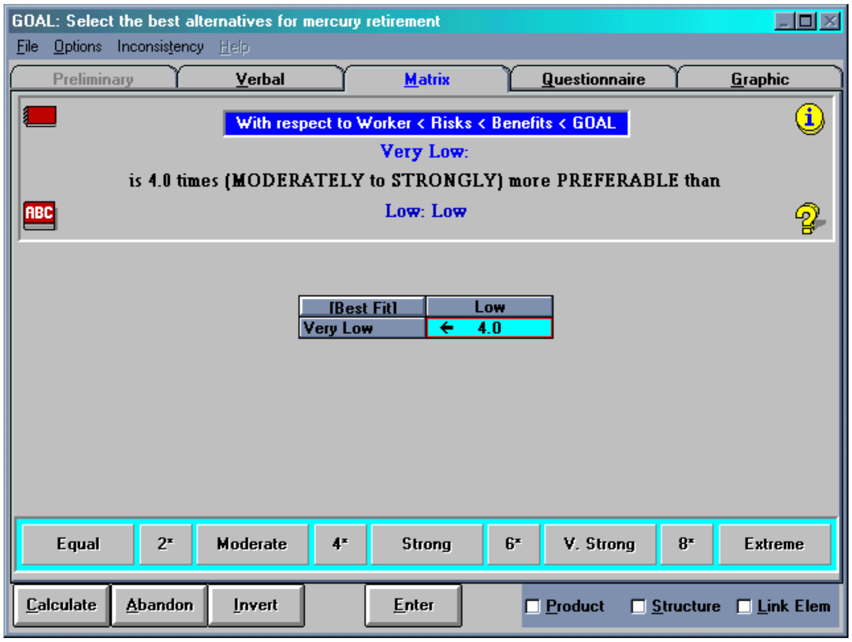
Derived Priorities with respect to Worker < Risks < Benefits < GOAL

INCONSISTENCY RATIO = 0.0

An Inconsistency Ratio of .1 or more may warrant some investigation.

Very Low	.800
Low	.200

Figure A-18 Derived Priorities for Worker Risk with Respect to Risks



GOAL: Select the best alternatives for mercury retirement

With respect to Worker < Risks < Benefits < GOAL

Very Low:

is 4.0 times (MODERATELY to STRONGLY) more PREFERABLE than

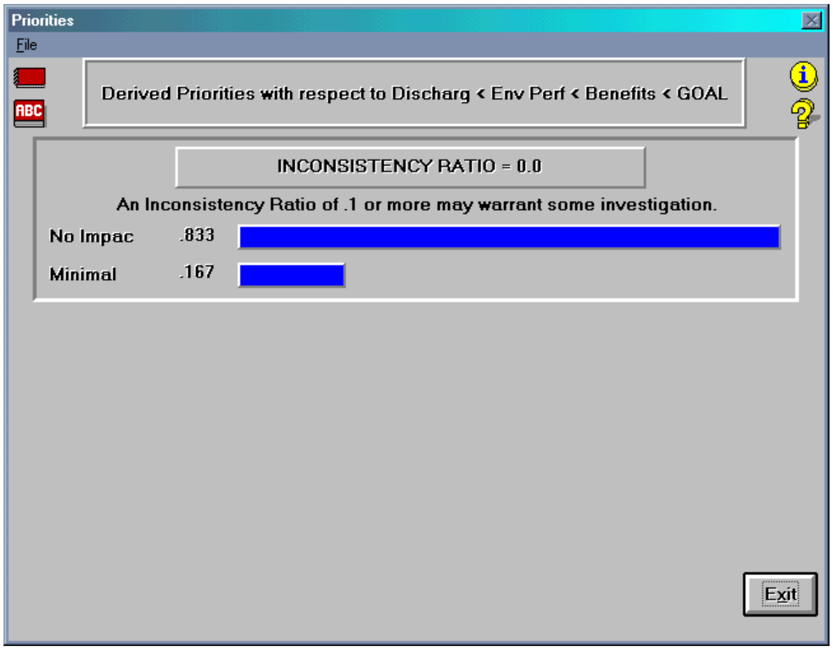
Low: Low

[Best Fit]	Low
Very Low	← 4.0

☐ Product ☐ Structure ☐ Link Elem

Figure A-19 Pairwise Judgements of Worker Risk Rating Scale Parameters

The derived priorities and pairwise judgements for the public risk and susceptibility to terrorist attack or sabotage criteria were identical to that of the worker risk shown in the above two figures.



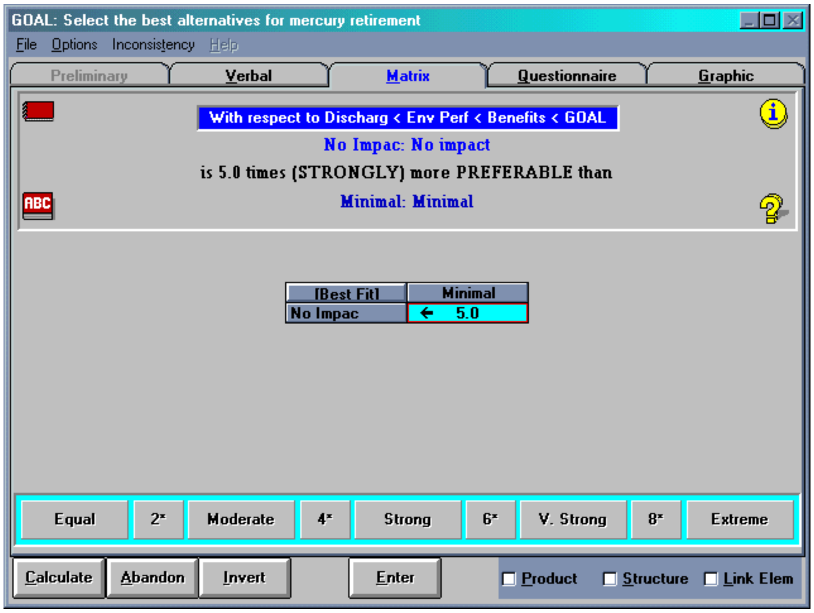
Derived Priorities with respect to Discharg < Env Perf < Benefits < GOAL

INCONSISTENCY RATIO = 0.0

An Inconsistency Ratio of .1 or more may warrant some investigation.

No Impac	.833
Minimal	.167

Figure A-20 Derived Priorities for Discharges During Treatment with Respect to Environmental Performance



With respect to Discharg < Env Perf < Benefits < GOAL

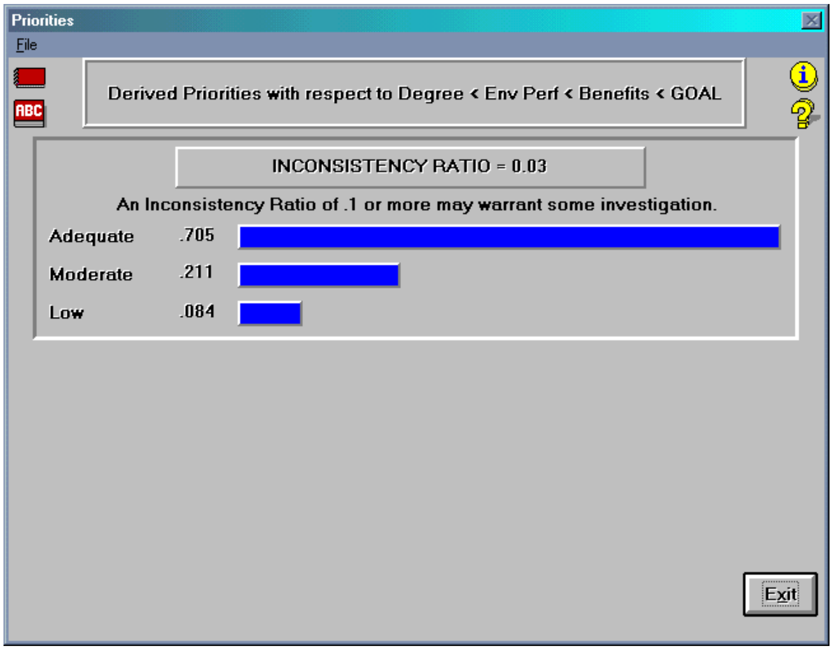
No Impac: No impact

is 5.0 times (STRONGLY) more PREFERABLE than

Minimal: Minimal

[Best Fit]	Minimal
No Impac	← 5.0

Figure A-21 Pairwise Judgements of Discharges During Treatment Rating Scale Parameters



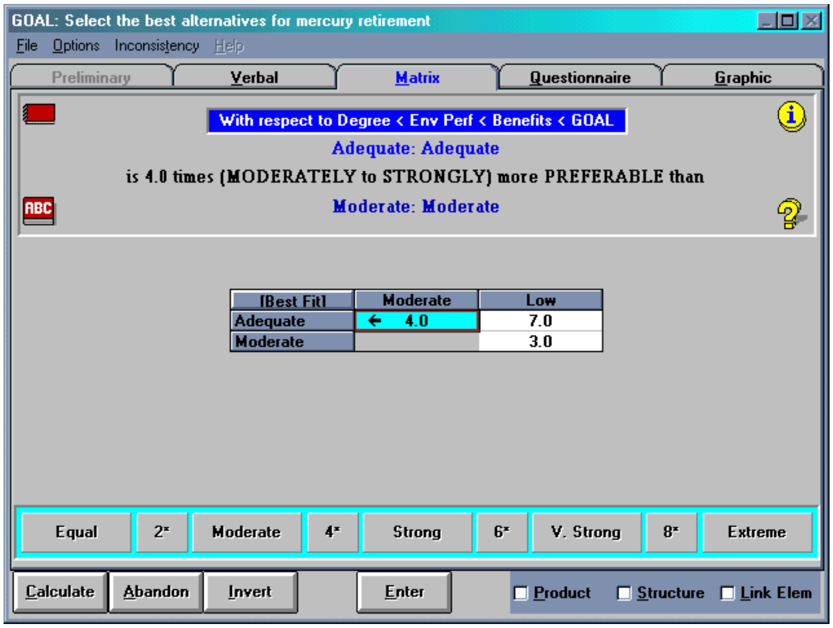
Derived Priorities with respect to Degree < Env Perf < Benefits < GOAL

INCONSISTENCY RATIO = 0.03

An Inconsistency Ratio of .1 or more may warrant some investigation.

Adequate	.705
Moderate	.211
Low	.084

Figure A-22 Derived Priorities for Degree of Treatment Performance Testing to Environmental Performance



With respect to Degree < Env Perf < Benefits < GOAL

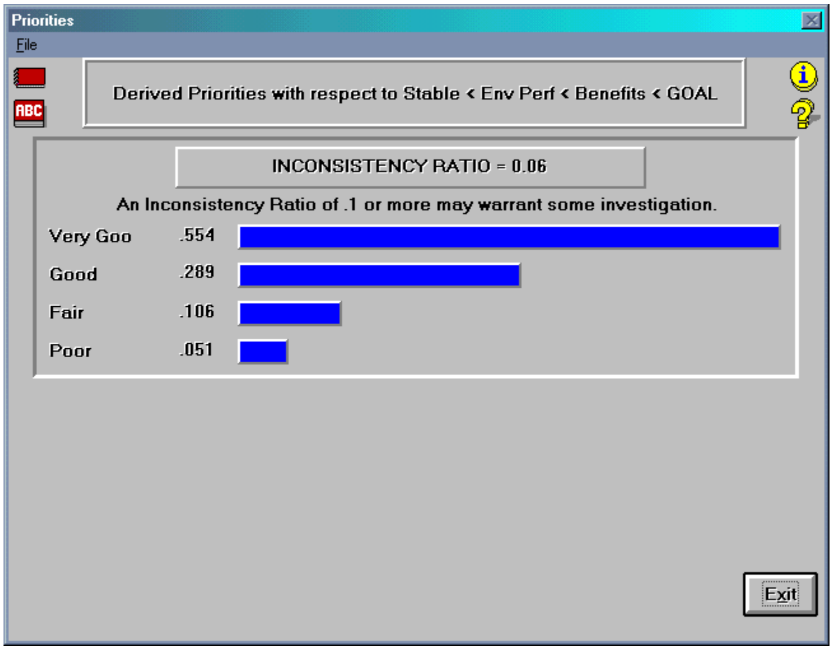
Adequate: Adequate

is 4.0 times (MODERATELY to STRONGLY) more PREFERABLE than

Moderate: Moderate

[Best Fit]	Moderate	Low
Adequate	← 4.0	7.0
Moderate		3.0

Figure A-23 Pairwise Judgements of Degree of Treatment Performance Testing Rating Scale Parameters



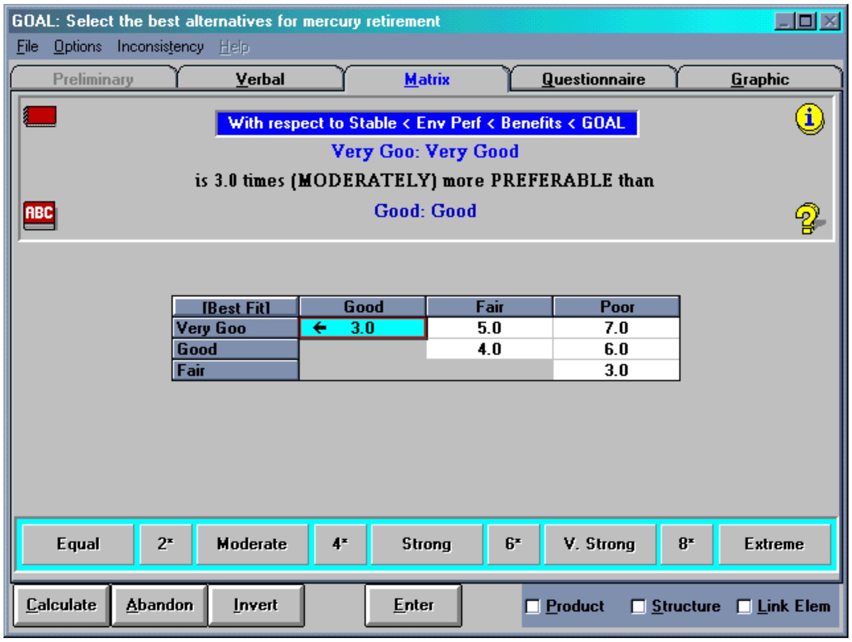
Derived Priorities with respect to Stable < Env Perf < Benefits < GOAL

INCONSISTENCY RATIO = 0.06

An Inconsistency Ratio of .1 or more may warrant some investigation.

Very Goo	.554
Good	.289
Fair	.106
Poor	.051

Figure A-24 Derived Priorities for Stability of Conditions in the Long Term to Environmental Performance



With respect to Stable < Env Perf < Benefits < GOAL

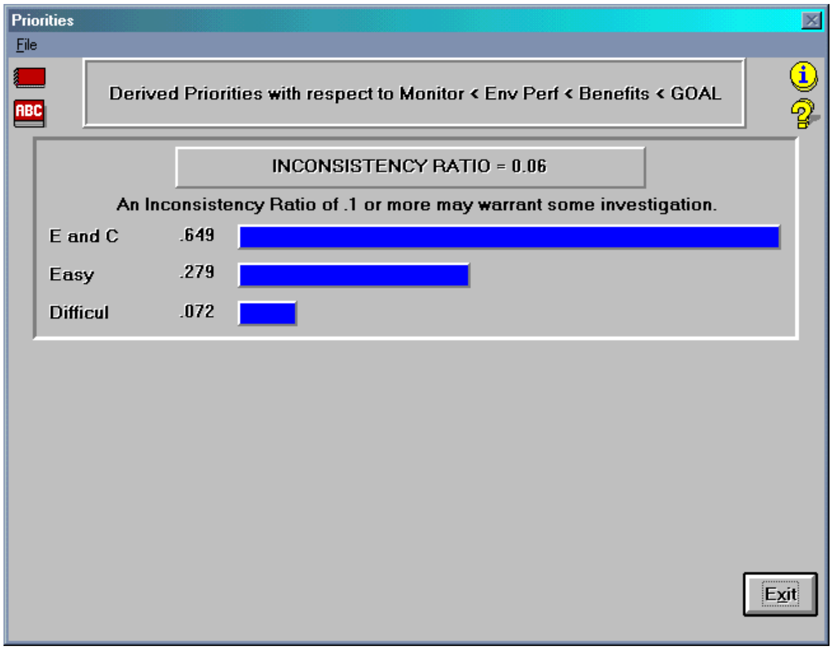
Very Goo: Very Good

is 3.0 times (MODERATELY) more PREFERABLE than

Good: Good

[Best Fit]	Good	Fair	Poor
Very Goo	← 3.0	5.0	7.0
Good		4.0	6.0
Fair			3.0

Figure A-25 Pairwise Judgements of Stability of Conditions in the Long Term Rating Scale Parameters



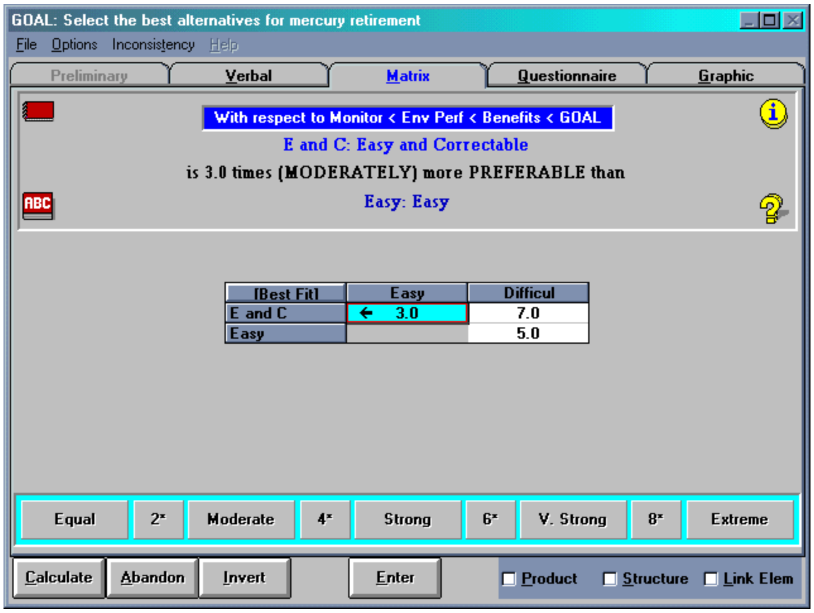
Derived Priorities with respect to Monitor < Env Perf < Benefits < GOAL

INCONSISTENCY RATIO = 0.06

An Inconsistency Ratio of .1 or more may warrant some investigation.

E and C	.649
Easy	.279
Difficul	.072

Figure A-26 Derived Priorities for Ability to Monitor to Environmental Performance



With respect to Monitor < Env Perf < Benefits < GOAL

E and C: Easy and Correctable

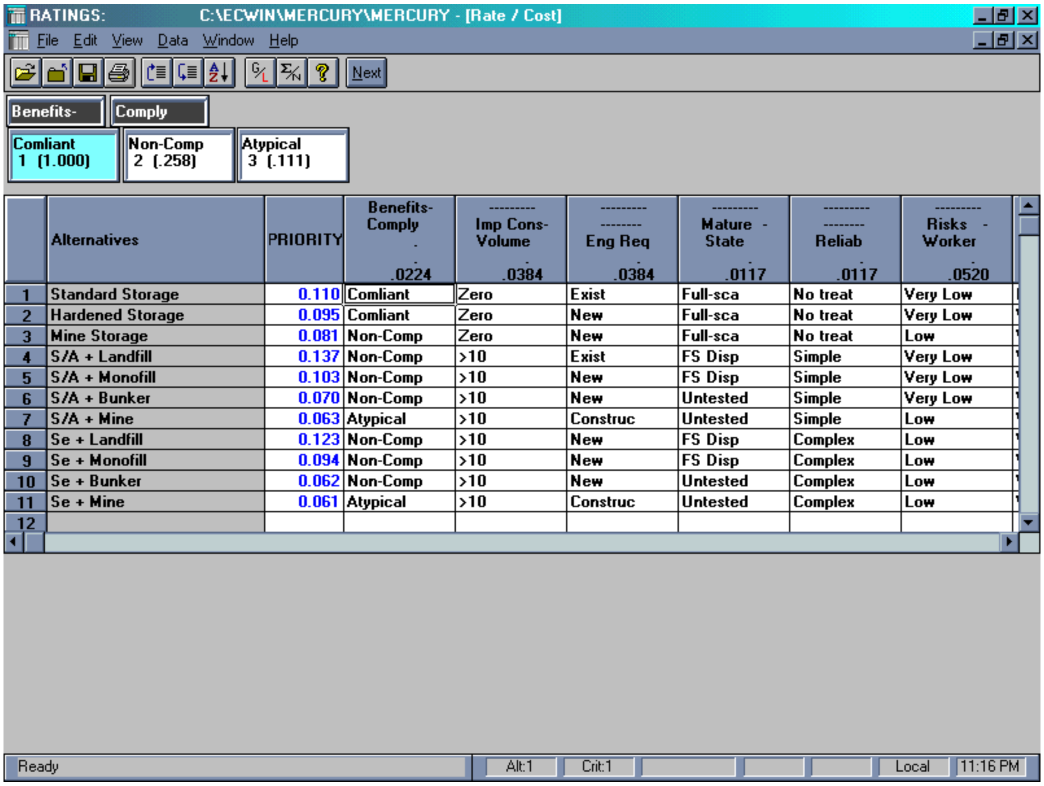
is 3.0 times (MODERATELY) more PREFERABLE than

Easy: Easy

[Best Fit]	Easy	Difficul
E and C	← 3.0	7.0
Easy		5.0

Figure A-27 Pairwise Judgements of Ability to Monitor Rating Scale Parameters

The derived priorities of the objectives with respect to the goal and of the rating intensities with respect to the sub-objectives or criteria were then fed into the ratings worksheet. A rating for each criterion for each alternative is then made. Figures A-28 and A-29 below display the completed ratings worksheet.

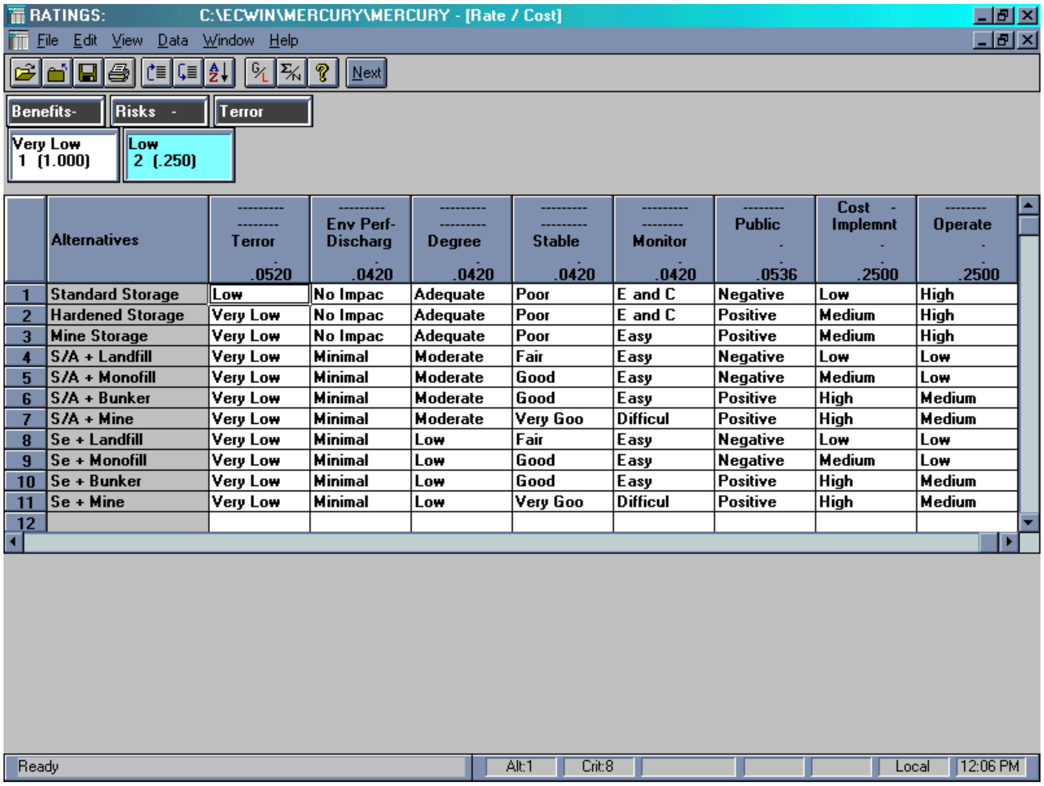


Benefits- | Comply

Comliant 1 (1.000) | Non-Comp 2 (.258) | Atypical 3 (.111)

	Alternatives	PRIORITY	Benefits- Comply .0224	--------- Imp Cons- Volume .0384	--------- -------- Eng Req .0384	--------- Mature - State .0117	--------- -------- Reliab .0117	--------- Risks - Worker .0520
1	Standard Storage	0.110	Comliant	Zero	Exist	Full-sca	No treat	Very Low
2	Hardened Storage	0.095	Comliant	Zero	New	Full-sca	No treat	Very Low
3	Mine Storage	0.081	Non-Comp	Zero	New	Full-sca	No treat	Low
4	S/A + Landfill	0.137	Non-Comp	>10	Exist	FS Disp	Simple	Very Low
5	S/A + Monofill	0.103	Non-Comp	>10	New	FS Disp	Simple	Very Low
6	S/A + Bunker	0.070	Non-Comp	>10	New	Untested	Simple	Very Low
7	S/A + Mine	0.063	Atypical	>10	Construc	Untested	Simple	Low
8	Se + Landfill	0.123	Non-Comp	>10	New	FS Disp	Complex	Low
9	Se + Monofill	0.094	Non-Comp	>10	New	FS Disp	Complex	Low
10	Se + Bunker	0.062	Non-Comp	>10	New	Untested	Complex	Low
11	Se + Mine	0.061	Atypical	>10	Construc	Untested	Complex	Low
12								

Figure A-28 Completed Ratings Worksheet (First Page)



Benefits- | Risks - | Terror

Very Low 1 (1.000) | Low 2 (.250)

	Alternatives	--------- -------- Terror .0520	--------- Env Perf- Discharg .0420	--------- --------- Degree .0420	--------- --------- Stable .0420	--------- -------- Monitor .0420	-------- Public .0536	Cost - Implemnt .2500	-------- Operate .2500
1	Standard Storage	Low	No Impac	Adequate	Poor	E and C	Negative	Low	High
2	Hardened Storage	Very Low	No Impac	Adequate	Poor	E and C	Positive	Medium	High
3	Mine Storage	Very Low	No Impac	Adequate	Poor	Easy	Positive	Medium	High
4	S/A + Landfill	Very Low	Minimal	Moderate	Fair	Easy	Negative	Low	Low
5	S/A + Monofill	Very Low	Minimal	Moderate	Good	Easy	Negative	Medium	Low
6	S/A + Bunker	Very Low	Minimal	Moderate	Good	Easy	Positive	High	Medium
7	S/A + Mine	Very Low	Minimal	Moderate	Very Goo	Difficul	Positive	High	Medium
8	Se + Landfill	Very Low	Minimal	Low	Fair	Easy	Negative	Low	Low
9	Se + Monofill	Very Low	Minimal	Low	Good	Easy	Negative	Medium	Low
10	Se + Bunker	Very Low	Minimal	Low	Good	Easy	Positive	High	Medium
11	Se + Mine	Very Low	Minimal	Low	Very Goo	Difficul	Positive	High	Medium
12									

Figure A-29 Completed Ratings Worksheet (Second Page)

The overall totals can be seen on the first page of the ratings worksheet which provides the priority of alternatives. The top nine alternatives were then extracted back to the pairwise comparison model so that sensitivity analysis on the objectives and criteria could be conducted to see how well the alternatives performed with respect to each of the objectives as well as how sensitive the alternatives are to changes in the importance of the objectives.

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APPENDIX B
SCREENING OF TECHNOLOGIES

This section is intended to briefly review the long-term retirement solutions that were identified in the Canadian Study (SENES, 2001) and explain why some were selected for further analysis. The analysis is presented in Tabular form after the list of references.

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Process Name and References	Brief Description	Included in Current Study?
Retorting References: EPA, 1998b SENES, 2001	Retorting is a high temperature, vacuum assisted batch process and is used for recovery of elemental mercury from Hg containing waste. Waste is placed into a bell type retort in drums or trays on a stationary base. The top bell unit is lowered, fastened and sealed. The vacuum is drawn to approximately 0.03 atmospheres. Electrical radiant heaters inside the retort raise the temperatures to about 675^{o} C, vaporizing the mercury. Downstream water-cooled condensers condense the mercury saturated air stream. Mercury is collected in a reservoir for transfer to a continuous triple distillation process for further purification.	**No**. A mercury recovery technique. Regarded as a well-established prior step for producing elemental mercury, some of which ends up in the pool of surplus mercury. See Section 1.3.2
Thermal Desorption – Fluidized Bed References: Philips, 1995 SENES, 2001	This technology is particularly useful on soil containing contaminants, such as mercury. Contaminated soil is screened and crushed so that the material sent into the fluidized bed unit is uniform in size. The soil is heated up to 1200^{o} F, by re-circulation of the exhaust gas that has already been treated and reheated through a radiant tube air pre-heater. The mercury-containing vapors are first filtered in a baghouse, cooled and condensed.	**No**. A mercury recovery technique. Not suitable for treating bulk elemental mercury, see Section 1.3.2
Liquid Waste Incineration Reference: SENES, 2001, citing Hennin, P. 2001 Conversation with Safety-Kleen Employee, March 2001	The mercury-bearing waste acceptance criterion is < 10 ppm. Liquid wastes are injected into the primary or secondary chambers of a stationary incinerator, depending on their heat content.	**No.** Not suitable for treatment of bulk elemental mercury. See Section 1.3.2
Rotary Kiln Incineration References: EPA, 1998a SENES, 2001	Non-wastewaters are fed into a furnace (thermal processor) equipped with a two-stage afterburner. The gas leaving the furnace is cooled through a two-stage scrubbing and cooling system using a combination of water and sodium hydroxide solution. A final stage of scrubbing and cooling in a venturi and separator is used. The gases exiting this final stage of cooling are passed through sulfur impregnated carbon to remove residual mercury before being exhausted to the atmosphere. Metallic mercury is recovered from each stage of the scrubbing/cooling process.	**No**. Not suitable for the treatment of bulk elemental mercury. See Section 1.3.2
Amalgamation Using Metals References: EPA, 1998b SENES, 2001	This is a well-established technology for elemental mercury. It has low air emissions of elemental mercury vapor. Other metals (Cu, Ni, Sn, Zn, Au, Ag) form an amalgam with mercury. It can also treat wastewater containing dissolved mercury salts. To further improve on amalgamation and stabilization, encapsulation of amalgamated mercury waste is possible and will limit the volatilization and leaching of mercury.	**Yes.** This is a class of treatment technologies that is represented in the present study by the ITS/NFS DeHg® process. See Section 3.2.3.

Process Name and References	Brief Description	Included in Current Study?
Ion Exchange References: EPA, 1998a SENES, 2001	Ion exchange applications are useful to remove Hg from aqueous streams at low concentrations (1 –10 ppb Hg). A synthetic resin or mineral is suspended in a solution where suspended Hg ions are exchanged onto the resin or mineral (packed column). Organomercury compounds do not ionize, thus are unsuitable for this technology.	**No**. Wastewater treatment technologies excluded. See Section 1.3.2
Amalgamation: ADA Technologies Process References: EPA, 1998c SENES, 2001	The ADA process stabilizes radioactively contaminated elemental mercury with a proprietary powdered sulfur mixture in a commercially available pug mill to produce a stable mercury sulfide product. The process operates at ambient temperature and pressure without addition of heat – reaction is exothermic at room temperature. Air in the mixing area is exhausted through a HEPA filter plus sulfur-impregnated carbon filter.	**Yes.** See Section 3.2.1.
Chemical Precipitation References: EPA, 1998a SENES, 2001	This process involves precipitating mercuric sulfide (HgS) from wastewaters containing $HgCl_2$ generated during prior oxidation and/or chemical leaching steps. Reagents used in precipitation include Na_2S and FeS.	**No**. Wastewater treatment technologies excluded. See Section 1.3.2
Amalgamation: Hg Absorbʋ References: Wescott, undated SENES,2001	Applicable to mixed wastes streams such as elemental mercury contaminated with radioactive materials. Amalgamation of the elemental mercury with Hg Absorbʋ, a manufactured product, produces a mercury amalgam meeting the TCLP of < 0.025 mg/l leaching criteria. Hg Absorbʋ contains granular zinc and citric acid, and it is wetted and mixed with mercury at a 3:1 ratio by volume until no free visible mercury is visible.	**Not explicitly**, but belongs to the class of treatment technologies that is represented in the present study by the ITS/NFS DeHg® process. See Section 3.2.3.
Chemical Oxidation References: EPA, 1998a SENES, 2001	This technology is primarily used to treat aqueous waste (Chemical Oxygen Demand (COD) <5000 mg/l), but may be applied to solids (slurry). It chemically oxidizes organomercury compounds and converts Hg^0 to $HgCl_2$ or HgO, which can be separated from waste matrix and further treated. Various oxidizing and proprietary agents are utilized (NaOCl, O_3, Cl_2, H_2O_2).	**No.** Does not treat bulk elemental mercury. See Section 1.3.2
Chemical Leaching/Acid Leaching References: EPA, 1998a SENES, 2001	This process is employed for mercury separation when mercury is present in an inorganic or organic media and when mercury in waste is at the percent level. Acid leaching (strong acids - H_2SO_4, HCl, HNO_3) is most commonly used to remove Hg from inorganic media. The leaching solution generates ionic soluble form of mercury that is filtered off for further treatment (precipitation, ion exchange, carbon adsorption). However, nitric acid is used for organic media leaching and it achieves both conversion of Hg to a soluble form and destruction of the organic content. It is referred to as oxidative acid leaching.	**No**. Does not treat bulk elemental mercury. See Section 1.3.2.

Process Name and References	Brief Description	Included in Current Study?
Stabilization (TMT) References: EPA, 1998b SENES, 2001	Involves precipitating mercuric sulfide (HgS) from scrubber wastewaters in off-gas treatment systems with trimercapto-s-triazine (TMT). Its insolubility in water is similar to that of mercuric sulfide, and it is a relatively stable final waste form. Polyelectrolytes coagulants/filters aids may be used to optimize Hg immobilization. The solids precipitate is removed by settling using circular clarifier and filtration for final polishing.	**No**. Wastewater treatment technologies excluded. See Section 1.3.2.
Leaching-Oxidation-Precipitation References: EPA, 1998a SENES, 2001	Depending on the form of mercury bearing waste (elemental, organomercury), a higher degree of waste matrix digestion must be achieved than either leaching or precipitation alone. This three-step process train (individual steps described before), has been demonstrated as an alternative to incineration, but cannot destroy dioxins, furans, or PCB.	**No.** Not intended for the treatment of bulk elemental mercury. See Section 1.3.2.
Amalgamation: DeHg^{SM} Process References: DOE, 1999a,b SENES, 2001	DeHg process is a two-step process capable of converting mercury-containing mixed waste of various matrices and chemical species to non-hazardous final waste forms. Waste pretreatment would consist of sorting, shredding and slurrying (if necessary) to create a homogeneous mixture. In the 1st step, wastes are treated using classical amalgamation to stabilize elemental mercury contained in the waste. The 2nd step is a chemical stabilization process using a proprietary reagent to break mercury complexes and allow for removal of the mercury from the waste slurry as a stable precipitant. The DeHg process operates at ambient temperature and pressure.	**Yes.** See Section 3.2.3.
ATG Stabilization References: DOE, 1999a SENES, 2001	The Allied Technology Group (ATG) process uses a dithiocarbamate formulation and small amount of proprietary liquid to produce a stabilized waste that satisfies the UTS treatment limits for mercury (0.025mg/l). It has been tested on ion-exchange waste material (mixed waste < 260 ppm Hg). The process equipment consists of a pug mill and mortar mixer and air treatment system. Presence of water < 10% is tolerable for the process. Higher water concentrations hinder the reaction process. Volume increases are small at 16% of the untreated waste volume. This process is most effective on Hg and Cr contaminants and is only moderately effective for Ba and Cd.	**No.** Not intended for the treatment of bulk elemental mercury. See Section 3.2.2.
Stabilization: Sachtleben-Lurgi Process References: EPA, 1998b SENES, 2001	Stabilization SLP involves precipitating mercuric sulfide (HgS) from acidic scrubber wastewaters with H_2S gas. Scrubbing off-gas from smelting of metal ores generates the wastewater.	**No.** Wastewater treatment technologies excluded. Industry-specific. See Section 1.3.2

Process Name and References	Brief Description	Included in Current Study?
Encapsulation: Sulfur Polymer Stabilization/ Solidification References: Kalb, undated SENES, 2001	Sulfur Polymer Cement (SPC) consist of 95% S reacted with 5% of organic modifier to enhance mechanical integrity and long-term durability. A two-stage process converts elemental Hg to HgS by reaction with SPC in its 1st stage. Equal masses of Hg and SPC are mixed in a reaction vessel previously blanketed with nitrogen, thus preventing HgO formation. Vessel is heated to 40^o C to accelerate the sulfide formation. Once the Hg is chemically stabilized, more SPC is added in a 2nd stage, and the mixture heated to 130^o C until a homogeneous molten mixture is formed. It is then poured into a suitable mold where it cools to form a monolithic solid waste form.	**Yes**. See Section 3.2.2.
Encapsulation: Sodium Sulfide Nonahydrate in Sulfur Polymer Cement References: EPA, 1998b SENES, 2001	Sulfur Polymer Cement (SPC) consist of 95% S reacted with 5% of organic modifier to enhance mechanical integrity and long-term durability. A one-stage process converts HgO to HgS by reaction with SPC and sodium sulfide nonahydrate. Sodium sulfide nonahydrate added at 7% w/w to the SPC mixture enhances the conversion reaction. The recommended mixing temperature range is 127-138^o C. SPC-stabilized waste achieves good unconfined compressive strength, it contains no water and is resistant to acids and salts for years. It is less resistant to strong alkali (> 10%), strong oxidizers (hot chromic acid, sodium chlorate-hypochlorite), hot solvents, and some metal slimes like copper.	**Yes.** Similar to BNL Sulfur Polymer Stabilization Solidification (SPSS) Process. See Section 3.2.2.
Sequestration of Mercury as a Stable Solid References: Institute of Gas Technology Endesco Services, Inc. 2000.	Mercury-containing soils and sediments can be treated by thermal desorption followed by sequestration. The thermal desorption process will cause the mercury to be removed from the soil. A condensation step will condense it into liquid. The liquid is then converted into a hard, unreactive, nonporous, monolithic solid form by using an inexpensive metal (amalgamation) for permanent disposal or recovered for later use by simple distillation. The metal used to amalgam Hg is treated by a reactive fluid so that Hg will coat, wet, and adhere to the metal. This is followed by vigorous mixing with a greater mass of Hg to expel the reactive fluid, remove porosity, and form a metallic slurry. The resulting amalgam (Hg at 50-80 % by weight) hardens in 1-2 days.	**Yes**. The thermal desorption phase is a mercury recovery process. The subsequent amalgamation step is represented by the ITS/NFS DeHg® process. See Section 3.2.3.
Mercury Stabilization in Chemically Bonded Phosphate Ceramics: References: Wagh, 2001 SENES, 2001	This is a room temperature setting process based on an acid base reaction between, MgO, KH_2PO_4 solution and solid or liquid waste streams. It forms a dense ceramic of high strength and low open porosity within 2 hours.	**No.** Only demonstrated on wastes containing up to 0.5% mercury. See Section 3.2.5.

Process Name and References	Brief Description	Included in Current Study?
Stabilization: Simultaneous Precipitation and Froth Flotation References: EPA, 1998b SENES, 2001	Heavy metal precipitated as sulfides has very fine particles, and is hard to dewater to separate from the reaction solution. This process involves precipitating mercuric sulfide (HgS) from wastewaters with H_2S gas in a continuously operated froth flotation column.	**No.** Wastewater treatment technologies excluded. See Section 1.3.2
Electro-oxidation References: Sobral, 2000 SENES, 2001	Recycling of mercury and activated carbon can be accomplished by electro-oxidizing mercury in a reaction system where the loaded carbon is the anode during the electrolysis of brine.	**No.** Industry-specific process. See Section 1.3.2.
Adsorption References: EPA, 1998c SENES, 2001	Inorganic mercury present in aqueous wastes can be effectively removed with carbon (granular or powder) at target pH ranges.	**No.** Aqueous wastes not considered in this study. See Section 1.3.2.
Stabilization of Mercury in an Inert Matrix References: EPA, 1998b SENES, 2001	Portland cements, cement kiln dust and fly ash are pozzolanic materials having hydraulic cementitious properties when mixed with free lime. Other materials include volcanic rocks, blast furnace slag and silica fume. Substantial reduction in mercury leachability is easily accomplished in most stabilization processes (waste with < 260 ppm total Hg). Difficult may arise when treating wastes with higher Hg concentration, elemental Hg and organomercury compounds.	**No.** Not suitable for the treatment of bulk elemental mercury. See Section 1.3.2.
GTS Duratek Stabilization References: DOE, 1999b SENES, 2001	This process utilises a Portland cement-based grout process for stabilization of sludges and laboratory residues.	**No.** Not suitable for the treatment of bulk elemental mercury. See Section 1.3.2
Mercury Sublimation References: Envirolight, 1999 SENES, 2001	This technology is applicable to treatment of lighting fixtures. Crushing of lamps releases Hg vapors through a furnace operating a ~ 1400^o C under negative pressure. The Hg gas exiting the furnace reacts with selenium in a smaller chamber (selenium sublimes at 800^o C) and forms a mercury selenide.	**Yes.** A selenide technology. See Section 1.3.2. See Section 3.2.4.
GZA/HM Process References: EPA, 1993a SENES, 2001	The GZA/HM technology utilizes the high specific gravity of mercury and adapts basic mining techniques into a process capable of recovering 99.8% of elemental mercury from soil matrixes.	**No.** A mercury recovery technique. See Section 1.3.2.

Process Name and References	Brief Description	Included in Current Study?
Remerc Process References: EPA, 1998a SENES, 2001	It is a two-step leach procedure. The first leach stage is conducted at a slightly acidic pH and uses sodium hypochlorite to extract the mercury. A vertical wash tower (thickener) washes the leach product. The overflow solution from this tower is transferred to the cementation step. The thickened leach residue from the tower contains about 300ppm of mercury and continues on to the second leach stage. The second leach step is identical to the first, except it is conducted at a more acidic pH.	**No.** Not suitable for the treatment of bulk elemental mercury. See Section 1.3.2.
Tallon Process References: Hall, undated SENES, 2001	This technology is applicable to the treatment of lighting fixtures. It uses a series of wet process steps: crushing, milling, segregation together with a hydrometallurgical step to yield a recyclable glass by-product.	**No.** Industry-specific. See Section 1.3.2.
Xtaltite^{TM} Synthetic Mineral Immobilization of Mercury Xtaltite^{TM} Synthetic Mineral Immobilization of Mercury References: EPA, 1998b SENES, 2001	This technology was developed for stabilization of high-level radioactive waste. It incorporates heavy metals (Hg, As, Cd, Pb) into an apatite type of mineral crystal structure.	**No.** Not proven for bulk elemental mercury.
Conventional Mines References: Freeman, 1989. Nordic Council of Ministers, 1999. SENES, 2001	Suitable repositories may be found in salt, potash, gypsum, limestone and underground granite mines. The main criteria for these mines to be used are, be dry, remain geologically stable and not cave in or close due to plastic flow of the mineral for a long time. Mines can range in depth down to 3000 ft. Stability and access problems would make deeper mines undesirable for hazardous waste storage or disposal. Pretreated waste containing mercury is placed in a stable semi-soluble form in containers. It could also be used as a long-term underground warehouse, if retrievability for recycling were desired.	**Yes.** Mined cavity taken as representative. See Section 3.3.1.
Solution Mine References: Freeman, 1989 SENES, 2001	Salt deposit occurs either as bedded deposits or as dome deposits. Stability considerations dictate that the depth for a solution-mined cavern for hazardous waste storage not exceed 3,000 ft.	**Yes.** Mined cavity taken as representative. See Section 3.3.1.

Process Name and References	**Brief Description**	**Included in Current Study?**
Secure Landfill Reference: SENES, 2001, citing Hennin, P., 2001, Conversation with Safety-Kleen Employee, March.	Hazardous wastes not meeting the slump test criteria are pretreated by solidification. The solidified wastes are initially deposited below grade in an excavated cell. Landfilling then proceeds above grade forming a mound that causes drainage of water precipitation from the landfill surface. Hazardous wastes are placed in the cell in a manner such that only compatible wastes are disposed of together. This can be accomplished by placing the waste either in separate areas or in individual control cells.	**Yes.** See Section 3.3.2.
Stabilization/ Solidification/ Landfill: Stablex Process Reference: SENES, 2001, citing Stablex. [n.d.] [online] Blainville, Quebec. Available at: http://www.envirobiz.com/homepages/stx/stx-ser2.htm	This is a silicate-type process whereby any soluble ions that are left [after chemical pretreatment] are bound with the silicates and the insoluble ions are trapped in a silicate lattice or matrix that is formed during the solidification process. Final hydration, or solidification, takes between 6 and 72 hours. The final Stablex material is placed in the landfill cells as a slurry so that it forms a continuous monolith within the cell. The compressive strength of the material is high, and the hydraulic conductivity is low within the cell.	**Yes,** to the extent that the landfill options selected for this study are representative of all landfill options. See Section 3.3.2.
Mercury Amalgamation Solidification/Stabilization (MASS) References: Spence, 1997 SENES, 2001	Unique features of these technologies are: stabilises either elemental or soluble mercury compounds, minimises the mercury vapor pressure inside the waste form, controls the oxygen potential inside the waste form to prevent oxidation of the amalgamating agents, solidifies mercury, other RCRA metals, and radionuclides inside a cementitious waste form.	**No.** Not enough information available.
Hydrometallurgical: Selective Precipitation of Mercury Sulfide References: EPA, 1993b SENES, 2001	Selective precipitation of mercury sulfide with thioacetamide to yield sulfide from a copper-mercury solution obtained by sulfuric acid leaching. Thioacetamide and thiourea will precipitate mercury sulfide from a sulfate solution at a pH ~ 2 so that it can be removed by filtration before significant copper is also precipitated.	**No.** Not enough information available. Wastewater treatment technology. See Section 1.3.2.
Hydrometallurgical: Selective Leaching of Sulfide Concentrates References: EPA, 1993b SENES, 2001	Selective leaching of sulfide concentrates with an acidic chlorobromide leach and a hypochlorite-bromine oxidant has been effective in a complex sulfide concentrate. The mercury is recovered as Hg^{+1} sulfide precipitate	**No.** Not enough information available.

Process Name and References	Brief Description	Included in Current Study?
Hydrometallurgical: Leaching of Mercury-Sulfur Residue References: EPA, 1993b SENES, 2001	The wash liquor from acid scrubbers operating on sulfide concentrate roasters is treated is treated to remove the dissolved mercury by cementation with aluminum metal pellets. It produces a solid residue, which is primarily elemental mercury.	**No.** Not enough information available. Wastewater treatment technology. See Section 1.3.2.
Hydrometallurgical: Recovery of Mercury and Selenium from Roaster Gas References: EPA, 1993b SENES, 2001	A sulfatization process is used to remove mercury from roaster gases. After dust removal from the mercury bearing off-gases, they are contacted with a recirculating 90% sulfuric acid in a sulfatizing tower and then in a weak acid scrubber to remove HCl and $HgCl_2$ gases. The product from the sulfatizing unit contains selenium (if present in concentrate) that upon washing leaves a complex mercury-selenium precipitate. A controlled potential sulfite-chloride leach procedure then recovers mercury as a precipitate ($Hg_2\ SO_3$) and elemental selenium.	**No.** Not enough information available. Off-gas treatment system not suitable for the treatment of bulk elemental mercury. See Section 1.3.2.
Hydrometallurgical: Ethylene Leaching References: EPA, 1993b SENES, 2001	Ethylene gas is the reagent used to form a strong complex with Hg^{+2}. The process is operated at a gas pressure of 4 atmospheres, and after the leach procedure, releasing the pressure can precipitate HgO.	**No.** Not enough information available. Not suitable for the treatment of bulk elemental mercury. See Section 1.3.2.
Mercury Reducing Bacteria – Completely Mixed Bioreactor References: EPA, 1993c SENES, 2001	Biological detoxification using mercury-resistant bacteria in a completely mixed, aerobic biological treatment process has been shown to have a capability for long-term removal of mercury from polluted water or soil slurry.	**No.** Not enough information available. Not suitable for the treatment of bulk elemental mercury. See Section 1.3.2.
Mercury Reducing Bacteria – Fixed Bed Bioreactor References: EPA, 1993d SENES, 2001	Process development of bioreactors utilizing Hg^{+2} reducing bacteria has shown that reduced Hg can be retained within a fixed bed bioreactor. This offers the possibility of reclaiming Hg^{+2} removed from the waste in a concentrated, less toxic and potentially reusable form. This bacterial reduction system might be utilized also for on-site remedial projects, since volatilized Hg is less toxic and bioavailable.	**No.** Not enough information available. Not suitable for the treatment of bulk elemental mercury. See Section 1.3.2.

APPENDIX C
ENVIRONMENTAL PERFORMANCE DATA

Available environmental performance data are presented in this appendix for the treatment technologies identified in this report. In the past several years EPA and DOE have evaluated various treatment technologies for wastes containing a wide range of mercury, from ‘low mercury’ solid wastes of less than 260 mg/kg to elemental mercury. The tests and programs conducted are summarized in Table C-1. Detailed information concerning each program is presented in Tables C-2 to C-6.

Table C-1 Summary of Available Environmental Performance Data

Reference	Participating Vendors/ Wastes Evaluated	Major Tests Conducted
Sanchez (2001). Evaluated mercury-contaminated soil, ~ 4,500 ppm	ATG BNL Unnamed vendor	Evaluate mercury leaching with respect to pH and liquid-to-solid ratio
USEPA (2002a). Evaluated mercury waste, ~ 5,000 ppm	Four vendors	Evaluate mercury leaching with respect to pH
USEPA (2002b). Evaluated elemental mercury	Three vendors. In addition, there was limited testing of simulated mercury selenide	Evaluate mercury leaching with respect to pH
USDOE (1999a and 1999b). Elemental mercury	NFS ADA	TCLP
USDOE (1999c, 1999d, 1999e). Mercury-contaminated waste, <260 ppm)	NFS GTS Duratek ATG	TCLP

Table C-2 Summary of Treatment Performance Data for Mercury Contaminated Soil from Sanchez (2001)

Property	Description and Purpose of Test	Result for ATG	Result for Unnamed Vendor	Result for BNL SPSS
Concentration reduction from treatment	The total concentration of the untreated material is always greater than the total concentration of the treated material. Sanchez cautions that it is unknown to what extent this reduction is due to dilution by the treatment process, volatilization, or sample heterogeneity	66% reduction in concentration, from untreated to treated	30% reduction in concentration, from untreated to treated	70% reduction in concentration, from untreated to treated
Acid and base neutralization capacity	Measures the buffering capacity. A high buffering capacity provides greater stability from external changes in disposal conditions	Increased from 1 mEq acid/gram (for untreated soil) to 10 mEq acid/gram (for treated soil).	Increased from 1 mEq acid/gram (for untreated soil) to 6 mEq acid/gram (for treated soil).	Very little difference between untreated and treated soil (both about 1 mEq acid/gram).
pH of treated waste	Identifies equilibrium pH of material.	pH = 12.7 (treated); pH = 7.8 (untreated)	pH = 10.2 (treated); pH = 6.8 (untreated)	pH = 9.7 (treated); pH = 6.6 (untreated)
Mercury solubility as a function of pH	Identifies mercury solubility in various pH conditions over the range of 2 to 13 at a Liquid to Solid (LS) ratio of 10. The pH conditions were adjusted using nitric acid and potassium hydroxide.	The mercury solubility was its lowest at pH 12.7 (at levels below UTS of 0.025 mg/L). From pH 2 to 10, the solubility was consistently greater than UTS. In disposal conditions, Sanchez theorizes that the alkaline matrix will result in uptake of carbon dioxide, and subsequently lower the pH of the matrix to 8-9 (where mercury solubility is higher).	The mercury solubility was its lowest at pH 10.2 (at levels below UTS of 0.025 mg/L). From pH 4 to 8, the solubility was consistently greater than UTS. In disposal conditions, Sanchez theorizes that the alkaline matrix will result in uptake of carbon dioxide, and subsequently lower the pH of the matrix to levels where mercury solubility is higher.	The mercury solubility was its lowest at pH less than 2 (at levels below UTS of 0.025 mg/L). From pH 2 to 13, the solubility was somewhat constant but consistently greater than UTS

Table C-2 Summary of Treatment Performance Data for Mercury Contaminated Soil from Sanchez (2001) (Continued)

Property	Description and Purpose of Test	Result for ATG	Result for Unnamed Vendor	Result for BNL SPSS
pH and solubility vs. LS ratio	The pH and mercury solubility was monitored at five different LS ratios from 0.5 to 10. (In comparison, the TCLP uses an LS of 20.) Lower LS ratios (ratio of liquid to solid quantities) provide an approximation of pore water concentrations.	For the treated waste, the pH was relatively constant at 12.7 for all LS variations. The solubility ranged from 0.001 mg/L (at highest LS ratio) to 5 mg/L (at lowest LS ratio) Therefore, the UTS limit of 0.025 mg/L was exceeded for the lower LS ratios	For the treated waste, the pH was relatively constant at 10 for all LS variations. The solubility was less than the UTS limit of 0.025 mg/L at all LS ratios, with concentration increasing with lower LS ratios.	For the treated waste, the pH slightly increased from 9.7 to 10.2 as LS decreased. The solubility was greater than the UTS limit of 0.025 mg/L at all LS ratios, with concentration decreasing with lower LS ratios.
Mercury availability	Mercury was extracted at two different pH values (4 and 8) at a high LS ratio (100) to avoid solubility limitations. Availability defines the fraction of total mercury present that might be released over an infinite time period under extreme environmental conditions.	Mercury availability at pH 8 was 10% of the total, while availability at pH 4 was 26% of the total. The availability of untreated waste at pH 8 was 0.2%, indicating that treatment increases availability.	Mercury availability at pH 4 and 8 was each 2.5% of the total. The availability of untreated waste at pH 4 and 8 was each 0.003%, indicating that treatment increases availability.	Mercury availability at pH 4 and 8 was 2.7% and 0.9%, respectively, of the total. The availability of untreated waste at pH 4 and 8 was each 0.003%, indicating that treatment increases availability.
Mass transfer rate	Mercury was extracted with deionized water following leaching times ranging from 2 hours to 8 days, generating 7 different samples. Unlike most leaching tests involving ‘shaker flasks,’ this test was conducted where only the surface of compacted waste was exposed to the leachant and no mixing occurred. The purpose of this test is to assess the release rate of mercury from compacted granular matrices under mass transfer-controlled release conditions.	The final pH of the leachant from the treated waste was 10.8 to 12.0, which is consistent with prior pH tests. The cumulative release of mercury was 0.03%, and similar to the release of the untreated mercury. The diffusivity was 1.3×10^{-16} m^2/s.	The final pH of the leachant from the treated waste was 7.9 to 9.4, which is slightly lower than in prior pH tests. The cumulative release of mercury was 0.0002%, and much less than the release of the untreated mercury. The diffusivity was 1.0×10^{-20} m^2/s.	The final pH of the leachant from the treated waste was 6.3 to 8.9, which is slightly lower than in prior pH tests. The cumulative release of mercury was 0.015%, and much less than the release of the untreated mercury. The diffusivity was 2.5×10^{-17} m^2/s.

Table C-2 Summary of Treatment Performance Data for Mercury Contaminated Soil from Sanchez (2001) (Continued)

Property	Description and Purpose of Test	Result for ATG	Result for Unnamed Vendor	Result for BNL SPSS
100-year release estimates	Based on prior measurements, the estimated quantity of mercury released over 100 years was estimated. Calculations are made at several different disposal pH conditions and two different rate-limiting step assumptions. These assumptions are either that the water percolates through the material (and therefore equilibrium concentrations limit the rate of release) or that the water flows around the material (and therefore mass transfer within the solid matrix limits the rate of release).	Several different estimates of release rate were obtained. At the equilibrium pH of the material (12.7), between 0.001 and 1.8% would be released. Much higher percentages (up to 30%) would be released at conditions of pH 5 (e.g., due to acidification during disposal). With a diffusion-controlled assumption, 0.4 percent of the material is released.	Several different estimates of release rate were obtained. At the equilibrium pH of the material (10.2), less than 0.009% would be released. Much higher percentages (up to 8%) would be released at conditions of pH 5 (e.g., due to acidification during disposal). With a diffusion-controlled assumption, 0.004 percent of the material is released.	Several different estimates of release rate were obtained. At the equilibrium pH of the material (9.7), 0.5% would be released. Similar percentages (0.4%) would be released at conditions of pH 5 (e.g., due to acidification during disposal). With a diffusion-controlled assumption, 0.2 percent of the material is released.

The Sanchez (2001) study used two different mercury-contaminated soils, each containing about 4,500 mg/kg mercury in addition to containing radionuclide components. Three treatment processes were used: the BNL amalgamation and encapsulation process, a Portland cement stabilization/solidification process by ATG, and a third vendor whose name was withheld from the study results at their request. Each vendor only evaluated one soil type.

Table C-3 Summary of Treatment Performance Data for Mercury Surrogate Waste from USEPA (2002a)

Property	Description and Purpose of Test	Result for Vendor A	Result for Vendor B	Result for Vendor C	Result for Vendor D
Waste loading	Correlates to the quantity of additives; a 100% waste loading indicates no dilution)	30%	72%	45%	25%
Volume increase	Vendor-reported, approximate increase in volume between untreated and treated form.	36% increase	No data	No data	25% increase
Air loss	Vendor-reported loss to air during treatment	Estimated 0.3%	No data	Estimated 0.05%	No data
Cation exchange capacity	Determines extractable quantities of certain alkali and alkaline earth metals; higher capacities indicate a higher potential to hold other cations such as toxic metals.	0.9 to 2.0 mEq/g treated; 1.7 mEq/g untreated	1.6 to 3.0 mEq/g treated; 1.5 mEq/g untreated	0.5 to 5.2 mEq/g treated; 1.7 to 2.0 mEq/g untreated	2.3 to 2.5 mEq/g treated; 1.3 mEq/g untreated
pH of treated waste	Identifies equilibrium pH of material.	~7.0 treated; 1.9 untreated	~6.2 treated; ~1.4 untreated	~8.9 treated; 1.8 untreated	~9.7 treated; ~1.6 untreated
Redox	Measures oxidation-reduction potential. An oxidizing (aerobic) environment is represented by a positive value	-30 to -60 mV treated; +520 mV untreated	60 to 120 mV treated; +550 mV untreated	-100 to +210 mV treated; +580 mV untreated	-20 to -90 mV treated; +580 mV untreated
Mercury solubility as a function of pH	Identifies mercury mobility in various pH conditions over the range of 2 to 12 at an LS ratio of 20 (the same LS as used for TCLP). The pH conditions were adjusted using nitric acid and sodium hydroxide.	The mercury solubility was consistently below UTS (0.025 mg/L) from pH 2 to 10. The concentration rose significantly at pH 12.	The mercury solubility was consistently above UTS (0.025 mg/L) from pH 2 to 10, with higher concentration at lower pH. The concentration dropped below UTS at pH 12.	The mercury solubility was highest at pH of 2. The concentration was at or below UTS at pH 8 to 12.	The mercury solubility was highest at pH of 4. The concentration was at or above UTS at other pH values, with a low at pH 12.
Percent leached as a function of pH	Uses above data for calculations of percentage leached during the test	The treated waste leached from 0.001 to 0.13% between pH 2 and 10; leaching increased to 3.5% at pH 12.	The treated waste leached less than 0.02% at pH 12. It leached a maximum of 13% mercury at lower pH.	The treated waste leached less than 0.06% at pH 4 and above, and up to 6% at pH 2.	The treated waste leached between 0.02% and 4% mercury

The USEPA (2002a) study used a surrogate waste comprised of five different compound and elemental forms of mercury, and other additives, to simulate a 'difficult to treat' waste. The mercury content was 5,000 ppm. Four treatment processes were used.

Table C-4 Summary of Treatment Performance Data for Elemental Mercury from USEPA (2002b)

Property	Description and Purpose of Test	Result for Vendor A	Result for Vendor B	Result for Vendor C	Result for HgSe
Waste loading	Correlates to the quantity of additives; a 100% waste loading indicates no dilution)	33%	44-55%	20%	---
Volume increase	Vendor-reported, approximate increase in volume between untreated and treated form.	1500% increase	No data	No data	---
Loss to Air	Vendor-reported loss to air during treatment	Estimated 0.3%	No data	None expected	---
Cation exchange capacity	Determines extractable quantities of certain alkali and alkaline earth metals; higher capacities indicate a higher potential to hold other cations such as toxic metals.	0.4 to 0.8 mEq/g treated	0.4 to 0.5 mEq/g treated	1.4 to 2.1 mEq/g treated	---
pH of treated waste	Identifies equilibrium pH of material.	11.0 treated	6.9 to 8.1 treated	~10 treated	---
Redox	Measures oxidation-reduction potential. An oxidizing (aerobic) environment is represented by a positive value	-460 mV treated	-10 to -80 mV treated	-650 to -850 mV treated	---
Mercury solubility as a function of pH	Identifies mercury mobility in various pH conditions over the range of 2 to 12 at an LS ratio of 20 (the same LS as used for TCLP). The pH conditions were adjusted using nitric acid and sodium hydroxide. The chloride addition (for one treated waste only) simulates co-disposal conditions.	The mercury solubility was below UTS (0.025 mg/L) at pH 2 and pH 11. The concentration was highest at pH 12, and in the pH range 6 to 8.	The mercury solubility was consistently below UTS (0.025 mg/L) from pH 2 to 10, with concentration increasing with increasing pH.	The mercury solubility was highest at pH of 2. The concentration was between the TCLP (0.2 mg/L) and the UTS from pH 6 to 12.	Reagent-grade mercury selenide was leached at pH 7 and 10 with and without chloride to simulate co-disposal. Leaching was lower at pH 7 and with no added chloride.
Percent leached as a function of pH	Uses above data for calculations of percentage leached during the test	The treated waste leached a maximum of 1.0% (pH 12) and a minimum of 0.00003 (pH 2).	The treated waste leached less than 0.0007% at pH 12, the maximum rate.	The treated waste leached less than 0.004% between pH 6 and 12, and up to 0.4% at pH 2.	The treated waste leached less than 0.00006% without added chloride and up to 0.0003% with chloride.

The USEPA (2002b) study used lab-scale batch sizes of elemental mercury (less than one kg). Three treatment processes were used.

Table C-5 Other DOE Elemental Mercury Studies

Property	Description or Purpose of test	Results: NFS DeHg Process (DOE 1999a)	Results: ADA Process (DOE 1999b)
Waste loading	Correlates to the quantity of additives; a 100% waste loading indicates no dilution)	20 to 25%	50 to 60%
TCLP from two waste sources	TCLP – current EPA standard, although the regulation does not apply to elemental mercury.	The results from 14 ‘two step’ treatment batches (amalgamation plus stabilization) showed results ranging from 0.02 to 0.12 mg/L, with four results below UTS. A ‘one step’ treatment (amalgamation only) produced much higher results, ranging from 0.05 to 7.5 mg/L.	Not detected (<0.1 mg/L) TCLP in five batches; additional testing of composites showed results of 0.035 to 0.048 mg/L (which is between UTS and TC limits)
Vapor measurements during treatment step	Quantifies air releases of mercury from the process	No information	Less than OSHA limit of 50 ug/m^3 in five batches

The waste was radioactively-contaminated mercury from DOE sites.

Table C-6 Other DOE Mercury Waste Studies

Reference and Vendor	Waste Type	TCLP Results	Weight or Volume Increase
DOE 1999e; NFS DeHg Process	Ion-exchange resin (<260 ppm mercury)	0.011 to 0.025 mg/L, treated, based on two samples	No information
DOE 1999d; GTS Duratek Process	Sludge (<260 ppm mercury)	0.001 to 0.031 mg/L, treated, based on two batches	No information
DOE 1999c; ATG Process	Ion-exchange resin (<260 ppm mercury)	5 of 7 different additive formulations resulted in treatment to below UTS. The overall range was 0.006 to 0.11 mg/L TCLP	15% weight and 24% volume, using formulation giving lowest TCLP measurements

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USEPA 2002b. U.S. Environmental Protection Agency. *Technical Background Document: Mercury Wastes. Evaluation of Treatment of Bulk Elemental Mercury*. Final Report. February 8, 2002.

APPENDIX D
EVALUATION OF TREATMENT AND DISPOSAL ALTERNATIVES

This appendix details the derivation of the values of the intensities assigned to each criterion for each of the eight alternatives involving treatment and disposal. This is conducted using individual information on treatment and disposal presented in the main section of this report. In most cases this integration was straightforward. Tables D-1 to D-8 in this appendix provide more detailed explanations for each alternative individually. Each table identifies the assigned value for the treatment disposal sequence based on information on the items separately. Explanations are included in these tables where needed. In several cases, information about a treatment step differs from the information about a disposal step. In such cases, information about the step likely to be the ‘bottleneck’ was used for the entire treatment/ disposal sequence. For example, the first criterion is compliance with current laws and regulations. In most cases, it is expected that the treatment process is relatively easy to conduct in the current regulatory framework and the disposal step is currently prohibited. Therefore, the composite value for the sequence as a whole is assigned the more stringent value associated with the disposal step.

The alternatives identified in this appendix are as follows:

- Stabilization/amalgamation followed by disposal in a RCRA- permitted landfill (Table D-1)
- Stabilization/amalgamation followed by disposal in a RCRA- permitted monofill (Table D-2)
- Stabilization/amalgamation followed by disposal in an earth-mounded concrete bunker (Table D-3)
- Stabilization/amalgamation followed by disposal in a mined cavity (Table D-4)
- Selenide treatment followed by disposal in a RCRA- permitted landfill (Table D-5)
- Selenide treatment followed by disposal in a RCRA- permitted monofill (Table D-6)
- Selenide treatment followed by disposal in an earth-mounded concrete bunker (Table D-7)
- Selenide treatment followed by disposal in a mined cavity (Table D-8)

Table D-1 Evaluation for Treatment Disposal Option: Stabilization/Amalgamation Followed by Disposal in a RCRA-Permitted Landfill

Criteria	Amalgamation/ Stabilization Treatment	RCRA-Permitted Landfill	Overall Sequence
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Non-compliant with LDRs	Non-compliant with LDRs (assigned the more restrictive value for the disposal step)
Implementation considerations: volume of waste	Volume increase about 15x	Not applicable (affected by treatment, not disposal)	Volume increase above 10x
Implementation considerations: engineering requirements	Simple components	An existing commercial landfill can be used	Existing facilities can be used (it is assumed that the treatment sequence can be quickly integrated into existing landfill treatment operations)
Maturity of the technology: state of maturity of the technology	Not commercial scale	Very mature in U.S.	Pilot treatment/ full-scale disposal
Maturity of the technology: expected reliability of treatment operation	Simple components and batch processing	Not applicable	Simple
Risks: worker risk	Very low	Very low	Very low
Risks: public risk	Verylow because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Risks: susceptibility to terrorism/sabotage	Verylow because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Environmental performance: discharges during treatment	Minimal discharges expected	Not applicable	Minimal
Environmental performance: degree of performance testing	Moderate: TCLP and additional testing performed	Not applicable	Moderate
Environmental performance: stability of conditions in the long term	Not applicable	Fair	Fair
Environmental performance: ability to monitor	Not applicable	Easy	Easy
Public perception	Neutral	Negative	Negative (the disposal step is permanent while treatment is temporary)
Implementation costs	Extremely variable estimates	Low (existing unit can be used)	Low (additive between treatment and disposal; even with unknowns still expected to be a lower cost alternative)
Operating costs	Costs will be from the initial treatment	Low	Low (additive between treatment and disposal; even with unknowns still expected to be a lower cost alternative)

Table D-2 Evaluation for Treatment Disposal Option: Stabilization/Amalgamation Followed by Disposal in a RCRA-Permitted Monofill

Criteria	Amalgamation/ Stabilization Treatment	RCRA-Permitted Monofill	Overall Sequence
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Non-compliant with LDRs	Non-compliant with LDRs (assigned the more restrictive value for the disposal step)
Implementation considerations: volume of waste	Volume increase about 15x	Not applicable (affected by treatment, not disposal)	Volume increase above 10x
Implementation considerations: engineering requirements	Simple components	New in-ground construction is required	A new facility must be constructed (monofill construction would require more complex effort than treatment sequence)
Maturity of the technology: state of maturity of the technology	Not commercial scale	Very mature in U.S.	Pilot treatment/ full-scale disposal
Maturity of the technology: expected reliability of treatment operation	Simple components and batch processing	Not applicable	Simple
Risks: worker risk	Very low	Very low	Very low
Risks: public risk	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Risks: susceptibility to terrorism/sabotage	very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Environmental performance: discharges during treatment	Minimal discharges expected	Not applicable	Minimal
Environmental performance: degree of performance testing	Moderate: TCLP and additional testing performed	Not applicable	Moderate
Environmental performance: stability of conditions in the long term	Not applicable	Good	Good
Environmental performance: ability to monitor	Not applicable	Easy	Easy
Public perception	Neutral	Negative	Negative (the disposal step is permanent while treatment is temporary)
Implementation costs	Extremely variable estimates	Medium (requires new construction)	Medium (additive between treatment and disposal)
Operating costs	Costs will be from the initial treatment	Low	Low (additive between treatment and disposal)

Table D-3 Evaluation for Treatment Disposal Option: Stabilization/Amalgamation Followed by Disposal in an Earth-Mounded Concrete Bunker

Criteria	Amalgamation/ Stabilization Treatment	Earth-Mounded Concrete Bunker	Overall Sequence
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Non-compliant with LDRs	Non-compliant with LDRs (assigned the more restrictive value for the disposal step)
Implementation considerations: volume of waste	Volume increase about 15x	Not applicable (affected by treatment, not disposal)	Volume increase above 10x
Implementation considerations: engineering requirements	Simple components	New in-ground construction is required	A new facility must be constructed (bunker construction would require more complex effort than treatment sequence)
Maturity of the technology: state of maturity of the technology	Not commercial scale	Technology has been applied but not widely used	Pilot treatment/ untested disposal
Maturity of the technology: expected reliability of treatment operation	Simple components and batch processing	Not applicable	Simple
Risks: worker risk	Very low	Very low	Very low
Risks: public risk	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Risks: susceptibility to terrorism/sabotage	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Environmental performance: discharges during treatment	Minimal discharges expected	Not applicable	Minimal
Environmental performance: degree of performance testing	Moderate: TCLP and additional testing performed	Not applicable	Moderate
Environmental performance: stability of conditions in the long term	Not applicable	Good	Good
Environmental performance: ability to monitor	Not applicable	Easy	Easy
Public perception	Neutral	Positive to neutral	Positive to neutral
Implementation costs	Extremely variable estimates	High (costs are likely higher than monofill)	High (additive between treatment and disposal)
Operating costs	Costs will be from the initial treatment	Medium	Medium (additive between treatment and disposal)

Table D-4 Evaluation for Treatment Disposal Option: Stabilization/Amalgamation Followed by Disposal in a Mined Cavity

Criteria	Amalgamation/ Stabilization Treatment	Mined Cavity	Overall Sequence
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Non-compliant with LDRs and unusual permitting may be required	Atypical permit required (assigned the more restrictive value for the disposal step)
Implementation considerations: volume of waste	Volume increase about 15x	Not applicable (affected by treatment, not disposal)	Volume increase above 10x
Implementation considerations: engineering requirements	Simple components	Construction would be more complex than other alternatives	A mine cavity construction is required (mine construction would require more complex effort than treatment sequence)
Maturity of the technology: state of maturity of the technology	Not commercial scale	Technology has been applied but not widely used	Pilot treatment/ untested disposal
Maturity of the technology: expected reliability of treatment operation	Simple components and batch processing	Not applicable	Simple
Risks: worker risk	Very low	Low	Low (assigned the more restrictive value from the disposal step)
Risks: public risk	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Risks: susceptibility to terrorism/sabotage	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Environmental performance: discharges during treatment	Minimal discharges expected	Not applicable	Minimal
Environmental performance: degree of performance testing	Moderate: TCLP and additional testing performed	Not applicable	Moderate
Environmental performance: stability of conditions in the long term	Not applicable	Very good	Very good
Environmental performance: ability to monitor	Not applicable	Difficult	Difficult
Public perception	Neutral	Positive to neutral	Positive to neutral
Implementation costs	Extremely variable estimates	High(costs are likely higher than monofill)	High (additive between treatment and disposal)
Operating costs	Costs will be from the initial treatment	Medium	Medium (additive between treatment and disposal)

Table D-5 Evaluation for Treatment Disposal Option: Selenide Process Followed by Disposal in a RCRA-Permitted Landfill

Criteria	Selenide Process	RCRA-Permitted Landfill	Overall Sequence
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Non-compliant with LDRs	Non-compliant with LDRs (assigned the more restrictive value for the disposal step)
Implementation considerations: volume of waste	Volume increase not known, assumed similar to others	Not applicable (affected by treatment, not disposal)	Volume increase above 10x
Implementation considerations: engineering requirements	More capital requirements and relatively complex	An existing commercial landfill can be used	New facilities are needed (it is assumed that the treatment sequence is more of a limiting factor here than for S/A)
Maturity of the technology: state of maturity of the technology	Commercial scale for mercury wastes but not for elemental mercury. Quantities of wastes treated are likely much less than quantities of elemental mercury.	Very mature in U.S.	Pilot treatment/ full-scale disposal
Maturity of the technology: expected reliability of treatment operation	Relatively complex and continuous processing	Not applicable	Complex
Risks: worker risk	Higher than other alternatives due to high temperatures and additional toxic chemical	Very low	Low (assigned the more restrictive value from the treatment step)
Risks: public risk	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Risks: susceptibility to terrorism/sabotage	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Environmental performance: discharges during treatment	Minimal discharges expected	Not applicable	Minimal
Environmental performance: degree of performance testing	Low: limited testing performed by EPA	Not applicable	Low
Environmental performance: stability of conditions in the long term	Not applicable	Fair	Fair
Environmental performance: ability to monitor	Not applicable	Easy	Easy
Public perception	Neutral	Negative	Negative (the disposal step is permanent while treatment is temporary)
Implementation costs	Extremely variable estimates	Low (existing unit can be used)	Low (additive between treatment and disposal; even with unknowns still expected to be a lower cost alternative)
Operating costs	Costs will be from the initial treatment	Low	Low (additive between treatment and disposal; even with unknowns still expected to be a lower cost alternative)

Table D-6 Evaluation for Treatment Disposal Option: Selenide Process Followed by Disposal in a RCRA-Permitted Monofill

Criteria	Selenide Process	RCRA-Permitted Monofill	Overall Sequence
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Non-compliant with LDRs	Non-compliant with LDRs (assigned the more restrictive value for the disposal step)
Implementation considerations: volume of waste	Volume increase not known, assumed similar to others	Not applicable (affected by treatment, not disposal)	Volume increase above 10x
Implementation considerations: engineering requirements	More capital requirements and relatively complex	New in-ground construction is required	New facilities are needed (for both treatment and disposal)
Maturity of the technology: state of maturity of the technology	Commercial scale for mercury wastes but not for elemental mercury. Quantities of wastes treated are likely much less than quantities of elemental mercury.	Very mature in U.S.	Pilot treatment/ full-scale disposal
Maturity of the technology: expected reliability of treatment operation	Relatively complex and continuous processing	Not applicable	Complex
Risks: worker risk	Higher than other alternatives due to high temperatures and additional toxic chemical	Very low	Low (assigned the more restrictive value from the treatment step)
Risks: public risk	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Risks: susceptibility to terrorism/sabotage	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Environmental performance: discharges during treatment	Minimal discharges expected	Not applicable	Minimal
Environmental performance: degree of performance testing	Low: limited testing performed by EPA	Not applicable	Low
Environmental performance: stability of conditions in the long term	Not applicable	Good	Good
Environmental performance: ability to monitor	Not applicable	Easy	Easy
Public perception	Neutral	Negative	Negative (the disposal step is permanent while treatment is temporary)
Implementation costs	Extremely variable estimates	Medium (requires new construction)	Medium (additive between treatment and disposal)
Operating costs	Costs will be from the initial treatment	Low	Low (additive between treatment and disposal; even with unknowns still expected to be a lower cost alternative)

Table D-7 Evaluation for Treatment Disposal Option: Selenide Process Followed by Disposal in an Earth-Mounded Concrete Bunker

Criteria	Selenide Process	Earth-Mounded Concrete Bunker	Overall Sequence
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Non-compliant with LDRs	Non-compliant with LDRs (assigned the more restrictive value for the disposal step)
Implementation considerations: volume of waste	Volume increase not known, assumed similar to others	Not applicable (affected by treatment, not disposal)	Volume increase above 10x
Implementation considerations: engineering requirements	More capital requirements and relatively complex	New in-ground construction is required	New facilities are needed (for both treatment and disposal)
Maturity of the technology: state of maturity of the technology	Commercial scale for mercury wastes but not for elemental mercury. Quantities of wastes treated are likely much less than quantities of elemental mercury.	Technology has been applied but not widely used	Pilot treatment/ untested disposal
Maturity of the technology: expected reliability of treatment operation	Relatively complex and continuous processing	Not applicable	Complex
Risks: worker risk	Higher than other alternatives due to high temperatures and additional toxic chemical	Very low	Low (assigned the more restrictive value from the treatment step)
Risks: public risk	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Risks: susceptibility to terrorism/sabotage	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Environmental performance: discharges during treatment	Minimal discharges expected	Not applicable	Minimal
Environmental performance: degree of performance testing	Low: limited testing performed by EPA	Not applicable	Low
Environmental performance: stability of conditions in the long term	Not applicable	Good	Good
Environmental performance: ability to monitor	Not applicable	Easy	Easy
Public perception	Neutral	Positive to neutral	Positive to neutral
Implementation costs	Extremely variable estimates	High (costs are likely higher than monofill)	High (additive between treatment and disposal)
Operating costs	Costs will be from the initial treatment	Medium	Medium (additive between treatment and disposal)

Table D-8 Evaluation for Treatment Disposal Option: Selenide Process Followed by Disposal in a Mined Cavity

Criteria	Selenide Process	Mined Cavity	Overall Sequence
Compliance with current laws and regulations	Would require permitting through existing regulatory structure	Non-compliant with LDRs and unusual permitting may be required	Atypical permit required (assigned the more restrictive value for the disposal step)
Implementation considerations: volume of waste	Volume increase not known, assumed similar to others	Not applicable (affected by treatment, not disposal)	Volume increase above 10x
Implementation considerations: engineering requirements	More capital requirements and relatively complex	Construction would be more complex than other alternatives	A mine cavity construction is required (mine construction would require more complex effort than treatment sequence)
Maturity of the technology: state of maturity of the technology	Commercial scale for mercury wastes but not for elemental mercury. Quantities of wastes treated are likely much less than quantities of elemental mercury.	Technology has been applied but not widely used	Pilot treatment/ untested disposal
Maturity of the technology: expected reliability of treatment operation	Relatively complex and continuous processing	Not applicable	Complex
Risks: worker risk	Higher than other alternatives due to high temperatures and additional toxic chemical	Low	Low (both treatment and disposal steps have slightly greater risks than other alternatives)
Risks: public risk	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Risks: susceptibility to terrorism/sabotage	Very low because large quantities of mercury will not be present	Very low (because underground)	Very low (very low risks for both treatment and disposal)
Environmental performance: discharges during treatment	Minimal discharges expected	Not applicable	Minimal
Environmental performance: degree of performance testing	Low: limited testing performed by EPA	Not applicable	Low
Environmental performance: stability of conditions in the long term	Not applicable	Very good	Very good
Environmental performance: ability to monitor	Not applicable	Difficult	Difficult
Public perception	Neutral	Positive to neutral	Positive to neutral
Implementation costs	Extremely variable estimates	High (costs are likely higher than monofill)	High (additive between treatment and disposal)
Operating costs	Costs will be from the initial treatment	Medium	Medium (additive between treatment and disposal)

APPENDIX E
DISPOSITION OF COMMENTS

The current report was first issued as a draft document on April 22, 2002. A presentation based on the April 2002 version of this report was made during the Northeast Waste Management Official's Association (NEWMOA) conference, *Breaking the Mercury Cycle*, held in Boston MA on May 1 to 3, 2002. Comments on the report were solicited and comments were subsequently received from the Defense Logistics Agency (DLA), EPA's Office of Solid Waste (OSW), EPA's Office of Research and Development's (ORD's) Quality Assurance Review office, and from Paul Randall of EPA ORD, who was EPA's Technical Lead Person (TLP) for the present work. The disposition of these comments is addressed below.

COMMENTS FROM PAUL RANDALL, ORD

Mr. Randall sent the following comments. Rather than changing the report, the answers to his questions are provided in a question and answer format.

Comments

"How can this information, this model, this software be used by the USEPA? What is required for a technical person at the USEPA to perform other analysis? Is this software costly or is it freeware? How many hours is required to learn this software? As you know, USEPA's Office of Solid Waste is the office that will most likely implement any suggestion. Is this mercury retirement model too complex to be implemented? Big picture questions: What overall impact can this study have? Mercury retirement model: How can this be implemented by others (state agencies, international)?

"Under conclusions and recommendations, what is required to implement these recommendations? For example, it says, ' additional expert choice analyses could be conducted in which certain alternatives are optimized.' Can a technical person in the USEPA do this, or does SAIC only have this expertise? How can the available information be revisited? How many hours would it take to re-input the information and arrive at an answer? How long did it take to arrive at a basic model for decision making? Is this mercury retirement model practical?

"How does the software take into consideration the varying effectiveness of each treatment technology? Please be specific. How are the intensities calculated to incorporate the effectiveness and leaching characteristics of each technology? It appears 3 of the technologies were lumped into a stabilization/amalgamation category."

DISCUSSION OF THESE POINTS IN A QUESTION AND ANSWER FORMAT IS PRESENTED BELOW.

RESPONSES

1) *How can this information, this model, this software be used by the USEPA?*

SAIC is providing the complete report and the input files to the EPA to use however they desire in the future. This includes this project and all derivative work that can be developed from the ideas contained in the project. EPA owns the product. Examples of how EPA can use these materials include: using the framework of the model with input from inter-Agency staff in revising the criteria weighting; and using the results in conjunction with other Agency data to further develop mercury retirement policy options.

2) *What is required for a technical person at the USEPA to perform other analysis?*

At a minimum, a technical person from EPA needs only the software, this report, and input files (whose essential elements are reproduced in this report). The software is relatively easy to learn, and the screen shots in this report can be used in guiding the analyst in learning. In addition, the web site www.expertchoice.com has many references, books, tutorials, example solutions, slide shows, etc. to download for free or purchase. Many books and dissertations have been written on the AHP algorithm, which is the engine of Expert Choice, and there are about 20,000 active users use it. One of the software developers, Dr. Forman, also teaches Expert Choice locally in the Washington D.C. area at George Washington University. In addition, some EPA staff may already be trained in its use or be familiar with the product and EPA may want to determine if this is the case.

3) *Is this software costly or is it freeware?*

The pricing depends on the single or team version, and number of licenses purchased. There is also a 15 day free trial demo. For a single user, the price is estimated to be in the range of $1,000. Such a user could replicate the analyses performed in this report and conduct similar evaluations.

4) *How many hours is required to learn this software? As you know, USEPA's Office of Solid Waste is the office that will most likely implement any suggestion. Is this mercury retirement model too complex to be implemented?*

SAIC built the model with the intent that EPA, not SAIC would be actually using it in the future. EPA should find it easy to implement. As analytical models go, this one is not particularly complex. The software can be learned in two or three days.

5) *Big picture questions: What overall impact can this study have? Mercury retirement model: How can this be implemented by others (state agencies, international)?*

The model is intended to be shared at will by the EPA in any manner. The model may be most suitable to be used centrally with results shared with a wider audience. As more experts get involved with wider expertise, the model can be tweaked as desired. In addition, when ideas are suggested that do not affect the outcomes significantly, they can be documented as considered but not included. This will help keep the model manageable when expanded to a larger audience. The results of the model can be used in development of EPA policy and recommendations to others such as states or the international community.

6) *Under conclusions and recommendations, what is required to implement these recommendations? For example, it says, " additional expert choice analyses could be conducted in which certain alternatives are optimized." Can a technical person in the USEPA do this, or does SAIC only have this expertise? How can the available information be revisited?*

First, it should be emphasized that any additional Expert Choice analysis would require the development of data, criteria, and intensities as described in the report. As noted above, we believe that technical persons within EPA can implement this process with a manageable amount of training. The expertise is not unique to SAIC. There are several ways in which the available information could be revisited, of varying levels of complexity.

One approach would be to take the database that has already been developed and change it – for example, by adding extra criteria, or more alternatives, or by changing the intensities. This could be done in a day or two through a brain-storming session.

A second method would involve developing a second Expert Choice model "from the ground up" which would be appropriate for certain alternatives such as choosing between specific storage options or specific stabilization treatment and disposal alternatives. This would require identifying alternatives and criteria and formulating a new model; any person familiar with Expert Choice and the alternatives would have the necessary expertise to do this.

Another method is to develop a separate algorithm (i.e., something other than Expert Choice). One example is an algorithm that was developed for the DOE's National Energy Technology Laboratory (NETL)[1], known as an "Optimization Tool Kit." The Tool-kit integrates proven program and project optimization and risk assessment approaches with advanced applications in the area of optimization under uncertainty and integrated program management. It runs in the Microsoft Windows® environment using the Microsoft Project® and Excel® platforms. These standard tools are augmented with Monte Carlo simulation software and optimization algorithms. The result is a powerful tool-kit that is easy to use, easy to explain, and provides a lot of documentation. It has more capabilities than does Expert Choice because, for example, it can be used for uncertainty analyses.

As noted above, this Tool-kit was developed for the US government. As such, it is also free to the EPA but would require modification for this particular application. It was developed by Larry Deschaine (SAIC) for a specific purpose (future energy production project selection), and would need to be customized to be usable to the Mercury retirement project (e.g., different decision variables and goals), which may best be conducted by SAIC. The tool would then be turned over to EPA to use, however desired, in conjunction with appropriate and effective EPA training. The DOE NETL paper provides a general description of the tool; a copy is attached. There already is a training manual on the tool, which would be tailored for EPA as well.

The level of effort required by SAIC to develop such a tool depends on what answers are needed and types of uncertainties. The conversion of the tool to the mercury project would take about 3-4 weeks, and additional runs and training would be on top of that. Tailoring the manual for the EPA would take about a week extra, which would involve modifying existing templates, etc. Additional time may be needed for training or integrating additional features requested by users. Further discussion of this tool is presented below.

7) *How many hours would it take to re-input the information and arrive at an answer?*

All of the information used in the model is available from this report and from the input files. It is a fairly straightforward exercise to duplicate the results presented in this report. Of course, the time needed to conduct modifications to the existing model is dependent on the types of changes proposed, but a great deal can be accomplished in a day or two of brain-storming.

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[1] Deschaine, L.; Rawls, P.; Manfredo, L.; Patel, J. "The DOE NETL Program and Project Source Selection, Risk Quantifier, Management Support, and Optimization Tool-Kit." Published at the Society for Computer Simulation's Advanced Technology Simulation Conference, Seattle WA, April 2001. A copy of this paper is attached.

8) *How long did it take to arrive at a basic model for decision making?*

Two sessions were conducted. In an initial session, two days were spent brainstorming to develop an initial set of criteria, weighting factors, and intensities. A period of a few weeks was spent researching and applying the available information to this initial framework. Towards the end of the project, an additional two-day session was spent to review the framework and discuss what changes to make to better use the available information. These sessions involved three members of SAIC's staff with experience in mercury retirement and risk assessment issues and one member of SAIC's staff with in-depth knowledge of the software.

9) *Is this mercury retirement model practical?*

The results of the model are practical: i.e., they result in recommendations that can be implemented. For example, one outcome of the study was the conclusion that it supports continuing to store elemental mercury for a few decades until the treatment technologies are more mature. This seems to be an eminently practical recommendation. Using and making refinements to the model is also practical (i.e., relatively easy), as described above..

10) *How does the software take into consideration the varying effectiveness of each treatment technology? Please be specific.*

The applied model used environmental performance as one criterion in assessing alternatives. This criterion was comprised of sub criteria consisting of (1) discharges during treatment; (2) degree of performance testing of the treatment technology; (3) stability of conditions in the long term; and (4) ability to monitor long term conditions. Therefore, the model did not explicitly take into account the varying effectiveness of each treatment technology. One reason is because EPA's OSW is conducting an ongoing review of this information and preliminary results or conclusions of this review were not available prior to the presentation of initial findings at the Boston conference. Secondly, deciding amongst different vendors is a specific application, or optimization, of an alternative. In place of these differences, other criteria relating to the technologies were used.

Effectiveness can be integrated into the model using the existing Expert Choice analysis or the above-mentioned algorithm tool for optimization. The difference between the Expert Choice analysis and the NETL algorithms are that the EC gives the average value of the team vote (i.e., single point averages), while the NETL algorithms provide the distribution of the uncertainty in the expert's knowledge and opinions. Given the data gaps and lack of clear conclusions involving treatment efficiency, such an algorithm may be the more appropriate tool. However, the EC software is much easier to use, whereas the NETL algorithms are more complex because they include stochastic simulation (MonteCarlo / Latin Hypercube) and machine learning (genetic algorithms) for decision optimization under uncertainty. For the DOE application, they have been integrated with Excel and other commercial off-the shelf software to make it a little easier to apply and read results.

11) *How are the intensities calculated to incorporate the effectiveness and leaching characteristics of each technology? It appears 3 of the technologies were lumped into a stabilization/amalgamation category.*

The leaching effectiveness of individual technologies was not assessed in this report. The three vendors discussed were placed into a single category for a number of reasons. First, not all data are publicly available or publicly attributable to a specific vendor. In other words, the results of a study cannot be traced back to a specific vendor without compromising prior agreements or decisions to 'blind' the data. Second, the data are being evaluated by the Office of Solid Waste (OSW) including the use of an external peer review process. It was felt that there is much to be gained to allow this review to continue and to not duplicate this particular assessment effort given the complexities that OSW is experiencing in assessing these data. Finally, without OSW concurrence, we did not want to take the position in this report of favoring one vendor over another.

Sections Changed to Address Paul Randall's Comments

Only one change was made: the end of Section S.4 was amended to clarify that evaluation of individual treatment technologies was not conducted as part of the methodology.

COMMENTS FROM OSW

OSW provided the following comments:

Comments

"Overall, I think the report is good and will help inform some of the discussions that will be occurring in the Quiksilver Caucus (QC)/EPA workgroups (and will be especially useful to some of the newcomers to the subgroups). Having said this, my main comment focuses on the conclusions and recommendations from page S-6.

"Rather than spend more money on further analyses (e.g., by adding additional experts, by optimizing certain alternatives in the Expert Choice Software, by performing a formal uncertainty analysis utilizing Monte-Carlo based techniques), it might make more sense to turn the process of selecting the best alternatives for mercury retirement over to the QC/EPA group. I don't know who besides SAIC was involved in drafting your report (maybe you could add a list somewhere in the report so everyone knows), but I'm assuming we will have a more diverse group (i.e., not only EPA HQs, but also States, Regions, DOD, DOE, USGS, and State organizations) available as part of the QC/EPA group.

"Here are a couple of other comments:

"- By making the storage option really expensive (i.e., by assuming that in addition to storing, eventually you would have to treat and dispose), the result is that storage doesn't look that great (at least not when you consider costs). You say as much on p. S-5. This is a critical assumption that greatly colors the result of the analysis, and it is buried in the report. We think this should be moved closer to the front.

"- The disposal options should consider additional environmental risks & costs (mine water and landfill leachate collection and treatment for starters). Yellowknife is the prime example of use of a mined shaft gone wrong. The water ate the concrete plugs and arsenic tailings ran out."

Sections Changed to Address OSW Comments

Recommendation Item # 1 in the Conclusions and Recommendations (Section S.7 and Section 5.0) was amended so as to clarify that, so far, the development of criteria and intensities was carried out by SAIC staff and that involving a more diverse group could lead to the development of further insights.

The opening Paragraph in Section 2 was amended, clarifying that SAIC developed the model, criteria, etc., and who was involved. An additional, shorter explanation was added to Section S.4 of the Executive Summary. ORD had a similar comment (see below).

A footnote to Table S-1 was added and additional discussion provided in Section S.4, to better explain the assumptions about how costs were considered for storage options

The Yellowknife 'case study' for mine disposal was added to Section 3.3.1 and its application to the environmental performance criteria is summarized in Section 3.3.6. The bibliography in Section 6 was adjusted accordingly.

No changes to the model are necessary as a result of the OSW comments.

COMMENTS FROM DLA

DLA provided the following comments.

Comments

"…assuming that peer review supports the EPA studies, the MMEIS will only analyze three alternatives in detail. These alternatives are: 1) consolidation and storage at one or more of the current mercury storage sites or other suitable locations, 2) sale of the mercury inventory, and 3) no action, maintaining storage at the four existing sites. The description of the DNSC MMEIS on page S-2 should be changed to reflect this revision.

"Two of the draft SAlC report's assumptions differ significantly from those in the DNSC MMEIS. Most important, the DNSC mercury is considered a commodity rather than a RCRA waste. Second, the draft SAIC report assumes that containment bunkers will be constructed if mercury is stored. Should one of the MMEIS storage alternatives be selected, DNSC could use existing warehouses or munition bunkers. Use of existing facilities might more than offset the monitoring and maintenance cost penalty of storage postulated on page 3-5 of the SAlC report."

Sections Changed to Address DLA Comments

The discussion of the MMEIS on page S-2 was revised as suggested. The DLA letter was added to the bibliography in Section 6.

Additional discussion regarding the 'RCRA waste' assumption was added to Section S.4 and Section 3.1.1. An additional example was extracted from the literature and the bibliography revised accordingly. Basically, SAIC made a conservative assumption that RCRA permits will be required for the storage of bulk elemental mercury.

The discussion in Section 3.1.5 was changed to better show that the use of existing facilities could result in lower costs.

An additional 'case study' of mercury storage was identified in the literature and added to Section 3.1.1 and the bibliography revised accordingly

No changes to the model are necessary as a result of the DLA comments.

ORD QA REVIEW

Comments in the ORD QA review that require changes are as follows:

Comments

"Volume of Waste. Section 2.3.2, Sub-criterion 2A, page 2-1, and Table 2-2, page 2-7. Both the text and the table list two intensity levels for volume of waste. However, Table A-1 (Appendix A, page A-13) lists three levels. This inconsistency should be resolved.

"Section S.5, page S-4, first full paragraph. The numerical rankings presented for the sub-criterion "State of maturity of the treatment technology" (0.717, 0.205, and 0.078) are not consistent with Table A-1, page A-13 (0.731, 0.188, 0.081).

"Section 2.3.7, page 2-5, last sentence of section. "Table 1" should be corrected to "Table 2-1."

"Table 3-3, page 3-12. Under the criterion "Risks: susceptibility to terrorism/sabotage," columns 2 and 3 say "Low" risks rather than "Very low" risks, as in columns 3 and 4. This appears to be a typo because there is no mention in the text as to why these treatment options would have different risk levels.

"Section 3.4, page 3-19. Bullets 2, 3, and 4 should be indented further to distinguish between the stabilization/amalgamation technologies and the selenide process. The paragraph above talks about "two treatment options," but the bullets appear to show five treatment options.

"Appendix A, Table A-1, page A-13. In the operating cost row, it appears that the value for "High" should be corrected to 0.078. In the volume of waste row, it appears that the value for "Increase greater than 10 times" should be corrected to 0.081.

"Appendix B, pages B-4 and B-5. Under "Chemical Leaching/Acid Leaching" and "Leaching-Oxidation-Precipitation," there are references to "EPA, 1999a." However, this item is not included in the Appendix B list of references.

"Defining "the team." Section S.4, page S-3, first paragraph. The Expert Choice software appears to have been used by a team of people for this application; however, "the team" is not defined. It would be useful to describe the membership of this team."

Sections Changed to Address ORD QA Review Comments

The number of intensity levels associated with the volume of waste (in Section 2.3.2 and Table 2-2) was changed to be made consistent with the number of intensity levels in Appendix A (3).

The rankings for technology maturity criteria in Section S.5 were changed to be made consistent with Appendix A, as suggested.

The referencing of Table 2-1 was changed as suggested.

The intensity listed in Table 3-3 for susceptibility to terrorist attack for two of the treatment methods was changed as suggested. The change is consistent with the intensity used in the model as identified in Table 3-6.

The formatting of Section 3.4 was changed as suggested.

The intensities for operating cost and volume of waste in Table A-1 were changed to be made consistent with Figure A-4 and Figure A-10, respectively, as suggested.

Referencing of Appendix B was corrected and confirmed to be consistent with the 2001 Canadian Study.

Clarification of the composition of “the team” that developed the model, etc., was made to Section S.4 and the opening paragraph of Section 2. OSW had a similar comment (see above).

No changes to the model are necessary as a result of the ORD QA comments.

DOE-NETL TOOL-KIT

If you are reading this report as a .pdf file or as a paper document in a 3-ring binder, the paper referenced in Footnote #1 included in this Appendix. If you are reading a Word document, the paper is available separately as a .pdf file.