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

Draft Report

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ACRONYMS AND SYMBOLS

AHP	Analytical Hierarchy Process
BNL	Brookhaven National Laboratory
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
g	grams
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
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
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: predict likely outcomes, plan projected and desired futures, facilitate group decision making, exercise control over changes in the decision making system, allocate resources, select alternatives, and do 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 for Environment Canada on the development of retirement and long-term storage options for

[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.

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). Among the alternatives that are being considered are storage, treatment and disposal options. 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.

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 treated 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.
- 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 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. For example, the treatment of wastewater streams is excluded for this reason.

- 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 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: 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

S.5 <u>Goals, Criteria and Intensities</u>

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 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)

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 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: 0.717. 0.205, and 0.078 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 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.[2] 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.

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

[2] 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.

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 in the process of assigning weights to the various criteria. This would ensure that a wider range of expertise and interests is incorporated into the analysis. 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)					
	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.

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 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. Finally, 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.

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: predict likely outcomes, plan projected and desired futures, facilitate group decision making, exercise control over changes in the decision making system, allocate resources, select alternatives, and do cost/benefit comparisons.

The Expert Choice software package incorporates the principles of AHP in an intuitive, graphically based and structured manner so as to be 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 Hg

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

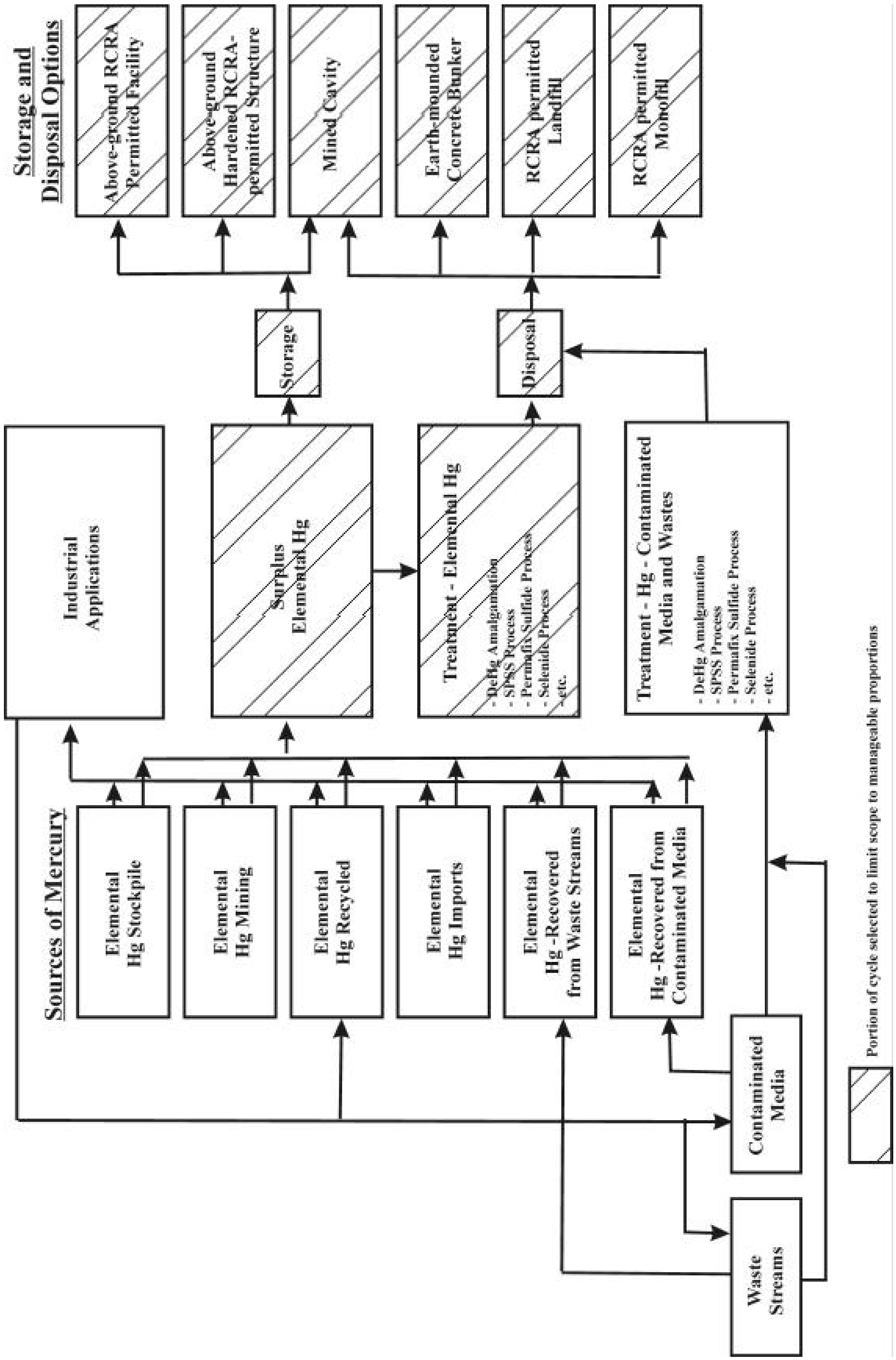

Figure 1-1 Simplified Schematic of the Mercury use and Disposal Cycle

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 both 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.
- 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. Wastewater streams are an example.
- 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 treated 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.

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. Two intensity levels have been chosen: a) zero or minimal increase; and b) 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, but 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 there 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.

Pairwise Comparison of Sub-Criteria

Expert Choice requires that these four sub-criteria be pairwise compared. This is described in Appendix A.

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 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 <u>Summary of Criteria and Intensities</u>

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 ext ent 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; or b) 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. 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 (SAIC 2002). The DNSC has also estimated the present annual costs associated with the storage of the 4,000 ton stockpile at its four sites; this was estimated as totaling \$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 an in-depth accounting.

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 similar design 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. The size 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 more general 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 criteria:

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 can be applied.

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.

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

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 releases 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 costs to construct a standard storage unit is assumed to be about $4 million; alternatively, an existing commercial site could be used which would require no additional costs. This is expected to be the lowest initial cost for any of the storage alternatives. In contrast, the estimated initial costs of $10 to $20 million for concrete hardened storage, while expected to be overstated since it is based on radioactive containment, are nonetheless higher than 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 mercury stockpile are assumed to be about $750,000 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 would be required and additional costs for such management would result. Therefore, operating costs include both the costs of maintaining storage integrity as well as the additional costs of eventual implementation of a long-term retirement option.

3.2 <u>Treatment Information</u>

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. As applicable, these are identified in conjunction with the vendor developing the technology: ADA / Permafix treatment, BNL sulfur polymer solidification, IT/NFS DeHg® process, and the selenide process. More detailed information is presented below to the extent information is publicly available.

Environmental performance of the treatment technologies have 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 also 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 of the material

$ 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
USDOE (1999a and 1999b). Elemental mercury	NFS ADA	TCLP
USDOE (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. (Permafix 2001)

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. (Permafix 2001)

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 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.

3.2.2 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^{o}C to 70^{o}C for several hours. This converts mercury to the mercuric sulfide form. Additional sulfur polymer cement is added and heated to 135^{o}C. 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 to 350-times this scale for treatment of the DLA stockpile of 4,400 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. (Kalb, 2001) This represents a volume increase from about 0.22 gallons (assuming pure elemental mercury) to 4 gallons, or 18 times. (Kalb, 2001) 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). (Fuhrmann 2002) Mass balance measurements show an estimated 0.3 percent mercury is released from the process vessel and captured in the air control system. (Kalb, 2001)

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. (Kalb, 2001) Sulfide additives which have been examined include sodium sulfide monohydrate and triisobutyl phosphine sulfide. (Fuhrmann 2002)

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). (BNL Response 2001)

Costs for treatment of the 4,400 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 accounted for. (BNL Response, 2001) Based on this information, the costs for the treatment of 1,500 tons of elemental mercury (approximately a ten-year supply at current use rates) 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 as 0.05 percent. Ambient air measurements have been measured 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 as $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 (approximately a ten-year supply at current use rates) 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 demonstrated for fluorescent lamps. In the U.S., an estimated 17 tons of mercury in lamps was disposed 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.[3] 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, is 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 is estimated to be a release rate of 0.03 percent.[4] Reagent-grade mercury selenide (i.e., not produced from a treatment step) was part of the EPA elemental mercury treatment study to evaluate 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)

No cost estimates are available for this process.

3.2.5 Treatment Technologies Not Considered

ATG

[3] 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.

[4] 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). These calculations result in the estimation that one million kg of lamps contain about 60 kg of mercury.

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 an increase of 16 percent from the untreated waste. The treated waste was in the form of a damp paste. Additional wastes generated include PPE, containers, etc. (USDOE, 1999c).

Costs for treatment were estimated as $1.73/kg waste. This is comprised of 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). (DOE, 1999d)

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

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

Criteria	Amalgamation/Stabilization Options: ADA / Permafix Treatment	BNL Sulfur Polymer Solidification	IT/NFS DeHg® Process	Overall for 3 Stabilization/ Amalgamation Options	Selenide Process
Risks: susceptibility to terrorism/sabotage	Low because large quantities of mercury will not be present	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				

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 will be 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 criteria:

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.

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. Less data were identified for the selenide process.

Public perception. The principal 'driver' of public perception to 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 to treat 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, disposal in an earth-mounded concrete bunker.

3.3.1 Disposal in a Mined Cavity

There are several examples of deep underground storage being used 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 both a buffer to emissions and stability in disposal. Reasons provided by the Swedish EPA in 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. (WIPP 2002) 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 to estimate the costs for this alternative. A storage capacity of 13,000 cubic meters is identified as being 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). Sweden estimates that in a 50-year time period 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). (Sweden, 1997) Applying these costs to a hypothetical 1,500 ton quantity of mercury results in costs ranging from $30 million to 90 million for disposal.

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. For example, 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 as $240 million and disposal costs are estimated as $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 1970's and 1980's 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 will be 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 criteria:

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

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 mine 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 Risk 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.

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. 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 by 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 uncertain 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

As a result, 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 between Table 3-1 and

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

	Risks			Environmental Performance					Cost	
Alternative	Worker Risk	Public Risk	Suscepti-bility to Terrorism/ Sabotage	Discharges During Treatment	Degree of Treatment Performance Testing	Stability of Conditions in the Long Term	Ability to Monitor	Public perception	Imple-mentation	Oper-ating
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

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.

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 influences 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 the effects from considering cost at different contributions to the overall ranking and therefore 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 isolate the effects towards 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 on results: 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 criteria. 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 analyzes 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 8's and 9's) as well as bright spots (e.g., ranks of 1's and 2's). 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: Values 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 criteria is equal (i.e., both implementation and operating costs contribute equally to the total 'cost score. The next columns list the sensitivity results for each of these two cost criteria. For example, for the implementation cost sensitivity analysis, the contribution of this criterion to the importance of all 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:

- <u>Identifying the importance of criteria on results</u>: 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 criteria. The ratio is relatively high for each of the two criteria indicating that each can significantly affect results for the overall objective.
- <u>Differences between implementation costs and operating costs</u>: 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 criteria 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.

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

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.

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.

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 single criteria 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 criteria 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. This would ensure that a wide range of expertise is incorporated into the analysis. 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. Additional experts could be solicited internal to EPA, or from certain attendees to the May 2002 mercury conference in Boston.

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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