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Economic and Environmental Analysis of Technologies to Treat Mercury and Dispose in a Waste Containment Facility

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ECONOMIC AND ENVIRONMENTAL ANALYSIS OF TECHNOLOGIES TO TREAT MERCURY AND DISPOSE IN A WASTE CONTAINMENT FACILITY

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NOTICE

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FOREWORD

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ACRONYMS

AHP	Analytic Hierarchy Process
ASTM	American Society for Testing and Materials
BNL	Brookhaven National Laboratory
CFR	Code of Federal Regulations
COTR	Contracting Officer’s Technical Representative
CQA	Construction Quality Assurance
CTA	Centralized Treatment Alternative
DLA	Defense Logistics Agency
DNSC	Defense National Stockpile Center
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
HDPE	High Density Polyethylene
LCCE	Life-Cycle Cost Estimate
LCRS	Leachate Collection and Removal System
LDR	Land Disposal Restrictions
LDS	Leak Detection System
ME	Macroencapsulation
MT	Metric Tons
MTA	Mobile Treatment Alternative
NME	No Macroencapsulation
MMEIS	Mercury Management Environmental Impact Statement
NEI	Nuclear Energy Institute
NPV	Net Present Value
O&M	Operations and Maintenance
OMB	Office of Management and Budget
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
UTS	Universal Treatment Standard
WF	Weighting Factor
WIPP	Waste Isolation Pilot Plant

ECONOMIC AND ENVIRONMENTAL ANALYSIS OF TECHNOLOGIES TO TREAT MERCURY AND DISPOSE IN A WASTE CONTAINMENT FACILITY

EXECUTIVE SUMMARY

This report is intended to describe an economic and environmental analysis of a number of technologies for the treatment and disposal of elemental mercury.[1] The analysis considers three treatment technologies that convert elemental mercury into a stable form of mercury. The technologies are identified as Option A, Option B, and Option C in this report. Several vendors use processing techniques and/or prepare economic information which has been claimed as proprietary; however, only non-proprietary information is presented in this report.

Each of the three treatment technologies is subject to a number of variations that include either a centralized treatment facility or one or more mobile treatment facilities, followed by either macroencapsulation or no macroencapsulation[2], with ultimate disposal in a monofill. Thus, there are twelve treatment and disposal alternatives all together:

1. Option A + no macroencapsulation + centralized treatment
2. Option A + no macroencapsulation + mobile treatment
3. Option A + macroencapsulation + centralized treatment
4. Option A + macroencapsulation + mobile treatment
5. Option B + no macroencapsulation + centralized treatment
6. Option B + no macroencapsulation + mobile treatment
7. Option B + macroencapsulation + centralized treatment
8. Option B + macroencapsulation + mobile treatment
9. Option C + no macroencapsulation + centralized treatment
10. Option C + no macroencapsulation + mobile treatment
11. Option C + macroencapsulation + centralized treatment
12. Option C + macroencapsulation + mobile treatment

Three different masses of mercury are being considered for each of the 12 alternatives:

a. 5,000 metric tons,
b. 12,000 metric tons, and
c. 25,000 metric tons.

Thus, 36 treatment and disposal alternatives are being considered. In addition, cost estimates have been prepared for storage of the three masses of elemental mercury in aboveground facilities, making a total of 39 cost estimates in all. It is assumed that 1,000 MT per year is treated and disposed of independent of the total mass. For the storage alternatives, it is assumed 5,000 MT is already in storage (approximately consistent with the existing amount in government stockpiles) and that the additional elemental mercury becomes available over 12 and 25 years respectively for the 12,000 MT and 25,000 MT alternatives (e.g., due to chlor-alkali plant closure).

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[1] Note – the analysis is restricted to the treatment and disposal or long-term storage of elemental mercury. This report does not consider the treatment and disposal of mercury-containing wastes nor radioactive mercury.

[2] No other waste will be commingled with the treated mercury in these monofills. Macroencapsulation in this report is a separate step after stabilization during which the treated mercury is sealed in polyethylene to limit mercury transport to the environment. If the stabilization process ends with the solidified product in some form of container, this container will be encapsulated in polyethylene in the macroencapsulation alternative. "No macroencapsulation" means that the stabilized mercury will be placed in the monofill exactly as it is generated by the stabilization process.

The results are presented in Section S.5 of this summary with conclusions and recommendations in Section S.6. Sections S.1 through S.4 discuss the background, approach and assumptions.

S.1 Background

The use of mercury in products and processes is decreasing. It is likely that in the future, the supply of mercury will far exceed the demand for mercury. In addition, the Department of Defense (DOD) and the Department of Energy (DOE) have stockpiled approximately 6,000 Metric Tons (MT) of mercury that is no longer needed. Therefore, strategies must be devised for managing the excess mercury. Currently, the most prevalent method is to store the elemental, liquid form in flasks and stockpile them in warehouses. The risks associated with this method of storing elemental mercury have been extensively discussed in the *Final Mercury Management Environmental Impact Statement* (DLA 2004).

Independently of DLA, EPA's Offices of Research and Development (ORD) and Solid Waste (OSW) have been working with DOE to evaluate technologies for permanently stabilizing and disposing of wastes containing mercury (e.g., DOE 1999a-1999e; USEPA 2001, 2002a,b). Other comprehensive studies carried out in the recent past include one by SENES Consultants (SENES 2001) who produced a draft report for Environment Canada evaluating 67 technologies for the retirement and long-term storage of mercury. In addition, OSW is considering revisions to the Land Disposal Restrictions (LDRs) for mercury. Land disposal of hazardous wastes containing greater than 260 mg/kg mercury is currently prohibited. OSW has pursued options which would allow land disposal of waste containing greater than 260 mg/kg mercury; however, no specific revisions are forthcoming (See Section 1.1 of this report for further information).

Using the above-referenced work as a starting point, EPA prepared report EPA/600/R-03/048, *Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* (USEPA 2002c). USEPA (2002c) Appendix B provides a concise review of the SENES 2001 mercury treatment technologies and why certain treatment technologies were not selected by the USEPA for further analysis. The purpose of the present work is the logical next step, which is to focus on just a few of the alternatives considered in EPA/600/R-03/048. This allows a more detailed breakdown and analysis of the stabilization/amalgamation alternatives than was possible in EPA/600/R-03/048, and also allows more effort to be applied to developing cost information.

S.2 Choice of Technologies

The first task was to narrow the choice of treatment technologies to just three.

The first step was to review the available literature and to hold consultations with EPA personnel in ORD and OSW. This resulted in a short-list of 6 treatment technologies identified as Options A through F. The list was then winnowed down to 3 treatment technologies by using the Kepner-Tregoe decision-making method as a tool[3]. Section 1.3.1 contains a brief summary of this method. It is further described in Section 2 and its use resulted in a final list of three treatment technologies, Options A, B, and C. See DOE (2001a).

S.3 Environmental Analysis

The method chosen for the environmental comparison of the twelve treatment and disposal alternatives is the Analytic Hierarchy Procedure (AHP) as embodied in the Expert Choice software. This is the same tool that was used for the analysis in EPA/600/R-03/048. Different selection criteria were used in the present AHP analysis than in the USEPA 2002c study to better define the

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[3] The Kepner-Tregoe method assigns a weight to each of a number of selected criteria. Each alternative is then scored against each criterion (e.g., on a scale from 1-10). The scores and corresponding weights are multiplied and then summed for each criterion, leading to a numerical ranking.

strengths/weaknesses and data gaps of each treatment technology. The AHP process is described in Section 1.3.2. Information and details of Expert Choice software and its usage are described in Appendices A and B.

The AHP was carried out as a brainstorming exercise by a team from SAIC and EPA. The team first developed the goal of the analysis: minimize environmental impacts during the life-cycle of the treatment and disposal of elemental mercury. Based on this goal, the team then developed and ranked criteria against which each alternative was compared. Criteria with largest weight and smallest rank as the most important issues. These criteria and subcriteria with relative weightings and rankings are provided in parentheses were:

C1. During routine operation of the stabilization facility (weighting: 0.065, ranking: 4)
    C1-1. -solid waste streams (other than final product) (0.750)
    C1-2. -atmospheric discharges (0.250)
C2. During abnormal or accidental operation of the stabilization facility (weighting: 0.188, ranking: 3)
    C2-1. -elemental mercury spills (0.833)
    C2-2. -spills other than elemental mercury (0.167)
C3. During transportation (weighting: 0.216, ranking: 2)
    C3-1. -of mercury to stabilization facility (0.747)
    C3-2. -of stabilized waste to monofill (0.119)
    C3-3. -of reagents to stabilization facility (0.134)
C4. During decommissioning of the stabilization unit (weighting: 0.038, ranking: 5)
C5. During storage in the monofill (weighting: 0.493, ranking: 1)
    C5-1. - expected difficulty of maintaining environmental conditions (up to 40 years) (0.200)
    C5-2. -expected long-term susceptibility to degradation (0.800)

The weights against each criterion or subcriterion are an indication of the relative importance and were assigned by the team using a brainstorming process known as “pairwise comparison.” The relative importance of criteria, from most to least is shown in Figure S-1. Each of the 12 treatment and disposal alternatives were then assigned an “intensity” or score relative to each of the criteria or subcriteria. Section 3.3 and USEPA 2002c provide details on “pairwise comparisons” and “intensities”. Summing these scores leads to a relative ranking of the alternatives, see Section S.5.

The above weightings show that, of the first-level criteria, the SAIC/EPA team assigned the greatest weight (almost 50%) to storage in the monofill. Of the subcriteria below storage in the monofill (C5-1 and C5-2), the greatest weight (80%) was assigned to the long-term susceptibility of the waste form to degradation (e.g., changes in the disposal environment as discussed in Section 3.3.5 and Appendix B). Therefore, scores for individual alternatives were strongly influenced by the team’s expectations about long-term behavior in the monofill.

The team also assigned considerable importance to transportation accidents, especially those that could involve the spillage of elemental mercury.

S.4 Economic Analysis

As described above, 36 treatment and disposal alternatives are being considered. In addition, cost estimates have been prepared for storage of the three masses of elemental mercury in aboveground facilities, making a total of 39 cost estimates in all.

Each of the thirty-six cost estimates for treatment and disposal includes the following elements[4]:

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[4] Note: the cost results do not contain estimates of the costs that might be incurred should there be an accident or malfunction (e.g., a spillage of elemental mercury during transportation or excessive leachate escaping from the monofill).

- Capital costs for the treatment facility,
- Capital costs for the macroencapsulation facility (if part of the alternative),
- Operating and maintenance costs for the treatment process,
- Operating and maintenance costs for the macroencapsulation process (if part of the alternative),
- Costs associated with the mobile treatment alternatives,
- Transportation costs associated with each alternative,
- Costs of storing elemental mercury prior to treatment,
- Decommissioning costs for the treatment facilities,
- Monofill engineering and construction costs,
- Monofill operating costs, and
- Costs of maintaining and monitoring the monofill for a thirty-year period following its closure.

Each of the three storage alternatives contains the costs of maintaining the existing stockpile (assumed to be 5,000 MT) in storage, adding to storage space as necessary, and transporting elemental mercury to the storage facility(ies).

The SAIC team developed process flow diagrams for each of the three technologies and the associated macroencapsulation process and a preliminary design for the monofill such that 1,000 MT of elemental mercury will be treated and disposed of each year.

The sources of information for the cost estimates included:

- Published work by the vendors of Options A, B, and C together with information gathered in telecons. This enabled the team to develop the 1,000-MT/year process flow diagrams and to obtain some information on costs.
- Code of Federal Regulation requirements for the construction and operation of a monofill.
- Standard industry sources of cost information such as Perry and Green's *Industrial Engineering Handbook* and Richardson Engineering Services' *Process Plant Construction Estimating Standards*.
- Telecons with equipment manufacturers.
- Websites of equipment manufacturers.
- The Mercury Management Environmental Impact Statement (MMEIS), published by the Defense Logistics Agency (DLA 2004). This contains detailed information on storage and transportation costs.

The SAIC team assigned uncertainty ranges to items that are input to the total cost. The final cost estimates and uncertainties were estimated by performing an uncertainty analysis using a triangular probability distributions in Crystal Ball® software (Decisioneering 2004)[5]. See Section 4.5 for a discussion of how input ranges of uncertainty were assigned.

S.5 Results

This section considers first the results of the environmental analysis and then the results of the economic analysis. The results from the environmental evaluation were considered independently from the economic evaluation (i.e., results from the environmental evaluation had no effect on the economic evaluation and vice versa). In principal, the economic viability of the various alternatives could have been considered as one of the top-level criteria in the AHP analysis, but this was not part of the scope of

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[5] Crystal Ball® is user-friendly software that facilitiates the performance of Monte Carlo-type analyses by linking to data in Excel spreadsheets.

the present analysis. An example of an AHP study in which both economic and environmental factors were considered can be found in USEPA (2002c).

S.5.1 Environmental Analysis – Results

Table S-1 shows the results for the twelve treatment and disposal alternatives (independent of mass). The AHP process scales all values to 100 percent. Thus the more alternatives analyzed the smaller the values for each alternative. The values in Table S-1 should be considered as being relative to each other, not as absolutes. The values in Table S-1 are normalized to 1000 points to make them whole numbers. The following are some observations derived from Table S-1:

- In general, mobile treatment alternatives score better than centralized treatment alternatives. The principal reason for this is that the authors made a simplifying assumption: for the centralized treatment alternatives, elemental mercury is transported to the central treatment unit, whereas the mobile treatment facility travels to the elemental mercury, in which case only the waste product is transported. In Section S.3, the transportation criterion (C.3) is assigned a weight of 0.216, with only the monofill being of greater concern. See Figure S-1 for the relative importance of each criteria and subcriteria. Of the transportation subcriteria, accidental mercury releases are assigned by far the greatest weight (0.747) so that alternatives in which mercury can be released during transportation have a relatively large unfavorable impact on the total score. Data and assumptions used by DLA (2004) were used to assess risks from mercury transport; these data are in Appendix A.
- There is a slight preference towards macroencapsulation alternatives over alternatives that do not include this additional treatment. This is principally because the polyethylene-macroencapsulated waste is expected to behave relatively well in the monofill and decrease the potential long-term leachability of mercury.
- All of the alternatives that include Option B technology score higher than options which include Option C technology. This is because the Option B waste form has a lower leaching rate in the monofill than does the Option C waste form (see Figure B-1 in Appendix B) and the Option B leaching rate is much less sensitive to changes in pH than is Options C. In addition, currently available data on the Option C technology suggest a relative high rate of volatilization of mercury, which in itself could present a release pathway and could also lead to decreased effectiveness (through deformation) of the encapsulation material over time (discussed in Appendix B).
- Cases which include Option A technology are more scattered; one Option A case scores highest while a different Option A case scores lowest. The Option A cases without macroencapsulation tend to score low because available data (see Figure B-1 in Appendix B) suggest that leaching rates from the Option A waste form are quite sensitive to small changes in pH. This conclusion should be caveated by noting that there are large uncertainties in the leaching results presented on Figure B-1.

The above observations were confirmed by performing analyses that addressed uncertainties by changing the intensities assigned to the various options. For example, changing the intensities of the four Option C cases to reflect relatively good environmental performance in the monofill considerably increased their scores and improved their ranking. In addition, the authors conducted a selection of sensitivity analyses on the relative importance of the criteria, as follows:

- Changing the weight of the final disposal criterion from 49.3% to 75% (i.e., more important)
- Changing the weight of the final disposal criterion from 49.3% to 25% (i.e., less important)
- Changing the weight of the transportation criterion from 21.6% to 40% (i.e., more important)
- Changing the weight of the transportation criterion from 21.6% to 10% (i.e., less important)

- Changing the weight of the abnormal/ accidental operations criterion from 18.8% to 40% (i.e., more important)
- Changing the weight of the abnormal/ accidental operations criterion from 18.8% to 10% (i.e., less important)
- Changing the weight of the routine operations criterion from 6.5% to 13% (i.e., more important)
- Changing the weight of the routine operations criterion from 6.5% to 3.2% (i.e., less important)
- Changing the weight of the decommissioning criterion from 3.8% to 7.6% (i.e., more important)
- Changing the weight of the decommissioning criterion from 3.8% to 1.8% (i.e., less important)

In each case the weights of the remaining criteria were changed (while keeping their relative magnitudes the same) to ensure that the sum of all the weights is 100%. The results of the analyses of the three most sensitive criteria, which are the first six bullets listed above, are shown in Table S-2. The remaining sensitivities are presented in Appendix A and are not presented here because they produce very small differences in the scores.

In all cases, the same two alternatives remain the most highly ranked for both the baseline analysis and the ten sensitivity analyses (i.e., Option A and Option B with mobile treatment and macroencapsulation). At the other extreme, the same single alternative remained the most unfavorably ranked in all cases (i.e., Option A with centralized treatment and no macroencapsulation). In between, there are minor changes in ranking. This helps show the stability in the results.

In addition to sensitivity analyses, the Team also performed uncertainty analyses. Uncertainty identifies the extent to which variation in the information and data influences the conclusions. Some of the areas of uncertainty include the following (see Appendix B):

- <u>Monofill Disposal Stability for Option C- long term</u>: Conflicting data are available regarding the degree of mercury vapor generation from the Option C process, which is an area of uncertainty affecting stability. Table S-3 shows that, if the long-term behavior of Option C-generated waste in the monofill is better than assumed in the base case, its ranking improves considerably. This issue is discussed in more detail in Section 3.8.
- <u>Monofill Disposal Stability for Option A</u>: As discussed above, a single alternative scored lowest in all sensitivity analyses (i.e., centralized treatment of Option A with no macroencapsulation). As an uncertainty analysis, intensity values of this alternative were changed to demonstrate how its score may rise, as follows:

    - Option A + no macroencapsulation + centralized treatment. Original score 48 (12th highest)
    - Analysis 1: Changing intensity of <40 year disposal condition from ‘moderate’ to ‘low’: slight increase in score to 55 (12th highest)
    - Analysis 2: Changing intensity of >40 year disposal condition from ‘moderate’ to ‘low’: significant increase in score to 84 (6th highest)
    - Analysis 3: Changing intensity of both the <40 year and >40 year disposal condition from ‘moderate’ to ‘low’: significant increase in score to 92 (4th highest)

This illustrates that consideration of sensitivities and uncertainties must be an important factor in decision-making. The recommendations below include one that addresses the desirability of obtaining better leaching data before making final choices between alternatives.

- Other Monofill Disposal Stability: An obvious area of uncertainty for all alternatives is the degree to which the disposal conditions will remain stable for both a short and a long period of time (less than 40 years and greater than 40 years, respectively). This range was demonstrated for one of the alternatives. In addition, the scale-up performance of the treatment technologies themselves is uncertain with regard to their ability to treat relatively large quantities of mercury for an extended period of time. In all cases, good mixing and operational consistency are expected to be critical in achieving long-term stability.
- Accidental Releases of Mercury During Operations: Risks of accidental releases of mercury during the mercury treatment step may be higher or lower than evaluated. This range was demonstrated for two of the alternatives.

The uncertainty analyses and results are described in Table S-3. Each row of the table represents an instance where data are changed for just one of the alternatives. As shown, a total of 11 different uncertainty analyses were conducted.

The 11 sets of uncertainty analysis results in Table S-3 show how the overall ranking of each alternative is affected as the intensities of individual criteria are changed. It would be expected that the largest changes in ranking would result from changing the subcriteria with the largest relative weights, i.e., the weight of the subcriteria times the weight of the criteria. As seen from Figure S-1 long-term disposal subcriteria has the largest relative weight.

As would be expected if the model worked properly, the uncertainty analyses showed that results change most significantly in the case of changing the intensity of the long term (>40 year) disposal criterion between ‘Moderate’ and ‘Low.’ This is shown for Reference Nos. 1 through 7. For example, as discussed above, the lowest-scored Option A alternative in Table 3-4 (Reference No. 3) significantly improves its score, from 48 (12th best) to 84 (6th best). Changes in the intensity of the shorter term (<40 year) value also improve the score, but not as much (Reference Nos. 2 and 4).

Uncertainty with regard to accidental releases (mercury spills) during operations have a relatively small effect on results. For example, an Option B alternative (Reference Nos. 8 and 9) still ranks high regardless of whether the intensity is given a value of low, moderate, or high.

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. As shown above, this suggests that uncertainty with regard to long-term storage and disposal represents one such parameter.

S.5.2 Economic Analysis – Results

The results of the economic analysis are shown in Tables S-4 and S-5. The results are presented as Net Present Values (NPV), for which the team used the OMB 30-year real discount rate of 3.5% per year. Note that the “best” estimates are the means that result from the Monte Carlo analysis and are not necessarily exactly the same as would result from a sum of point estimates without uncertainty distributions. Tables S-4 and S-5 prompt a number of observations and conclusions.

- The most striking result is that the Option C cases cost far more than do the others. Analysis of the calculations reveals that there is one parameter that drives almost the whole of this difference – the cost of reagents. The cost was provided by the vendor for the amalgamation and stabilization of elemental mercury. No attempt was made to adjust it for potential economies of scale. The actual cost of reagents for the Option C process is proprietary and cannot be quoted here but calculations show that the NPV for Option C reagent costs alone for the 5,000 MT case is approximately $123M. For Option A the comparable costs are approximately $8M and for Option B approximately $3.4M. Therefore, for the alternatives that treat 5,000MT, the reagent costs alone account for more than $100M difference between the costs of Option C process and those of the Option A or Option B processes, with correspondingly larger differences for the 12,000 MT and 25,000 MT alternatives.

- As noted, the composition of the Option C reagents is proprietary. In any future decision making process, the cost per kg of treated Hg will need to be examined in more detail.
- The Option B process consistently exhibits the lowest costs. As noted above, it has the lowest reagent cost. In addition, it has the least mass increase of the three technologies – the mass multipliers for waste form production are 1.63 (Option B), 3.26 (Option A), and 5.66 (Option C)[6] . This affects other items such as transportation costs.
- The best estimates for the NPV of alternatives that include mobile treatment are somewhat higher than those for alternatives that include treatment at fixed facilities. In addition, the uncertainty ranges are much wider. Both of these principally result from the wide uncertainty bands assigned to mobile treatment alternatives –20% to +200% for capital costs and –50% to + 100% for O&M costs. These wide ranges were assigned because the mobile treatment option is not well defined (e.g., the number of treatment units is not known). There are also extra costs associated with assembling and disassembling the equipment and moving it from site to site.
- The cost of storage is relatively modest. Note that these storage costs were derived from data in the MMEIS. For example, for continued storage of 5,000 MT for 35 years, the NPV is $11.6M. Continuing to store elemental mercury for years or even decades is a reasonable course of action.

S.6 Conclusions and Recommendations

- One key reason why the Option C process alternatives fall in the bottom half of Table S-1 is that the team assigned considerable importance to what is known about mercury vapor evolution from the Option C waste form. However, the data in this area are not of high quality and further research is needed to confirm that this relatively unfavorable weighting of the Option C process is justified.
- The data on leaching performance as a function of pH strongly favor Option B (see Figure B-1 in Appendix B). There is considerable scatter in the leaching data for the other two processes. Further research in this area could help to provide greater confidence in the stability of waste forms in typical monofill environments.
- The effectiveness of macroencapsulation in the long term is uncertain. Further assessment of the long-term effectiveness of macroencapsulation would be valuable.
- As noted above, the predicted cost of the Option C cases is much greater than those of the other two processes. A large portion of this difference can be attributed to reagent costs. It would be useful to perform an investigation to see whether the Option C process can be run with a cheaper mix of reagents, or whether economies of scale might lead to reduced costs in this area. Since the mix of reagents in the Option C process is proprietary (but not in the other two cases) it was not possible to perform any further analyses in the course of this project.
- The Option B process consistently exhibits the lowest costs. As noted above, it has the lowest reagent cost. In addition, it has the least mass increase of the three technologies. This affects other items such as transportation costs.
- The best estimates for the NPV of alternatives that include mobile treatment are somewhat higher than those for alternatives that include treatment at fixed facilities. In addition, the uncertainty ranges are much wider. Both of these principally result from the wide uncertainty bands on mobile treatment alternatives –20% to +200% for capital costs and –50% to + 100%

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[6] See Sections 4.1.2.1, 4.1.2.2, and 4.1.2.3 for discussion of these multipliers.

for O&M costs. There are also extra costs associated with assembling and disassembling the equipment and moving it from site to site. The mobile treatment alternative needs to be much better defined if the uncertainty bands are to be reduced.

- The storage alternatives are reasonably economical and, as shown in the previous report EPA/600/R-03/048 do not pose large environmental risks. It would still be cost effective to continue to store elemental mercury for a number of years or decades in anticipation that there might be a breakthrough in treatment technologies.

Table S-1. Environmental Analysis - Summary of Baseline Results for 12 Evaluated Alternatives

Treatment Scenario			Overall Ranking	
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Score (as fraction of 1,000)**	**Rank (Best to Worst)**
Option A	With	Mobile	117	1
Option B	With	Mobile	117	1
Option B	Without	Mobile	108	3
Option A	With	Fixed	98	4
Option B	With	Fixed	98	4
Option B	Without	Fixed	89	6
Option C	Without	Mobile	73	7
Option C	With	Mobile	73	7
Option A	Without	Mobile	66	9
Option C	Without	Fixed	57	10
Option C	With	Fixed	57	10
Option A	Without	Fixed	48	12
Number of alternatives evaluated			12	—
Total			1,000	—
Average score (total divided by 12, the number of alternatives)			83	—

Shading indicates the highest-ranking alternatives.

Distributive mode; overall inconsistency factor from Expert Choice software: 0.02 (good).

Average value is provided for reference and identifies the average score for the twelve evaluated technologies.

Table S-2. Environmental Sensitivity Analysis

Treatment Scenario			Ranking[a]													
			Baseline (from Table S-1)		Importance on Disposal				Importance on Transport				Importance on Accidents			
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**			**Sensitivity: High**		**Sensitivity: Low**		**Sensitivity: High**		**Sensitivity: Low**		**Sensitivity: High**		**Sensitivity: Low**	
			Score	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
Option A	With	Mobile	117	1	124	1	110	1	120	1	115	1	108	1	120	1
Option B	With	Mobile	117	1	124	1	110	1	120	1	115	1	108	1	120	1
Option B	Without	Mobile	108	3	111	5	105	3	113	3	105	5	101	3	110	3
Option A	With	Fixed	98	4	115	3	82	7	85	4	106	3	94	4	100	4
Option B	With	Fixed	98	4	115	3	82	7	85	4	106	3	94	4	100	4
Option B	Without	Fixed	89	6	102	6	78	9	79	9	96	6	88	6	90	6
Option C	Without	Mobile	73	7	60	7	85	5	84	7	66	7	76	7	72	7
Option C	With	Mobile	73	7	60	7	86	4	85	4	66	7	76	7	72	7
Option A	Without	Mobile	66	9	48	11	84	6	81	8	57	11	71	9	64	9
Option C	Without	Fixed	57	10	52	9	61	10	52	10	60	9	64	10	54	10
Option C	With	Fixed	57	10	52	9	61	10	52	10	60	9	64	10	54	10
Option A	Without	Fixed	48	12	39	12	56	12	47	12	48	12	57	12	44	12
Average			83	—	83	—	83	—	83	—	83	—	83	—	83	—
Total			1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—

Shading indicates the highest-ranking alternatives. In the sensitivity analysis for each criterion, the importance of the criterion is set at higher or lower than its baseline value, as identified in the text. The four other criteria comprise the remainder, proportional to their original contributions.

a. Scores normalized to total 1,000.

Table S-3. Uncertainty Analysis for Mercury Management Alternatives

Ref. No.	Alternative			Criteria	Change in Intensity for Uncertainty Analysis		Initial Result (Table S-1)		Uncertainty Analysis Result	
					Baseline	Change	Score	Rank	Score	Rank
0	All			Baseline for comparison: Same results as Table S-2			—	—	—	—
1	**Treatment Process**	**Macro-Encapsulation**	**Fixed or Mobile Facility**	Monofill Disposal, >40 years	Moderate	Low				
	Option C	Without	Mobile				73	7	99	3
	Option C	With	Mobile				73	8	99	3
	Option C	Without	Fixed				57	10	82	6
	Option C	With	Fixed				57	11	82	6
2	Option A	Without	Fixed	Monofill Disposal, <40 years	Moderate	Low	48	12	55	12
3				Monofill Disposal, >40 years	Moderate	Low			84	6
4				Monofill Disposal, both <40 years and >40 years	Moderate	Low			92	4
5	Option B	With	Mobile	Monofill Disposal, <40 years	Low	Moderate	117	2	108	2
6				Monofill Disposal, >40 years	Low	Moderate			76	6
7				Monofill Disposal, both <40 years and >40 years	Low	Moderate			68	9
8	Option B	Without	Mobile	Accidental Releases (Mercury Spills)	Moderate	Low	108	3	117	1
9						High			102	3
10	Option C	With	Fixed		Moderate	Low	57	11	66	9
11						High			51	11

Table S-4. Net Present Value Estimates

Treatment Scenario			Net Present Value Estimates in Millions of Dollars								
			5,000 Metric Tons			12,000 Metric Tons			25,000 Metric Tons		
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Min.**[a]	**Best**[b]	**Max.**[c]	**Min.**[a]	**Best**[b]	**Max.**[c]	**Min.**[a]	**Best**[b]	**Max.**[c]
Option A	With	Fixed	77.1	82.7	89.0	149	161	174	245	265	287
Option A	With	Mobile	75.8	99.2	128	143	191	251	232	315	415
Option A	Without	Fixed	60.2	65.4	71.3	117	128	141	184	203	224
Option A	Without	Mobile	57.7	79.8	107	105	150	207	169	242	341
Option B	With	Fixed	32.3	34.3	36.4	62.2	66.2	70.6	102	109	116
Option B	With	Mobile	32.4	40.9	50.7	60.5	78.3	97.5	98.4	127	160
Option B	Without	Fixed	22.7	24.3	26.2	42.8	46.1	49.9	69.6	75.2	81.8
Option B	Without	Mobile	22.3	29.3	38.0	40.9	54.2	71.7	65.1	87.5	118
Option C	With	Fixed	162	178	197	342	378	418	579	639	707
Option C	With	Mobile	138	203	292	290	429	617	490	732	1,040
Option C	Without	Fixed	146	163	181	306	341	381	517	578	647
Option C	Without	Mobile	119	184	270	247	386	573	421	656	967
Long-Term Storage[d,e]			10.4	11.6	12.8	26.1	29.0	31.9	51.3	57.0	62.7

a. Fifth percentile of the distribution derived from the Crystal Ball® analysis.

b. Mean of the distribution derived from the Crystal Ball® analysis.

c. Ninety fifth percentile of the distribution derived from the Crystal Ball® analysis.

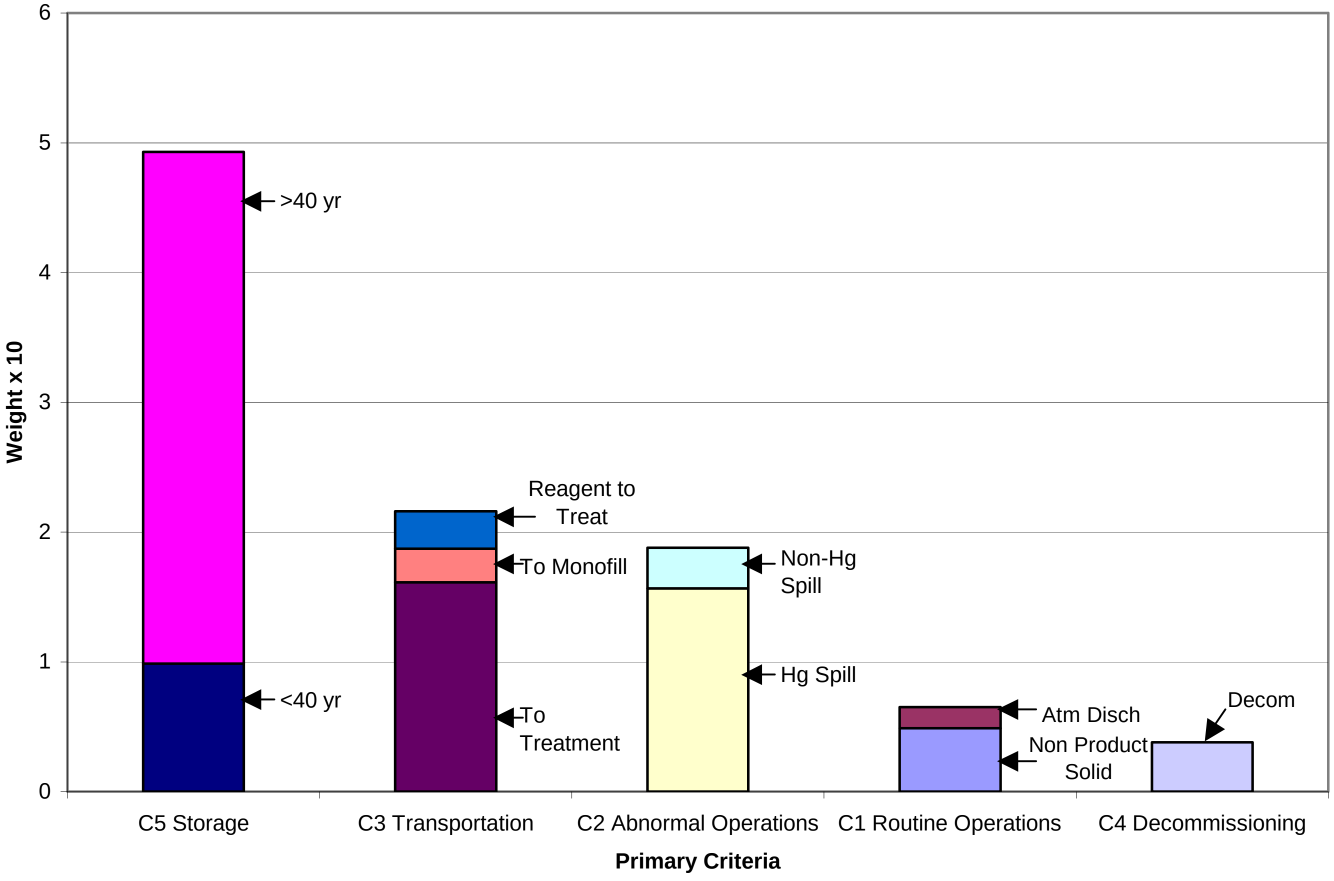
d. Not derived from Crystal Ball® analysis – best estimate based on MMEIS data (DLA 2004) with ±10% uncertainties.

e. Cost of shipping elemental mercury to the storage location not included. Upper bound transportation costs derived from MMEIS data are $0 (5,000 MT), $1.0M (12,000 MT), and $2.3M (25,000 MT). These are at most small percentages of the total cost of long-term storage.

Table S-5. Net Present Value Estimates Expressed as Cost per Metric Ton of Treated Mercury

Treatment Scenario			**Net Present Value Estimates in Dollars**								
			5,000 Metric Tons			**12,000 Metric Tons**			**25,000 Metric Tons**		
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Min.**	**Best**	**Max.**	**Min.**	**Best**	**Max.**	**Min.**	**Best**	**Max.**
Option A	With	Fixed	15,400	16,600	17,800	12,400	13,400	14,500	9,800	10,600	11,500
Option A	With	Mobile	15,200	19,800	25,600	11,900	15,900	20,900	9,300	12,600	16,600
Option A	Without	Fixed	12,000	13,100	14,300	9,800	10,700	11,800	7,400	8,100	9,000
Option A	Without	Mobile	11,600	16,000	21,400	8,800	12,500	17,300	6,800	9,700	13,600
Option B	With	Fixed	6,500	6,900	7,200	5,000	5,500	5,900	4,100	4,400	4,600
Option B	With	Mobile	6,500	8,200	10,100	5,100	6,500	8,100	3,900	5,100	6,400
Option B	Without	Fixed	4,500	4,900	5,200	3,600	3,800	4,200	2,800	3,000	3,300
Option B	Without	Mobile	4,500	5,900	7,600	3,400	4,500	6,000	2,600	3,500	4,700
Option C	With	Fixed	32,400	35,600	39,400	28,500	31,500	34,800	23,000	25,600	28,300
Option C	With	Mobile	27,600	40,600	58,400	24,200	35,800	51,400	19,600	29,300	41,600
Option C	Without	Fixed	29,200	32,600	36,200	25,500	28,400	31,800	20,700	23,100	25,900
Option C	Without	Mobile	23,800	36,800	54,000	20,600	32,200	47,800	16,800	26,200	38,900
Long-Term Storage			2,100	2,300	2,600	2,200	2,400	2,700	2,100	2,300	2,500

Figure S-1. AHC Criteria and Subcriteria Relative Weights



1.0 INTRODUCTION

This section provides background on the need for the long-term disposal of elemental mercury and discusses the outline of the remainder of this report.

1.1 Background

The use of mercury in products and processes is decreasing. It is likely that in the future, the supply of mercury will far exceed the demand for mercury. In addition, the Department of Defense (DOD) has stockpiled more than 4,800 tons of mercury that are no longer needed, and the Department of Energy (DOE) has also accumulated large volumes of elemental mercury. Therefore, strategies must be devised for managing the excess mercury. Currently, the most prevalent method is to store the elemental, liquid form in flasks and stockpile them in warehouses. The risks associated with this method of storing elemental mercury have been extensively discussed in the *Final Mercury Management Environmental Impact Statement* (DLA 2004).

Independently of DLA, EPA's Offices of Research and Development (ORD) and Solid Waste (OSW) have been working with DOE to evaluate technologies for permanently stabilizing and disposing of wastes containing mercury (DOE 1999a-1999e; USEPA 2001, 2002a,b). Other comprehensive studies carried out in the recent past include one by SENES Consultants (SENES 2001) who produced a draft report for Environment Canada evaluating 67 technologies for the retirement and long-term storage of mercury. In addition, OSW is considering revisions to the Land Disposal Restrictions (LDRs) for mercury. Land disposal of hazardous wastes containing greater than 260 mg/kg mercury is currently prohibited. For several years OSW has pursued options which would allow land disposal of waste containing greater than 260 mg/kg mercury. These actions include the following:

- Land Disposal Restrictions: Treatment Standards for Mercury-Bearing Hazardous Waste. Notice of Data Availability. Federal Register January 29, 2003 (Volume 68, Page 4481). Presents OSW studies regarding the treatment of elemental mercury and wastes with >260 mg/kg mercury. EPA additionally concludes that changes to national regulations are impractical at this time.
- Hazardous Waste Management System; Identification and Listing of Hazardous Waste; Chlorinated Aliphatics Production Wastes; Land Disposal Restrictions for Newly Identified Wastes; and CERCLA Hazardous Substance Designation and Reportable Quantities. Proposed Rule. Federal Register August 25, 1999 (Volume 64, page 46521). EPA proposed, as an option, an alternative treatment standard for a hazardous waste containing >260 mg/kg mercury which would allow land disposal under certain disposal conditions. This alternative was not ultimately adopted.
- Potential Revisions to the Land Disposal Restrictions Mercury Treatment Standards. Advance notice of proposed rulemaking (ANPRM). Federal Register May 28, 1999 (Volume 64, Pages 28949-28963). This notice presents options, issues, and data relevant to potential revised mercury treatment standards.

At this time, however, no specific revisions to the LDRs for mercury-containing wastes are forthcoming.

Using the above-referenced work as a starting point, EPA prepared report EPA/600/R-03/048, *Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* (USEPA 2002c). In this report, EPA evaluated two types of treatment technologies: 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 Perma-Fix sulfide process. These were grouped as a single class because they have very similar characteristics when compared against the criteria defined by the team (comprised of SAIC staff) and modeled in a computer program that uses the Analytic Hierarchy Process (AHP) as an aid to decision making, 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 were three storage alternatives for elemental mercury: a) storage in an aboveground RCRA- permitted facility; b) storage in a hardened RCRA-permitted structure; and c) storage in a mined cavity.

The purpose of the present work is the logical next step, which is to focus on just a few of the alternatives considered above. This allows a more detailed breakdown and analysis of the stabilization/amalgamation alternatives than was possible in EPA/600/R-03/048, and also allows more effort to be applied to developing cost information.

1.2 Scope of Work

The scope of work requested by EPA was to provide an economic and environmental analysis of the following:

Three treatment technologies, identified as Options A, B, and C to protect certain proprietary information

- Two macroencapsulation alternatives:
  a. Dispose of the treated mercury with macroencapsulation, and
  b. Dispose of the treated mercury without macroencapsulation.
- The alternatives are further divided as follows:
  i. Build a fixed treatment facility at one site to which all of the bulk elemental mercury is transported and dispose of in a collocated monofill, or
  ii. Build a portable waste treatment facility and take it to the sites at which the bulk elemental mercury is stored. Dispose of the treated waste in a centralized monofill.

Combining all the cases above gives 12 alternatives for treatment and disposal[7]. The work includes performing an environmental comparison of these twelve alternatives.

The final part of the work is to develop Life Cycle Cost Estimates (LCCEs)[8] for the foregoing 12 alternatives and the further alternative of storing bulk elemental mercury in an aboveground structure, making 13 alternatives in all. For each of these combinations, SAIC considered alternatives that will treat; a) 5,000 MT; b) 12,000 MT; and c) 25,000 MT of elemental mercury[9]. This gives 39 alternatives for economic analysis.

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[7] The authors aware that there are more alternatives than this (e.g., transportation from the centralized treatment site to a remote monofill). However, the authors believe that the extra insights to be gained would not be worth the effort required to keep track of the proliferating alternatives this would generate.

[8] A lifecycle cost estimate is one that provides costs for all elements of a project's lifetime, including preliminary design, final design, startup, operation, and decommissioning.

[9] The basis for selecting 5,000 MT, 12,000 MT, and 25,000 MT was initially that these are multiples of the DLA stockpile numbers. Later EPA analysis (Randall 2005) estimated the quantity of mercury contained in chlor-alkali cells in the US and Western Europe as about 15,000 MT with another 10,000-12,000 MT in the rest of the world. Although opinion varies widely as to the rate at which these cells will close, there is good reason to believe that enough plants will close world-wide within the next 15-20 years to overwhelm dwindling world demand for mercury, thereby posing a question as to its environmentally appropriate disposition.

1.3 Approach

There are three major parts to the required analysis:

- Choice of the three treatment technologies
- Environmental analysis
- Economic analysis

1.3.1 Choice of Three Technologies

The first step was to review the available literature and to hold consultations with EPA personnel in ORD and OSW. This resulted in a short-list of 6 technologies, identified as Options A through F. The references used in this analysis are provided in Section 5.2.

The list was then winnowed down to 3 technologies by using the Kepner-Tregoe decision-making method as a tool. This method is described in Section 2. It essentially involves:

- Developing a list of criteria against which the technologies are ranked
- Assigning a weight to each criterion, on a scale from 1-10, with 10 indicating that the criterion is extremely important and 1 indicating that the criterion is unimportant
- Scoring each technology against each criterion, again on a scale from 1-10, with 10 indicating that the technology performs well against the criterion and 1 indicating that it performs poorly
- For each technology, multiplying the score against a criterion by the weight of that criterion and summing over all criteria. The sums then provide a ranking for the criteria that allows the top 3 to be chosen.

1.3.2 Environmental Analysis

The method chosen for the environmental comparison of the twelve treatment and disposal alternatives is the Analytic Hierarchy Procedure (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 Analytic Hierarchy Process
- It allows the user to incorporate both data and qualitative judgments

- 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

The environmental comparison is described in Section 3. Appendix A contains information on the AHP and on how the inputs to the Expert Choice software were specifically developed for the present work. Appendix B contains further detail on the use of the AHP.

1.3.3 Economic Analysis

As described above, 36 treatment and disposal alternatives are being considered. In addition, cost estimates have been prepared for storage of the three masses of elemental mercury in aboveground facilities, making a total of 39 cost estimates in all.

The thirty-six cost estimates (based on the Process Flow Diagrams) for treatment and disposal includes the following elements[10]:

- Capital costs for the treatment facility,
- Capital costs for the macroencapsulation facility (if part of the alternative),
- Operating and maintenance costs for the treatment process,
- Operating and maintenance costs for the macroencapsulation process (if part of the alternative),
- Costs associated with the mobile treatment alternatives,
- Transportation costs associated with each alternative,
- Costs of storing elemental mercury prior to treatment,
- Decommissioning costs for the treatment facilities,
- Monofill engineering and construction costs,
- Monofill operating costs, and
- Costs of maintaining and monitoring the monofill for a thirty-year period following its closure.

Each of the three storage alternatives contains the costs of maintaining the existing stockpile (assumed to be 5,000 MT) in storage, adding to storage space as necessary, and transporting elemental mercury to the storage facility(ies).

The SAIC team developed process flow diagrams for each of the three treatment technologies and the associated macroencapsulation process and a preliminary design for the monofill such that 1,000 MT of elemental mercury will be treated and disposed of each year.

The sources of information for the cost estimates included:

- Published work by the vendors of the three treatment options together with information gathered in telecons. This enabled the team to develop the 1000-MT/year process flow diagrams and to obtain some information on costs.
- Code of Federal Regulation requirements for the construction and operation of a monofill.

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[10] Note that these cost do not contain any contingency for the occurrence of accidents or malfunctions (e.g., spillage of elemental mercury during transportation or remediation of excessive leakage from a monofill).

- Standard industry sources of cost information such as Perry and Green's *Industrial Engineering Handbook* and Richardson Engineering Services' *Process Plant Construction Estimating Standards*.
- Telecons with equipment manufacturers.
- Websites of equipment manufacturers.
- The Mercury Management Environmental Impact Statement (MMEIS), published by the Defense Logistics Agency (DLA). This contains detailed information on storage and transportation costs.

The SAIC team assigned uncertainty ranges to items that are input to the total cost. The final cost estimates and uncertainties were estimated by performing an uncertainty analysis using Crystal Ball® software (Decisioneering 2004).

The economic and uncertainty analyses are described in Chapter 4. Appendices C-G provide further detail about cost imputs.

2.0 SELECTION OF TECHNOLOGIES FOR EVALUATION

The contract with EPA required SAIC to consider three different chemical treatment alternatives. The purpose of this chapter is to show how the three alternatives were selected. The chapter describes criteria that were used for this purpose. These criteria were discussed with EPA and represent a consensus.

2.1 Criteria for Selection of Technologies

In the previous project for EPA ORD (*Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* - USEPA 2002c), criteria were developed when evaluating each potential management alternative (consisting of a treatment technology followed by a disposal method). These criteria included costs, risks, environmental performance, state of maturity, and other factors. The cost criteria and non-cost criteria were given equal importance in the 2002 analysis. Subcriteria were given varying weights based on the evaluation team's consensus. The complete list of criteria used is given in Table 2-1. This list from the 2002 project proved useful as a starting point for identifying important issues for the present project.

Table 2-1. Criteria Chosen for the AHP Analysis in Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury, August 2002.

- Non-cost Criteria (0.5)*
    - 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)
- Cost Criteria (0.5)
    - Implementation costs (0.5)
    - Operating costs (0.5)

** The figures in parentheses give the weights assigned to each of the criteria and sub-criteria using the process of pairwise comparison that is at the core of the Analytic Hierarchy Process (AHP). At each level, the weights are determined independently and add to one. Higher weights indicate greater importance.*

2.1.1 Identifying Critical Issues

This chapter focuses on the treatment technology step only, prior to further encapsulation and placement of the treated elemental mercury in a monofill. The critical environmental pathway that was evaluated is mercury leaching following disposal. The purpose of the selection process is to identify technologies for further study. Therefore the developed criteria are at a screening level, allowing for more detailed review later in the process.

The proposed issues are presented in Table 2-2. The following six issues are identified:

1. Appropriateness of technology for the treatment of elemental mercury
2. Type of leaching performance data
3. Results of leaching performance tests
4. Extent of environmental and cost information
5. Costs and Complexity
6. Development

Each of these issues is assigned a weighting factor of between 1 and 10 to account for its perceived importance. Table 2-2 provides the consensus suggestions for these weighting factors. The first three issues are assigned a weighting factor of 10, reflecting the team's view that the ability to treat elemental mercury with the end product having satisfactory leaching performance is the primary objective of the technology. Having adequate information about environmental performance and costs is deemed relatively important (a weight of 8), otherwise it is hard to perform a credible analysis of the technology. Finally, expected costs and the current state of development are deemed somewhat less important because these issues can potentially be worked on and improved over time.

2.1.2 Evaluation of the Technologies

One important aspect of the evaluation is to identify any 'pass/ fail' criteria for a particular issue. For example, if a particular technology fails to meet some minimum criterion, then the technology would be dropped from consideration. An example of such a criterion is included in the first row of Table 2-2, where the technologies, at a minimum, should at least in theory be capable of treating elemental mercury.

An additional aspect is the effectiveness with which each technology addresses each issue. This aspect is addressed by providing a score, as is laid out in Table 2-2. Like the issue weighting factors, the score ranges from 1 – 10.[11] For each issue, the score for a particular technology is multiplied by the weight. This product is then summed over all issues to give a total score for the technology. This method of ranking technologies is known as Kepner-Tregoe Decision Analysis.

2.1.3 Identifying Candidate Processes

Many treatment processes are available for reducing the mobility of mercury in various wastes. However, only a small number of these are expected to be practical for elemental mercury treatment. It is possible to evaluate any number of candidate treatment processes using the criteria in Table 2-2. To avoid inefficient research into technologies that are impractical or only marginal in meeting the project objectives, the following types of technologies were excluded from the evaluation:

- Mercury recovery or extraction technologies, where the intent is to remove or separate the mercury from a waste for recycling or further treatment

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[11] For some issues, the scoring process outlined in Table 2-2 allows a score of greater than 10. In this case, the score is capped at 10. Similarly, there is the possibility that some scores can be zero or negative. In this case, the score is not allowed to fall below 1.

- Technologies which treat wastewaters or combustion exhaust gases
- Technologies which focus on the treatment of LDR "low mercury" wastes (i.e., less than 260 mg/kg total mercury)

Six technologies were identified as having been used for treating wastes with, at a minimum, percent levels of mercury. They are identified as Options A through F. References used for this part of the analysis are listed in Section 5.2.

Any number of additional treatment technologies can in principle be evaluated.

2.2 Scoring Results

The resulting scores for each technology with respect to each criterion are presented in Table 2-3. The following subsections discuss the information that forms the basis for the scoring results presented in Table 2-3.

2.2.1 Option A

The Option A process was one of three technologies evaluated by EPA for elemental mercury treatment, in which leaching was evaluated with respect to pH in oxidizing conditions (see Figure B-1). Other available data for the treatment performance of elemental mercury includes TCLP and ASTM testing by the developer of the technology . Several other treatment performance results are available for mercury wastes, including work in which mercury leaching as a function of pH and liquid-solid ratio was investigated.

Data are available regarding the formation of mercuric sulfide under long-term conditions; these data are not specific to any particular technology but can potentially be useful for sulfur-based treatment processes in general. For example, as discussed in Appendix B, mercuric sulfide (HgS) production may degrade to from HgS2 anion under alkaline anaerobic conditions. One potential application of the result is that such conditions would favor the transformation of residual elemental mercury to this stable form. An alternative application is that in an anaerobic monofill in damp or wet conditions, ionic mercury (Hg+) and/or ionic mercury bisulfide (HgS2=) may form and result in increased leaching over time.

In the EPA study for elemental mercury treatment, OSW identified highly variable leaching as a function of pH (as shown in Figure B-1 of Appendix B); laboratory quality control checks suggest the reported data are valid (EPA, 2002b). The results suggest the inherent uncertainties of using a relatively small set of studies to identify if the observed results represent actual performance of the treatment process or are a result of heterogeneity in the treated waste, treatment variation, or other factors. This uncertainty is equally relevant for Technology Options B and C.

The Option A process remains in active development. It has been demonstrated at pilot-scale on liter quantities of mixed-waste elemental Hg from National Laboratories, and in treatability studies for a major gold-mining corporation (Randall 2005). After this corporation conducted its own evaluation, it selected Vendor A for potential treatment of its by-product elemental Hg from foreign mining operations, and has licensed the technology. There are also plans to build a process facility in Kazakhstan that will treat elemental mercury and mercury-contaminated soil. Therefore, it appears that technology A is approaching commercial-scale operation.

2.2.2 Option B

Information available for the Option B process closely parallels that available for Option A. The treatment of elemental mercury was evaluated by EPA; TCLP testing of treated elemental mercury was conducted by DOE. In addition, existing general mercuric sulfide formation data can similarly be applied to the sulfur-based Option B technology.

USEPA data show a trend in leaching results with respect to pH, with results lowest in acidic conditions and highest in basic conditions (see Figure B-1). The results were consistently below the UTS level at all but the highest range of pH.

The Option B process has been used for the treatment of approximately 7600 kg (3.5 tons) of radioactive elemental mercury since 2001. Therefore the process is in active use and development.

2.2.3 Option C

Information available for the Option C process includes elemental mercury treatment data by USEPA and DOE TCLP testing of treated elemental mercury. The Option C process was also used for the experimental treatment of mercury-containing soil in DOE's MER-03 program, where mercury leaching as a function of pH and liquid-solid ratio was investigated.

The USEPA data shows a trend in leaching results with respect to pH, with the lowest leachable levels present in basic conditions (see Figure B-1). At pH levels above 6, the mercury solubility was between the UTS and TC levels.

There is no indication of commercial use beyond bench-scale treatment, although the Option C process remains in active development/ sponsorship.

2.2.4 Option D

Option D is a selenide process, for which very little environmental data are available.. USEPA investigated the leaching of mercury selenide with respect to pH and chloride anion concentrations, although testing was conducted only on a simulated waste treatment residual. The process was developed for the vapor-phase treatment of elemental mercury generated from lamps, batteries, etc.; it could likely be adapted to a starting point for elemental mercury.

This process is in commercial use in Europe, making it one of the few treatment processes in use at larger than bench scale. However, the scale of the equipment is expected to be small relative to the quantities of mercury present in the DLA stockpile (for example). The process is also relatively complex due to the high temperatures and continuous processing.

2.2.5 Option E

Option E uses a dithiocarbonate formulation and a small amount of proprietary liquid to produce a stabilized waste form. This technology has the disadvantage of not having been applied to elemental mercury. Numerous applications of the technology have been conducted in the DOE MER programs where percent levels of mercury in wastes were tested. Its potential application to elemental mercury, therefore, is unknown.

EPA studies have shown that the leachable mercury concentrations were consistently above the UTS level for most of the pH range. The MER-03 study results are consistent in that the mercury solubility was found to be lowest at the alkaline pH levels.

The development status of the Option E process is not known.

2.2.6 Option F

Sulfur-impregnated activated carbon has been used for many years in the cleanup of mercury-contaminated flue gas. However, only limited information is available with regard to how such a material may treat mercury-containing wastes. Only limited results are available for the testing of a simulated mercury-contaminated soil. Its potential application towards elemental mercury is unknown.

Available data show a wide range of testing with respect to leaching variables including pH and chloride content of the leaching solution. In addition, an additional treatment step of cement stabilization is conducted following activated carbon treatment in some cases. The leachable mercury concentrations were consistently below the UTS level for pH 4 and above.

This technology remains in the research stage. However, it is based on the use of readily available materials. In addition, use/ research for mercury removal from flue gas can be transferred to solid waste applications.

2.3 Conclusions

The results of the scoring are presented in Table 2-3. Three technologies (Options A, B, and C) have similar scores. The remaining three technologies (Options D, E, and F) also have similar scores but significantly lower than the other three technologies. These results support the choice of the Options A, B, and C processes for more detailed evaluation.

Table 2-2. Elemental Mercury Treatment Technology Evaluation

Proposed Issue	**Weighting Factor (1-10) for Issue**	**Proposed Evaluation Criteria and Scores for Each Technology**	**Minimum Acceptable Result (if any)**
Appropriateness of technology for the treatment of elemental mercury	10	10 – The technology has been tested on elemental mercury (100%) 6 – The technology has been tested on mercury-containing wastes/ soils with percent levels of *elemental* mercury 5 – The technology has been tested on mercury-containing wastes/ soils with percent levels of *any form of* mercury 1 – The technology has been tested only on low mercury content wastes (e.g., <260 mg/kg)	The technology should be applicable to elemental mercury treatment, at least in theory.
Type of leaching performance data	10	Points for each of the following (maximum 10 points): + 1 point – TCLP (or similar) testing has been conducted + 2 points – leaching as a function of pH variation + 2 points – leaching as a function of liquid/ solid ratio + 2 points – long-term stability testing + 2 points – leaching in various oxidation/ reduction conditions + 1 point – leaching in the presence of various anions	None
Results of leaching performance tests	10	Results of leaching performance tests (maximum score 10 points; minimum 1 point): -2 points to +2 points – Extent to which data trends (if any) are logical, and results for sample duplicates give reasonable results. -2 points to +2 points – Extent to which sampling and analysis procedures are well documented and minimize possible errors - 1 points to + 5 points – For conditions which may be encountered in a monofill (e.g., pH), the leaching results are (1) below universal treatment standards (UTS) in most relevant conditions (+ 5 points); (2) some results are above UTS but still below the TC (+ 2 points); (3) results are higher than the TC level in critical instances (- 1 point). + 1 point – Where two or more studies are available, contradictory findings are not reached.	None

Table 2-2. Elemental Mercury Treatment Technology Evaluation (continued)

Proposed Issue	Weighting Factor (1-10) for Issue	Proposed Evaluation Criteria and Scores for Each Technology	Minimum Acceptable Result (if any)
Results of leaching performance tests	10	Results of leaching performance tests (maximum score 10 points; minimum 1 point): -2 points to +2 points – Extent to which data trends (if any) are logical, and results for sample duplicates give reasonable results. -2 points to +2 points – Extent to which sampling and analysis procedures are well documented and minimize possible errors - 1 points to + 5 points – For conditions which may be encountered in a monofill (e.g., pH), the leaching results are (1) below universal treatment standards (UTS) in most relevant conditions (+ 5 points); (2) some results are above UTS but still below the TC (+ 2 points); (3) results are higher than the TC level in critical instances (- 1 point). + 1 point – Where two or more studies are available, contradictory findings are not reached.	None
Extent of environmental and cost information	8	Extent of environmental and cost information (maximum score 10 points): + 2 points – Data available from multiple sources (e.g., vendor test, EPA). + 2 points – One or more EPA/ DOE test documents (e.g., MER program) + 1 point – If not evaluated in the MER program, information is available from the DLA EIS + 2 point – Patents, conference papers, and/or journal articles + 1 point – If no patents, etc., then other product literature is available. + 2 points – Information on both costs and environmental performance are available from resources + 2 points – Process information is available to verify/ expand the cost data + 1 point – General treatment information is available (e.g., sulfide or selenide chemistry) which is not technology specific, but still useful. - 1 point – Critical information is not in English.	None
Costs and Complexity	5	10 – Costs and Complexity are expected to be significantly lower than typical (non-mercury) hazardous waste stabilization/ solidification (S/S) processes 5 – Costs and Complexity are expected to be about the same as typical hazardous waste S/S processes. 1 – Costs and Complexity are expected to be significantly higher than typical hazardous waste S/S processes.	None
Level of Development of Technology	5	10 – The technology is actively in use for mercury treatment/ disposal at a scale which would be practical for treating >5,000 tons 5 – The technology remains in the testing/ development stage by a sponsoring organization 3 – The development status is not known 1 – The technology has been developed but no present sponsor is evident	Must be capable of commercial deployment in the future

Table 2-3. Elemental Mercury Treatment Technology Evaluation

Proposed Issue	Weighting Factor (WF)	Preliminary Result (score between 1 and 10) for Technology Type; Multiply by Weighting Factor to Obtain Score for Each Issue					
		Option A	Option B	Option C	Option D	Option E	Option F
Appropriateness of technology for the treatment of elemental mercury	10	10 x WF = 100	10 x WF = 100	10 x WF = 100	9 x WF = 90	5 x WF = 50	5 x WF = 50
Availability of leaching performance data	10	6 x WF = 60	4 x WF = 40	5 x WF = 50	3 x WF = 30	5 x WF = 50	5 x WF = 50
Results of leaching performance tests	10	2 x WF = 20	7 x WF = 70	5 x WF = 50	3 x WF = 30	4 x WF = 40	4 x WF = 40
Extent of environmental and cost information	8	10 x WF = 80	6 x WF = 48	6 x WF = 48	3 x WF = 24	5 x WF = 40	4 x WF = 32
Costs and Complexity	5	5 x WF = 25	5 x WF = 25	5 x WF = 25	2 x WF = 10	5 x WF = 25	5 x WF = 25
Development	5	8 x WF = 40	5 x WF = 25	5 x WF = 25	8 x WF = 40	3 x WF = 15	6 x WF = 30
Final Score		325	308	298	224	220	227

3.0 ENVIRONMENTAL ANALYSIS USING THE ANALYTIC HIERARCHY PROCESS

3.1 Finalized List of Alternatives

This is the finalized list of treatment alternatives for both the environmental analysis (using the Analytic Hierarchy Process (AHP)) and the cost analysis (see Chapter 4). A description of the AHP is included in Appendix A.

1. Option A+no macroencapsulation+centralized treatment
2. Option A+no macroencapsulation+mobile treatment
3. Option A+macroencapsulation+centralized treatment
4. Option A+macroencapsulation+mobile treatment
5. Option B+no macroencapsulation+centralized treatment
6. Option B+no macroencapsulation+mobile
7. Option B+macroencapsulation+centralized treatment
8. Option B+macroencapsulation+mobile treatment
9. Option C+no macroencapsulation+centralized treatment
10. Option C+no macroencapsulation+mobile treatment
11. Option C+macroencapsulation+centralized treatment
12. Option C+macroencapsulation+mobile treatment

3.2 Assumptions and Ground Rules

The first stages of the analytic hierarchy process were carried out in a brainstorming meeting in June 2004 involving both EPA and SAIC personnel. To assist in the process, all participants discussed and agreed to some ground rules, as follows:

- The intent of the AHP is to address environmental effects, not costs. An economic analysis of the twelve alternatives was performed after completion of the AHP and is described in Chapter 4.
- Since there are twelve alternatives, the effort required to pairwise compare these against each AHP criterion[12] would be excessive - 12x11/2= 66 pairwise comparisons per criterion. Therefore, the team instead defined a range of "intensities" for each criterion[13].
- The environmental ranking arising from the AHP exercise is not sensitive to the total mass of mercury (5,000, 12,000, or 25,000 tons). Therefore, there is no need to specify a mass for the AHP[14].
- "No macroencapsulation" means that the stabilized waste will be placed in the monofill exactly as it is generated by the stabilization process. If the process ends with the waste solidifying in some form of container, this container will be given no credit for reducing the rate of leaching.
- "Macroencapsulation in the best available medium" means macroencapsulation in a separate step after stabilization. It was agreed that, for the purposes of both the AHP and the cost analyses, the macroencapsulation technology will be the ARROW-PAK system, in which waste is sealed in polyethylene containers prior to disposition in a monofill. The already-formed polyethylene containers will be purchased from the manufacturers and filled and sealed at the stabilization site.

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[12] See Appendix A for an explanation of AHP criteria.

[13] See also Appendix A for an explanation of AHP intensities.

[14] There was some discussion about whether the mass of mercury might affect some of the criteria (e.g., higher transportation risks for higher quantities), but this would not influence the rankings because all options would be affected the same way.

The ARROW-PAK system is expected to be available in a variety of sizes; the cost and environmental analyses will incorporate appropriate assumptions for container size[15].

- While many elements of the design and construction of the monofill will be independent of the disposal alternatives, there might be some features that are technology dependent, such as the composition of the liner and adjustments to the fill material to maintain pH. As discussed in Appendix B, lime can be added to maintain (or promote) basic conditions and sulfur can be added to maintain (or promote) acidic conditions, although many other soil and environmental conditions will influence the ability of the monofill to maintain these pH conditions.

3.3 AHP Brainstorming Session

The EPA/SAIC brainstorming team defined a goal, developed criteria and subcriteria, and assigned a range of intensities to each subcriterion.

3.3.1 The Goal

The goal is simply stated: "Minimize environmental impact during life cycle." Having this goal helps the project team keep focused.

3.3.2 Development of Criteria and Subcriteria

The team brainstormed a list of criteria and subcriteria that they considered to be potential discriminators among the twelve options in terms of environmental performance. Those criteria and subcriteria are listed in Table 3-1.

3.3.3 Pairwise Comparison to Rank the Criteria and Subcriteria

The team pairwise compared each of the criteria, and then each of the subcriteria, in order to develop weights that are intended to be a measure of the relative importance of each criterion and subcriterion. The Expert Choice matrices for criteria and subcriteria are shown in Table 3-2. The resulting weights, as calculated by Expert Choice software, are summarized in Table 3-1.

3.3.4 Development of "Intensities" for each Criterion and Subcriterion

As noted above, there are 12 alternatives. In principle, each of these should be pairwise-compared against each of the criteria or subcriteria, leading to the need to perform 10 criteria x (12x11/2) = 660 pairwise comparisons. This is a rather large number (e.g., one comparison per minute would take 11 brainstorming hours), so the team decided to use an optional AHP technique whereby the criteria are first assigned "intensities." These intensities are summarized in Table 3-1. As can be seen, these are quite simple, most of them simply being "low," "medium," or "high." "Low" should be taken as meaning "low potential impact on the environment," etc., so that "low" is always the most desirable outcome.

For the two subcriteria that are not allocated low, medium, or high intensities, one (the possibility of mercury spills during transportation) is simply allocated two intensities – either a mercury spill is not possible ("no," the most desirable situation), or a mercury spill is possible ("yes").[16] The other (the

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[15] The fact that the ARROW–PAK technology was used in the present work does not mean that EPA endorses it as the best available macroencapsulation process.

[16] The simplicity of the intensities for the possible spillage of mercury during transportation is made possible because of a simplifying assumption that was made in SAIC's original proposal. Either elemental mercury is treated at a centralized stabilization facility and disposed of in a collocated monofill, in which case elemental mercury is transported to the treatment location and could hypothetically be spilled en route: or mobile treatment facilities are sent to the current storage locations and

possibility of spills of stabilized waste during transportation) is assigned three intensities ("none," transportation of "encapsulated" waste, and transportation of "non-encapsulated" waste.

In order to convert each assignment of intensities into a score or weight that can be used in Expert Choice's ultimate calculation of the relative ranking of technologies, the team pairwise-compared the intensities, as is summarized in the last column of Table 3-1.

The next step is to assign each alternative an intensity with respect to each criterion or subcriterion. Thus, each alternative needs ten intensity assignments and there are 120 such assignments in total. The team decided that they did not have enough knowledge at their fingertips to make these assignments. Instead, the team identified factors and phenomena that need to be evaluated before deciding on the intensity assignments. These factors are listed in Appendix B. After the brainstorming meeting, SAIC gathered relevant information and made intensity assignments that were subsequently reviewed by the EPA team. The basis for assigning the intensities is also discussed in Appendix B. This allowed Expert Choice to be run so as to provide a baseline ranking of the twelve alternatives.

3.3.5 Assignment of Intensities to Alternatives

The results from Appendix B are summarized in Table 3-3. Appendix B describes in detail the available data and the assignment of these intensities. As shown in Table 3-1, the assignment of intensities for monofill disposal has a significant affect on results; information below is included to further describe the data and limitations of information relevant to this particular criterion. As detailed in Appendix B, factors included consideration of volatilization, presence of favorable pH conditions, long-term stability of the waste, and long-term stability of the encapsulating material (if present).

Available data suggest that each of the technologies appear to perform best in different environmental conditions (e.g., acidic or basic conditions). The alternatives were evaluated based on the conditions expected to result in the lowest leachate concentrations, although as discussed previously land disposal of treated elemental mercury is currently prohibited and therefore comparison of results to other regulatory levels (e.g., UTS levels) is of interest but not as important as identifying the optimal range of disposal conditions for each technology.

One benefit of macroencapsulation is to act as a barrier against disposal conditions which may increase mobility of mercury from the treated waste. For example, all of the wastes leach mercury at different pH. If landfill conditions deviate from the 'optimal' conditions suggested by available data, then a waste without macroencapsulation would be expected to leach higher amounts of mercury than a macroencapsulated one.

There is considerable uncertainty with regard to leaching performance over the long term. For example, as discussed in Appendix B, mercuric sulfide (HgS) production is favored under alkaline anaerobic conditions. One potential application of the result is that such conditions would favor the transformation of residual elemental mercury to this stable form. An alternative application is that in an anaerobic monofill in damp or wet conditions, ionic mercury (Hg+) and/or ionic mercury bisulfide (HgS2=) may form and result in increased leaching over time.

In addition, incomplete data are available for many factors which affect leaching, such as pH buffering capacity, or performance under conditions as a function of oxidizing/ reduction conditions (i.e., aerobic/ anaerobic).

3.4 Results of the Baseline Expert Choice Analysis

The 12 alternatives identified in Section 3.1 above were evaluated using the Expert Choice software. The data from Tables 3-1 and 3-3 were used as inputs to the model. While the input to the model is

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elemental mercury is stabilized there, so that elemental mercury will not be transported and there is no chance of a spill. It is recognized that the real world situation may involve some transportation of both elemental mercury and of treated waste.

somewhat narrative (e.g., intensities such as ‘low,’ ‘medium,’ and ‘high’), 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 alternatives are evaluated partially against each other, so that the total score will always equal unity no matter how many alternatives are evaluated. In addition, as the number of alternatives increases or decreases, the score of each alternative will change to maintain the same sum of scores of all alternatives (i.e., unity). In this manner, the results are best interpreted as scores *relative* to each other, rather than the *absolute* value of an alternative’s score.

Table 3-4 presents the Expert Choice results for each of the twelve alternatives discussed in the previous section of this report. The table shows the score, and corresponding ranking, of each alternative when considering all criteria. 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 following are some observations from Table 3-4:

- In general, mobile treatment alternatives score better than centralized treatment alternatives.
- There is a slight preference for macroencapsulation alternatives over alternatives which do not include this additional treatment.
- All of the alternatives that include Option B technology score higher than alternatives that include Option C technology. Alternatives that include Option A technology are more scattered; one Option A alternative scores highest while a different Option A alternative scores lowest.

Several additional analyses were conducted to explain or confirm these results. First, the team evaluated whether results were reasonable based on the preferences and intensities assigned above. Second, the team conducted additional sensitivity and uncertainty analyses with the Expert Choice software to identify how changes in the preferences and intensities affect the rankings in Table 3-4. The results of the sensitivity and uncertainty analyses are presented in Section 3-7. The reasonableness of the above three conclusions derived from analysis of the AHP model output - is evaluated below (Sections 3.6.1 – 3.6.3.)

Another important consideration is the difference between the results for each alternative. It must be determined if the magnitudes 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 alternative and another indicate that no discernible difference exists between the two. A determination of what is ‘small’ is addressed primarily through the sensitivity and uncertainty analyses, as identified in Section 3.7. In general, differences of 5 to 10 points out of 1000 can easily result from small changes in the intensities or weightings, and therefore such differences between various alternatives are not expected to be significant.

3.4.1 Factors Which Influence the Scoring of Mobile Treatment Versus Centralized Treatment Alternatives

Table 3-3 shows that transportation factors differ significantly between mobile and centralized treatment alternatives. In other words, the greatest differences in intensities between mobile and centralized treatment alternatives result from two of the three transportation factors (transport of mercury and transport of waste). As shown in Table 3-1, transportation factors (particularly the transport of mercury) significantly affect the scoring.

As explained previously, for all alternatives involving mobile treatment there is no transport of elemental mercury, but there is transport of treated waste. The importance of these differences in intensities is shown in Table 3-1, which shows that concerns about the transport of elemental mercury (0.747) are much higher than concerns about the transport of treated waste (0.119). In addition, Table 3-1 shows that the potential environmental impacts during the transportation phase of the mercury lifecycle were determined to be the second-most important criterion (i.e., the weight of 0.216 is the second-highest weight).

In summary, Tables 3-1 and 3-3 shows that it is reasonable to expect mobile treatment alternatives to score higher than do centralized treatment alternatives, all other things being equal. This is because, by assumption, there is no transport of elemental mercury associated with the mobile treatment alternatives whereas, in the centralized treatment alternatives, all of the elemental mercury is transported to a centralized treatment facility. The Team determined that potential impacts of elemental mercury spills during transportation represent a significant potential risk, which should be minimized.

As discussed in Section 3.3.4, there is some simplification of the mobile and centralized treatment alternatives. Mobile treatment is assumed to occur at a location with a fairly sizable quantity of mercury, such as a DLA stockpile site, a chlor-alkali facility, or a mercury waste recovery facility. In the first two examples, there will be no transport of elemental mercury (i.e., the mercury is already at the site). In the third example, relatively small quantities of elemental mercury or mercury-containing wastes (e.g., thermometers) are sent by individual generators to a mercury recovery facility, and the recovered elemental mercury is assumed to be treated without further transport. Therefore, the mobile treatment alternatives as evaluated by the project team do not completely account for all movements of mercury, although the transportation of these smaller shipments likely will be required regardless of whether treatment occurs in a centralized location or a mobile location.

3.4.2 Factors Which Influence the Scoring of Macroencapsulation Versus Non-Macroencapsulation Alternatives

Table 3-3 can again be used to identify the factors that significantly affect the scoring for macroencapsulation and non-macroencapsulation alternatives. These occur with the transportation of treated waste (i.e., for mobile treatment alternatives), and for the short-term disposal of treated mercury in the monofill for two of the three treatment technologies (i.e., Options A and B). For each of these criteria, macroencapsulation results in reduced risk versus non-macroencapsulation. In particular, Table 3-1 shows that potential environmental impacts during the disposal phase of the mercury lifecycle were determined to be the most important criterion (i.e., 0.493 is the highest weight), showing that differences in intensities associated with this criterion are expected to be very important. As shown in Table 3-3, differences in the macroencapsulation options result in different intensities for the short term (<40 years) and/or long term (>40 years) disposal. Appendix B identifies how these intensities were assigned.

Because macroencapsulation is primarily intended to reduce risks in the disposal phase, it is reasonable to expect that these alternatives score higher than do alternatives that do not incorporate macroencapsulation.

3.4.3 Factors Which Influence the Scoring of the Three Technology Options

There was significant scattering between each of the four alternatives associated with the Option A technology, while there was a certain amount of clustering associated with the other two technologies. Table 3-3 assists in explaining the results for the Option B and Option C technologies. Table 3-3 shows that all six alternatives (including all four Option C alternatives) with an intensity of ‘Moderate’ for long-term (>40 year) monofill stability have the lowest scores. As suggested by these results, and verified in the uncertainty analysis (Section 3.7), the assigned intensity of this criterion is a principal factor in the overall score for these six technologies. All four Option B alternatives have an intensity of ‘Low’ for this criterion.

With respect to Option A, the results suggest that the technology has advantages and drawbacks, which somewhat complicates the trends. It also suggests that other major differences between the alternatives (i.e., centralized versus mobile treatment, and macroencapsulation versus non-macroencapsulation) significantly affect the score for the Option A alternatives.

3.5 Sensitivity and Uncertainty Analyses

Both sensitivity analyses and uncertainty analyses were conducted using the Expert Choice software. These analyses served two functions: (1) to provide insight into how the overall scores were generated, and (2) to identify how changes in the emphasis or intensities of different criteria would influence the results. For this analysis, sensitivity refers to changes in emphasis of the different criteria (e.g., the five first-level criteria identified in Table 3-1). Uncertainty refers to changes in the assignments of the intensities (e.g., the values identified in Table 3-3). No analyses were conducted which changed the overall structure of the model (e.g., adding new criteria).

3.5.1 Sensitivity Analyses

A sensitivity analysis is a type of 'what-if?' analysis. The intent is to identify how the results would change if a particular criterion was deemed to be more (or less) important than that considered in the baseline analysis results of Table 3-4. In particular, the sensitivity analysis changed the weights of each of the five first-level criteria identified in Table 3-1. These changes were considered as follows:

- Changing the weight of the final disposal criterion from 49.3% to 75% (i.e., more important)
- Changing the weight of the final disposal criterion from 49.3% to 25% (i.e., less important)
- Changing the weight of the transportation criterion from 21.6% to 40% (i.e., more important)
- Changing the weight of the transportation criterion from 21.6% to 10% (i.e., less important)
- Changing the weight of the abnormal/ accidental operations criterion from 18.8% to 40% (i.e., more important)
- Changing the weight of the abnormal/ accidental operations criterion from 18.8% to 10% (i.e., less important)
- Changing the weight of the routine operations criterion from 6.5% to 13% (i.e., more important)
- Changing the weight of the routine operations criterion from 6.5% to 3.2% (i.e., less important)
- Changing the weight of the decommissioning criterion from 3.8% to 7.6% (i.e., more important)
- Changing the weight of the decommissioning criterion from 3.8% to 1.8% (i.e., less important)

In making these changes, the importance of each of the other four criteria was reduced proportionally so that the contributions from all six criteria add to 100 percent. The sensitivity analysis results of the three most sensitive criteria, which are the first six bullets listed above, are summarized in Table 3-5. The remaining sensitivities are presented in Appendix A and make very small differences to the scores.

The sensitivity analysis considered large, but not extreme, changes in the weights of the first-level criteria. The first column of results in Table 3-5, labeled 'baseline,' corresponds to the results in Table 3-4. In this column, the importance of each of the five criteria is equal to the percentages listed in Table 3-1 (e.g., transportation is 21.6%). The next columns list the sensitivity results for each of the first six of the ten scenarios identified above. For example, for the transportation (high importance) sensitivity analysis, the contribution of this criterion to the importance of all non-cost criteria was moved from 21.6% (i.e., the 'baseline' reflected in the first results column) to 40% (+/- 0.2%). The importance of each of the other four first-level criteria was reduced proportionally so that the contributions from all five criteria add to 100 percent.

Some specific observations include the following:

- As shown in Table 3-5, the same two alternatives remained the highest for both the baseline analysis and the six sensitivity analyses (i.e., Option A and Option B with mobile treatment and macroencapsulation). At the other extreme, the same single alternative remained the lowest in all cases (i.e., Option A with centralized treatment and no macroencapsulation). This helps show the stability in the results. Even as the weightings are changed over a wide range, both the rankings and the absolute scores change in predicable ways.
- The baseline score is in between the extremes of the range for each alternative, again validating the general model performance. For example, for the first row in Table 3-5, when evaluating potential risks from transportation, the alternative score moves from 115 (for low importance) to 120 (for high importance). A score of 117 (the baseline) is achieved when the weighting is midway between these extremes.
- The rank of each alternative is unchanged from the baseline when evaluating the potential for accidents from operations, routine operations, and decommissioning. This suggests that the alternatives are not sensitive to these criteria using the assigned intensities.

3.5.2 Uncertainty Analyses

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.

This section of the analysis discusses some of the sources of uncertainty identified in Appendix B that are expected to impact the results and demonstrate their effect for selected alternatives. These areas of uncertainty include the following:

- <u>Monofill Disposal Stability for Option C- long term</u>: Conflicting data are available regarding the degree of mercury vapor generation from the Option C process, which is an area of uncertainty affecting stability. This issue is discussed in more detail in Section 3.8.
- <u>Monofill Disposal Stability for Option A</u>: As discussed above, a single alternative scored lowest in all sensitivity analyses (i.e., centralized treatment of Option A with no macroencapsulation). As an uncertainty analysis, intensity values of this alternative were changed to demonstrate how its score may rise.
- <u>Other Monofill Disposal Stability:</u> An obvious area of uncertainty for all alternatives is the degree to which the disposal conditions will remain stable for both a short and a long period of time (less than 40 years and greater than 40 years, respectively). This range is demonstrated for one of the alternatives. In addition, the scale-up performance of the treatment technologies themselves is uncertain with regard to their ability to treat relatively large quantities of mercury for an extended period of time.
- <u>Accidental Releases of Mercury During Operations</u>: Risks of accidental releases of mercury during the mercury treatment step may be higher or lower than evaluated. This range is demonstrated for two of the alternatives.

A series of different analyses were conducted using the Expert Choice software 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 3-6. Each row of the table represents an instance where data are changed for just one of the alternatives. As shown, a total of 11 different uncertainty analyses were conducted.

The 11 sets of uncertainty analysis results in Table 3-6 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 changing the intensity of the long term (>40 year) disposal criterion between 'Moderate' and 'Low.' This is shown for Reference Nos. 1 through 7. For example, the lowest-scored Option A alternative in Table 3-4 (Reference No. 3) significantly improves its score, from 48 (12th best) to 84 (6th best). Changes in the intensity of the shorter term (<40 year) value also improve the score, but not as much (Reference Nos. 2 and 4).

Uncertainty with regard to accidental releases (mercury spills) during operations have a relatively small effect on results. For example, an Option B alternative (Reference Nos. 8 and 9) still ranks high regardless of whether the intensity is given a value of low, moderate, or high.

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. As shown above, this suggests that uncertainty with regard to long-term storage and disposal represents one such parameter.

Further uncertainty analyses can 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. This was not feasible in the course of the present work.

3.6 Release Rates of Mercury

This section presents the results of a preliminary estimate of the quantity of mercury which may be released from monofill disposal. Mercury may be released as a result of leaching and volatilization mechanisms. For this preliminary analysis, the leachate concentration is multiplied by estimates of the infiltration rate and the landfill area (i.e., the leachate volume) to estimate a leaching release rate. Similarly, the quantity of mercury lost to volatilization is estimated to be equal to the quantity of landfill gas generated multiplied by the gas concentration. The resultant estimates are intended to provide a range reflective of uncertainty, and are based on simplified approaches to the actual physical mechanisms.

As shown in Figure B-1, the quantity of mercury present in leachate is dependent on site-specific environmental conditions such as pH; such conditions may vary over time. The results of Figure B-1 were used as a guide in estimating the range of mercury concentration. Specifically, a lower bound of leachate concentration for each of the three technologies is generally at or slightly below the universal treatment standard (UTS) of 0.025 mg/L. For this analysis, a lower bound of 0.01 mg/L and an upper bound of 1 mg/L are used. This wide range of concentration is intended, in part, to represent a range of uncertainty. In practice, the actual concentrations may even be outside this range.

The results of a study (Wong, 1997) of four Florida landfills capped with synthetic liners were used to estimate infiltration; the hypothetical mercury waste monofills also have synthetic liners and using a report such as Wong (1997) simplifies the analysis by avoiding the need for site-specific modeling. This is intended to provide an order-of-magnitude result, because these parameters may also change over time particularly due to (1) differences in waste properties and (2) the quantity of water entering the monofill, which is typically not equal to the quantity of leachate leaving the monofill due to unsteady-state conditions. Based on Wong (1997), it is assumed that 5% of the rainfall infiltrates through the liner. For the above reasons, there is variability associated with this percentage.

The sizes of the monofills are based on data presented in Appendices E through G of this report.

The sizes of the monofills are dependent on the technology type and whether or not the waste is encapsulated; rather than evaluating each case separately an upper and lower end of the range is provided for each waste quantity.

The quantity of mercury released (volatilized) is a function of the gas generation rate and the mercury concentration. No data are available for gas generation rates from hazardous waste landfills; rather, a great deal of information is available for municipal solid waste landfills (MSWLs) (AP-42; EPA 1998). These MSW rates were used as a bounding estimate, as release rates for the case of a mercury monofill are expected to be much less because of the absence of mechanisms available which would generate landfill gas. The concentration of mercury in the gases is based on the volatilization data in Appendix B with the upper bound corresponding to untreated elemental mercury.

Table 3-7 summarizes the results for both volatilization and leachate release mechanisms. Table 3-7 shows ranges of leachate generation in the range of <1 to 1,500 g/yr and ranges of volatilization in the range of 1 to 1,000 g/yr. These compare to the following data:

- The Swedish EPA (2003) has set a goal of 0.5 to 10 grams per year mercury for the leaching of mercury waste in a deep rock repository. This goal is based on the assumption that the mercury will have localized effects to fish at a hypothetical small lake. The Swedish EPA goals represent the leaching pathway. The values in Table 3-7 (up to 1,500 g/yr) are in line with these Swedish EPA goals, considering that the high end of the ranges in Table 3-7 represent undesirable scenarios.

- The quantity of mercury vapor estimated to be released from monofill disposal (up to 1 kg/yr) is insignificant as compared to other sources such as coal combustion (about 43 tons per year).

Table 3-1. Goal, Criteria, and Subcriteria from EPA/SAIC AHP Brainstorming Session, June 17 and 18, 2004

Goal: Minimize Environmental Impacts During Life Cycle

<table>
<tr><th>First-Level Criterion (weights as calculated by Expert Choice in parentheses)</th><th>Second-Level Criterion (weights as calculated by Expert Choice in parentheses)</th><th>Purpose of Criterion</th><th>Intensities[a]</th><th>Expert Choice Pairwise Comparison Matrix for Intensities[c]</th></tr>
<tr><td>C1. --during routine operation of the stabilization facility[b]
(0.065)</td><td>C1-1. -solid waste streams (other than final product)
(0.750)</td><td>To assess the amount of solid waste (other than the final product) requiring disposal</td><td>low (1.0)
moderate (0.65)
high (0.265)</td><td><table><tr><td></td><td>Low</td><td>Mod.</td><td>High</td></tr><tr><td>Low</td><td>▨</td><td></td><td>3</td></tr><tr><td>Mod.</td><td>▨</td><td>▨</td><td></td></tr><tr><td>High</td><td>▨</td><td>▨</td><td>▨</td></tr></table></td></tr>
<tr><td></td><td>C1-2. -atmospheric discharges
(0.250)</td><td>To assess the level of atmospheric discharges from the facility</td><td>low (1.0)
moderate (0.55)
high (0.303)</td><td><table><tr><td></td><td>2
Low</td><td>Mod.</td><td>High</td></tr><tr><td>Low</td><td>▨</td><td>3</td><td>3</td></tr><tr><td>Mod.</td><td>▨</td><td>▨</td><td></td></tr><tr><td>High</td><td>▨</td><td>▨</td><td>▨</td></tr></table></td></tr>
<tr><td>C2. --during abnormal or accidental operation of the stabilization facility
(0.188)</td><td>C2-1. -elemental mercury spills
(0.833)</td><td>To assess the potential for environmentally harmful spills of liquid elemental mercury during accident conditions</td><td>low (1.0)
moderate (0.55)
high (0.303)</td><td><table><tr><td></td><td>2
Low</td><td>Mod.</td><td>High</td></tr><tr><td>Low</td><td>▨</td><td>2</td><td>3</td></tr><tr><td>Mod.</td><td>▨</td><td>▨</td><td></td></tr><tr><td>High</td><td>▨</td><td>▨</td><td>▨</td></tr></table></td></tr>
<tr><td></td><td>C2-2. -spills other than elemental mercury
(0.167)</td><td>To assess the potential for environmentally harmful spills of materials other than liquid elemental mercury during accident conditions</td><td>low (1.0)
moderate (0.55)
high (0.303)</td><td><table><tr><td></td><td>2
Low</td><td>Mod.</td><td>High</td></tr><tr><td>Low</td><td>▨</td><td>2</td><td>3</td></tr><tr><td>Mod.</td><td>▨</td><td>▨</td><td></td></tr><tr><td>High</td><td>▨ 2</td><td>▨</td><td>▨</td></tr></table></td></tr>
<tr><td>C3. --during transportation
(0.216)</td><td>C3-1. -of mercury to stabilization facility
(0.747)</td><td>To assess the potential for accidental spills of elemental mercury during transportation</td><td>No (1.0)
Yes (0.111)</td><td><table><tr><td></td><td>2</td><td>Yes</td></tr><tr><td>No</td><td>▨</td><td></td></tr><tr><td>Yes</td><td>▨</td><td>▨</td></tr></table></td></tr>
<tr><td></td><td>C3-2. -of stabilized waste to monofill
(0.119)</td><td>To assess the potential for accidental releases of stabilized waste during transportation to monofill</td><td>None (1.0)
Encapsulated (0.225)
Not encapsulated (0.127)</td><td><table><tr><td>No</td><td></td><td>E</td><td>NE</td></tr><tr><td>N</td><td>▨</td><td>9</td><td>7</td></tr><tr><td>E N</td><td>▨</td><td>▨</td><td></td></tr><tr><td>NE</td><td>▨</td><td>▨</td><td>▨</td></tr></table></td></tr>
<tr><td></td><td>C3-3. --of reagents to stabilization facility
(0.134)</td><td>To assess the potential for accidental releases of reagents during transportation</td><td>low (1.0)
moderate (0.405)
high (0.164)</td><td><table><tr><td></td><td>5
Low</td><td>Mod.</td><td>High</td></tr><tr><td>Low</td><td>▨</td><td>2</td><td>5</td></tr><tr><td>Mod.</td><td>▨</td><td>▨</td><td></td></tr><tr><td>High</td><td>▨</td><td>▨</td><td>▨</td></tr></table></td></tr>
</table>

2

3

Table 3-1. Goal, Criteria, and Subcriteria from EPA/SAIC AHP Brainstorming Session, June 17 and 18, 2004 (continued)

First-Level Criterion (weights as calculated by Expert Choice in parentheses)	**Second-Level Criterion** (weights as calculated by Expert Choice in parentheses)	**Purpose of Criterion**	**Intensities**[a]	**Expert Choice Pairwise Comparison Matrix for Intensities**			
C4. –during decommissioning of the stabilization unit (0.038)	None	To assess the potential for potentially harmful environmental effects during decommissioning	low (1.0) moderate (0.55) high (0.303)		Low	Mod.	High
				Low			3
				Mod.			
				High			
C5. --during storage in the monofill (0.493)	C5-1. - expected ease of maintaining environmental conditions (up to 40 years) (0.200)	To assess the potential for excessive leaching during storage	low (1.0) moderate (0.225) high (0.127)		2 Low	Mod.	High
				Low		2	7
				Mod.			
				High			
	C5-2. -expected long-term susceptibility to degradation (0.800)	To assess long-term stability	low (1.0) moderate (0.225) high (0.127)		5 Low	Mod.	High
				Low		2	7
				Mod.			
				High	5		

a In order of decreasing desirability. Values in parentheses are weightings calculated by the Expert Choice software after the pairwise comparison that is summarized in the adjacent column.

2

b Includes macroencapsulation where relevant.

c. Shaded areas represent areas of the matrix that are not used by the Expert Choice Software. The numbers in the matrices represent the relative importance of the intensities as determined by pairwise analysis. For example, in the case where there is a 2 in the cell that has "low" to the left and "mod" above, the team judged that it is twice as desirable for a technology to have a low intensity than a moderate intensity. For a more detailed explanation of the Expert Choice matrices, see Appendix A.

Table 3-2. Expert Choice Matrices for Criteria and Subcriteria

Table 3-2a. – First Level Criteria

	C1.[a]	**C2.**	**C3.**	**C4.**	**C5.**
C1.		-3[b]	-4	2	-7
C2.			1	5	-3
C3.				7	-3
C4.					-9
C5.					

a. The numbering system is explained in Table 1

b. A positive number implies that the criterion in the left hand column is more important than the criterion in the top row. A negative number implies that the criterion in the top row is more important than the criterion in the left hand column.

Table 3-2b. – Second level criteria Associated with Criterion 1

	C1-1.	**C1-2.**
C1-1.		3
C1-2.		

Table 3-2c. – Second Level Criteria Associated with Criterion 2

	C2-1.	**C2-2.**
C2-1.		5
C2-2.		

Table 3-2d. – Second level criteria Associated with Criterion 3

	C3-1.	**C3-2.**	**C3-3.**
C3-1.		7	5
C3-2.			1
C3-3.			

Table 3-2e. – Second Level Criteria Associated with Criterion 5

	C5-1.	**C5-2.**
C5-1.		-4
C5-2.		

Table 3-3. Assignment of Intensities to Treatment and Disposal Alternatives[1]

Treatment and Disposal Option	Routine Operations		Accidental Releases		Transportation			Decom-missioning	Monofill Storage	
	Solid Waste Discharges	Atmospheric Discharges	Mercury Spills	Other Spills	Mercury to Treatment	Waste to Monofill	Reagents		< 40 years	> 40 years
Option A+ NME[a] + CTA[c]	Moderate[e]	Low	Moderate	Low	Yes	No	Low	Low	Moderate	Moderate
Option A+ NME[b] + MTA[d]	Moderate	Low	Moderate	Low	No	NME	Low	Low	Moderate	Moderate
Option A+ ME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Low	Low
Option A+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Low	Low	Low	Low
Option B+ NME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Moderate	Low
Option B+ NME + MTA	Moderate	Low	Moderate	Low	No	NME	Low	Low	Moderate	Low
Option B+ ME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Low	Low
Option B+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Low	Low	Low	Low
Option C+ NME + CTA	Low	Low	Moderate	Low	Yes	No	Moderate	Low	Low	Moderate
Option C+ NME + MTA	Moderate	Low	Moderate	Low	No	NME	Moderate	Low	Low	Moderate
Option C+ ME + CTA	Low	Low	Moderate	Low	Yes	No	Moderate	Low	Low	Moderate
Option C+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Moderate	Low	Low	Moderate

1. The assignment of these intensities is discussed in Appendix B. The uncertainty analysis (Section 3.7.2) helps to quantify the impacts of these selections.

a. NME = Not Macroencapsulated. b. ME = Macroencapsulated.

c. CTA = Centralized Treatment Alternative. d. MTA = Mobile Treatment Alternative.

Table 3-4. Environmental Analysis - Summary of Baseline Results for 12 Evaluated Alternatives

Treatment Scenario			Overall Ranking	
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Score (as fraction of 1,000)**	**Rank (Best to Worst)**
Option A	With	Mobile	117	1
Option B	With	Mobile	117	1
Option B	Without	Mobile	108	3
Option A	With	Fixed	98	4
Option B	With	Fixed	98	4
Option B	Without	Fixed	89	6
Option C	Without	Mobile	73	7
Option C	With	Mobile	73	7
Option A	Without	Mobile	66	9
Option C	Without	Fixed	57	10
Option C	With	Fixed	57	10
Option A	Without	Fixed	48	12
Number of alternatives evaluated			12	—
Total			1,000	—
Average score (total divided by 12, the number of alternatives)			83	—

Shading indicates the highest-ranking alternatives.
Distributive mode; overall inconsistency factor from Expert Choice: 0.02 (good).
Average value is provided for reference and identifies the average score for the twelve evaluated technologies.

Table 3-5. Environmental Sensitivity Analysis

Treatment Scenario			Ranking[a]													
			Baseline (from Table 3-4)		Importance on Disposal				Importance on Transport				Importance on Accidents			
Treatment Process	Macro-Encapsulation	Fixed or Mobile Facility			Sensitivity: High		Sensitivity: Low		Sensitivity: High		Sensitivity: Low		Sensitivity: High		Sensitivity: Low	
			Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Option A	With	Mobile	117	1	124	1	110	1	120	1	115	1	108	1	120	1
Option B	With	Mobile	117	1	124	1	110	1	120	1	115	1	108	1	120	1
Option B	Without	Mobile	108	3	111	5	105	3	113	3	105	5	101	3	110	3
Option A	With	Fixed	98	4	115	3	82	7	85	4	106	3	94	4	100	4
Option B	With	Fixed	98	4	115	3	82	7	85	4	106	3	94	4	100	4
Option B	Without	Fixed	89	6	102	6	78	9	79	9	96	6	88	6	90	6
Option C	Without	Mobile	73	7	60	7	85	5	84	7	66	7	76	7	72	7
Option C	With	Mobile	73	7	60	7	86	4	85	4	66	7	76	7	72	7
Option A	Without	Mobile	66	9	48	11	84	6	81	8	57	11	71	9	64	9
Option C	Without	Fixed	57	10	52	9	61	10	52	10	60	9	64	10	54	10
Option C	With	Fixed	57	10	52	9	61	10	52	10	60	9	64	10	54	10
Option A	Without	Fixed	48	12	39	12	56	12	47	12	48	12	57	12	44	12
Average			83	—	83	—	83	—	83	—	83	—	83	—	83	—
Total			1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—

Shading indicates the highest-ranking alternatives. In the sensitivity analysis for each criterion, the importance of the criterion is set at higher or lower than its baseline value, as identified in the text. The four other criteria comprise the remainder, proportional to their original contributions.

a. Scores normalized to total 1,000.

Table 3-6. Uncertainty Analysis for Mercury Management Alternatives

Ref. No.	Alternative			Criteria	Change in Intensity for Uncertainty Analysis		Initial Result (Table 3-4)		Uncertainty Analysis Result	
					Baseline	Change	Score	Rank	Score	Rank
0	All			Baseline for comparison: Same results as Table 3-4			—	—	—	—
1	**Treatment Process**	**Macro-Encapsulation**	**Fixed or Mobile Facility**	Monofill Disposal, >40 years	Moderate	Low				
	Option C	Without	Mobile				73	7	99	3
	Option C	With	Mobile				73	8	99	3
	Option C	Without	Fixed				57	10	82	6
	Option C	With	Fixed				57	11	82	6
2	Option A	Without	Fixed	Monofill Disposal, <40 years	Moderate	Low	48	12	55	12
3				Monofill Disposal, >40 years	Moderate	Low			84	6
4				Monofill Disposal, both <40 years and >40 years	Moderate	Low			92	4
5	Option B	With	Mobile	Monofill Disposal, <40 years	Low	Moderate	117	2	108	2
6				Monofill Disposal, >40 years	Low	Moderate			76	6
7				Monofill Disposal, both <40 years and >40 years	Low	Moderate			68	9
8	Option B	Without	Mobile	Accidental Releases (Mercury Spills)	Moderate	Low	108	3	117	1
9						High			102	3
10	Option C	With	Fixed		Moderate	Low	57	11	66	9
11						High			51	11

Table 3-7. Preliminary Release Rates for Mercury Monofill Disposal

Pathway	Mercury Quantity, MT	Hg Concentration	Design Basis	Monofill size, acre	Release, g/yr
Leachate	5,000 MT	0.01 – 1 mg/L	5% Infiltration Rate; Precipitation of 5 –60 in/yr (continental U.S. range)	0.6 – 1	0.2 – 300
	12,000 MT			1.3 – 2.2	0.3 – 700
	25,000 MT			3 – 5	0.8 – 1,500
Volatilization	1,000 MT/yr	0.01 – 10 mg/m3	Maximum gas generation 100 m3/MT (AP-42)	---	1 – 1,000

4.0 ECONOMIC ANALYSIS

The purpose of this chapter is to provide estimates of the cost of various methods for the long-term disposition of elemental mercury. As previously described, twelve treatment alternatives are under consideration:

1. Option A + no macroencapsulation + centralized treatment
2. Option A + no macroencapsulation + mobile treatment
3. Option A + macroencapsulation + centralized treatment
4. Option A + macroencapsulation + mobile treatment
5. Option B + no macroencapsulation + centralized treatment
6. Option B + no macroencapsulation + mobile treatment
7. Option B + macroencapsulation + centralized treatment
8. Option B + macroencapsulation + mobile treatment
9. Option C + no macroencapsulation + centralized treatment
10. Option C + no macroencapsulation + mobile treatment
11. Option C + macroencapsulation + centralized treatment
12. Option C + macroencapsulation + mobile treatment

Three different masses of mercury were considered for each of the treatment alternatives:

a. 5,000 metric tons,
b. 12,000 metric tons, and
c. 25,000 metric tons.

Thus, 36 treatment and disposal alternatives were considered. In addition, cost estimates have been prepared for long-term storage of the three masses of elemental mercury in aboveground facilities without any treatment or disposal efforts, making a total of 39 cost estimates in all. This chapter presents the approach, the cost estimate results, and the assumptions used in producing the cost estimates.

Each of the thirty-six cost estimates for treatment and disposal includes the following elements:

- Capital costs for the treatment facility,
- Capital costs for the macroencapsulation facility (if part of the alternative)
- Operating and maintenance costs for the treatment process,
- Operating and maintenance costs for the macroencapsulation process (if part of the alternative),
- Costs associated with the mobile treatment alternative,
- Transportation costs associated with each alternative,
- Costs of storing elemental mercury prior to treatment
- Decommissioning costs for the treatment facilities,
- Monofill engineering and construction costs,
- Monofill operating costs, and
- Costs of maintaining and monitoring the monofill for a thirty-year period following its closure.

Each of the three storage alternatives contain the costs of maintaining the existing stockpile (assumed to be 5,000 MT) in storage, adding to storage space as necessary, and transporting elemental mercury to the storage facility(ies).

In this chapter, Sections 4.1, 4.2, 4.3, and 4.4 describe the assumptions and bases for the cost estimates of the treatment and encapsulation processes, the monofill, storage, and transportation respectively. Section 4.5 discusses uncertainties, and Section 4.6 presents results and interpretation. Various appendices contain detail on input to the cost estimates: Appendix C – Option A Treatment Process; Appendix D – Option B Treatment Process; Appendix E – – Monofill Estimate for Option A Treatment Process; Appendix F – Monofill Estimate for Option B Treatment Process; and Appendix G - Monofill Estimate for Option C Treatment Process. Note that there is no Appendix for the Option C Treatment Process. This is because the Option C vendors provided a great deal of proprietary material. However, the Option C costs were calculated on the same basis as were the costs for the other options.

4.1 Assumptions and Bases for Cost Estimates

This section describes the assumptions and bases for the cost estimates: 4.1.1 General Assumptions; 4.1.2 Mercury Treatment Processes; 4.1.3 Macroencapsulation; 4.1.4 Mobile Treatment alternative; 4.1.5 Monofill; 4.1.6 Storage; and 4.1.7 Transportation.

4.1.1 Background and General Assumptions

- Possibly the most important general assumption is that mercury will be treated at a rate of 1,000 Metric Tons (MT) per year. This is a reasonable assumption in light of the rate at which surplus elemental mercury is becoming available, as is described below.
- For treatment and disposal alternatives, it is assumed that the treatment facility will continue in operation until all of the mercury has been treated and placed in a monofill. This will take 5 years for 5,000 MT, 12 years for 12,000 MT and 25 years for 25,000 MT. Once all of the mercury has been treated, the monofill will be finally closed and monitored for 30 further years.
- For continuing storage alternatives, it is assumed that costs will be calculated for the same length of time as for the corresponding treatment alternative: 5 +30 years for 5,000 MT; 12 + 30 years for 12, 000 MT; and 25 + 30 years for 25,000 MT.
- Costs for each scenario are presented as a Net Present Value (NPV) of a future stream of 2004 constant dollar costs using a 30-year real discount rate of 3.5% per year provided by the Office of Management and Budget (OMB 2004a, 2004b).

According to the Mercury Management Environmental Impact Statement (MMEIS; DLA 2004), the principal amounts of elemental mercury currently in storage at Federal sites in the US are kept in 76 lb (34 kg) flasks at four sites: (a) the New Haven Depot near New Haven, IN; (b) the Somerville Depot in Hillsborough, NJ; (c) the Warren Depot near Warren, OH; and (d) in a building at the U.S. Department of Energy's Y-12 National Security Complex in Oak Ridge, TN.

At New Haven, Somerville, and Warren, the flasks are stored in 30-gal (114-1) steel drums for extra protection, called "overpacking." Each drum contains 6 flasks. The overpack drums meet the U.S. Department of Transportation's (DOT's) packaging requirements for shipping hazardous materials by highway or rail (*Title 49 Code of Federal Regulations* [CFR] 173.164(d)(2)). The drums are banded together in groups of 5 and stored on metal catch trays. The catch trays are on 4-ft (1.2m) square wooden pallets. Each drum contains 456 lb (207 kg) of elemental mercury, and each pallet carries 2,280 lb (2.28 tons or ~ 1 metric ton (MT)).

Many of the flasks at New Haven, Somerville, and Warren are of the older, welded variety made in the 1940s and 1950s. At Y-12, however, the mercury was transferred to newer, seamless flasks in the mid-1970s. These flasks are much less susceptible to leakage and have not been overpacked. They are stored in groups of 45 on wooden pallets that measure 38 in by 38 in by 20 in (96 cm by 96 cm by 51 cm). Thus, each pallet carries 3,420 lb (1,554 kg ~ 1.5 MT) of elemental mercury[17]. The amount of mercury at each site is summarized in Table 4-1.

Table 4-1. Current U.S. Government Mercury Stockpiles[a]

Location	Owner	Quantity in Storage tons/(MT)	Number of Flasks	Number of Drums
New Haven Depot	DNSC	614 (557)	16,151	2,692
Somerville Depot	DNSC	2,885 (2,617)	75,880	12,647
Warren Depot	DNSC	621 (563)	16,355	2,726
Y-12, Oak Ridge	DNSC	770 (699)	20,276[b]	3,379[c]
	DOE	1,130 (1,026)	29,724[b]	4,954[c]
Total	DNSC	4,890 (4,436)	128,662	21,444
	DOE	1,130 (1,026)	29,724	4,954[c]
	All	**6,020 (5,462)**	**158,386**	**26,398**

a. Source: DLA (2004).
b. These stockpiles are collocated in Y-12.
c. Number of drums required to overpack the flasks (currently not overpacked).

Alternative 1 – 5,000 MT

For the case of continued storage, Alternative 1 is quite close to the status quo at DNSC and DOE locations. Therefore, Alternative 1 is costed as if storage will continue there and can be scaled directly from Appendix D of the MMEIS. For example, the current DNSC stockpile of 4,436 metric tons requires approximately 200,000 ft^2 (18,581 m^2) of forklift-accessible flat space inside a structure. 5,000 MT would therefore require ~ 225,000 ft^2 (~ 21,000 m^2), an increase of a factor of 1.127, and items such as rent can be scaled accordingly.

The need for storage will not vanish immediately even if the waste is treated. For the centralized treatment alternative, it is assumed that elemental mercury will be transported from the current storage locations to the treatment facility at a rate of 1,000MT per year for five years. Each 1,000 MT occupies 45,000 ft^2 (~ 4,200 m^2). The MMEIS gives information that can be translated into a cost per MT per year for storing elemental mercury. As the stockpile is depleted, the analysis simplifies by assuming that the storage costs throughout the year are those for the amount of mercury in storage at the mid-point of the year, and that storage costs will decrease accordingly until all the mercury has been treated. The same rate of depletion of the existing stockpile is assumed for both the centralized and mobile treatment alternatives.

Alternative 2 – 12,000 MT

For this alternative, it is assumed, as for alternative 1, that there is 5,000 MT of elemental mercury in existing storage. The remaining 7,000 MT becomes available at a uniform rate over a period of 12 years, i.e., at a rate of 583 MT/yr[18]. For the case of continued storage, therefore, the amount in the stockpile will increase by this amount each year, and additional storage space needs to be made available. As explained above, the amount of mercury in storage at the mid-point of each year is multiplied by the unit yearly cost per MT to provide an estimate of total storage costs per year.

When the waste is treated at a centralized facility, it is assumed that the 583 MT/yr of "new" elemental mercury is transported directly to the treatment facility, thus obviating the need for intermediate

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[17] In the cases where this mercury is transported to a central treatment facility, it is assumed that they will first be placed 6 at a time in 30-gal steel drums in order to satisfy DOT requirements.

[18] Note that the assumption that there is about 5,000 MT in existing storage and that additional elemental mercury becomes available at a rate of a few hundred MT per year is consistent with data in Appendix D of the MMEIS.

storage. The remaining 417 MT/yr required to make up the assumed treatment rate of 1,000 MT/yr is drawn down from storage. Every year, therefore, there is need for 18,800 ft^2 (1,747 m^2) less storage space. The same rate of depletion of the existing stockpile is assumed for both the centralized and mobile treatment alternatives.

Alternative 3 – 25,000 MT

For this alternative, it is assumed, as for Alternative 1, that there is 5,000 MT of elemental mercury in existing storage. The remaining 20,000 MT becomes available at a uniform rate over a period of 25 years, i.e., at a rate of 800 MT/yr. For the case of continued storage, therefore, the amount in the stockpile will increase by this amount each year, and additional storage space needs to be made available.

When the waste is treated at a centralized facility, it is assumed that the 800 MT/yr is transported directly to the treatment facility, thus obviating the need for intermediate storage. The remaining 200 MT/yr required to make up the assumed treatment rate of 1,000 MT/yr is drawn down from storage. The same rate of depletion of the existing stockpile is assumed for both the centralized and mobile treatment alternatives.

Observation

Note that the authors of Appendix D of the MMEIS calculated that approximately 388 MT of elemental mercury was added to inventory in 1997. As noted above, the 12,000 MT and 25,000 MT alternatives assume that elemental mercury becomes available at the rate of 583 MT/yr and 800 MT per year, respectively. These rates are within a factor of about two of the 1997 experience. The current work did not include an analysis of whether there is enough mercury in consumer inventories in the US and a sufficient rate of decommissioning to ensure that total amounts of 12,000MT or 25,000 MT will in fact be made available for long-term disposal. However, the assumed rate of disposal of 1,000 MT per year is not unreasonable.

4.1.2 Mercury Treatment Processes

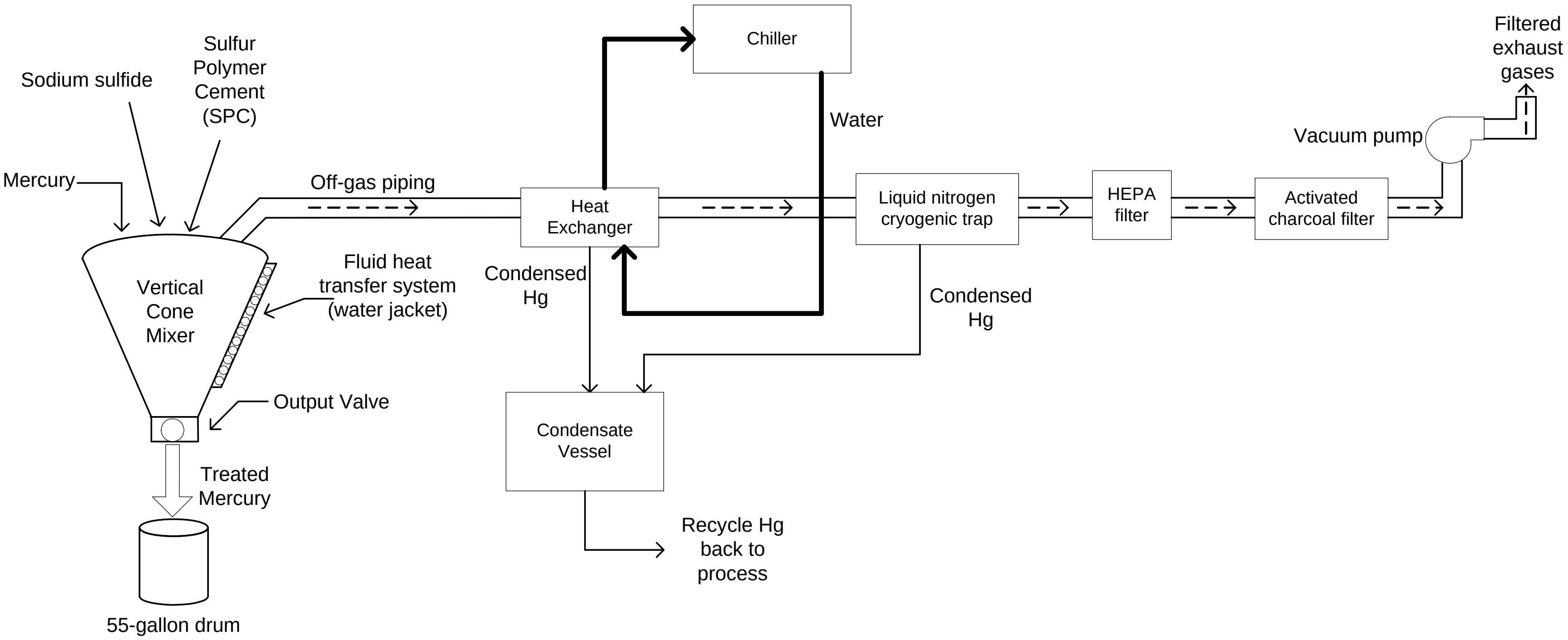
This section provides assumptions and bases for the costs of each of the three treatment technologies.

4.1.2.1 Option A

Option A is a process developed to treat elemental mercury and mercury contaminated waste and debris. Option A is a two stage, single vessel batch process that results in mercuric sulfide stabilized in a sulfur polymer matrix. In the process’ first step, mercury is reacted with powdered sulfur polymer cement and additives to form a stable mercury sulfide compound. Next, the chemically stabilized mixture is melted, mixed, and cooled to form a monolithic solid waste form in which the stabilized mercury particles are microencapsulated within a sulfur polymer matrix.

A process diagram is shown in Figure 4-1. The process’s two main steps, (1) reaction of mercury with sulfur and (2) melting/mixing in a sulfur polymer matrix, occur in a vertical mixer/dryer. The process requires some heating, so the mixer is jacketed for heat transfer. The process produces some mercury vapor, so a ventilation system is required to filter out the vapor. Since the process is heated, heat exchangers are included in the ventilation system.

Figure 4-1. Option A Process



Appendix C includes further diagrams for the Option A process that show the equipment and materials used for the cost estimates. Each of the diagrams shows the sizing for process capacity, reagent consumption, and the major equipment. The assumptions shown on the process diagram are described below.

The following is the key information for sizing the Option A process: one 35 ft^3 mixer can process 525 kg per shift. This mixer size was based on published information in which the vendor states that a 35 ft^3 mixer is under development. This represents a scaling up by a factor of 35 from the pilot mixer of 1 ft^3. Five mixers in parallel operating two shifts per day can process the assumed mass of mercury per year (1,000 metric tons). The major equipment necessary to operate these mixers is shown on the process diagram, which lists the major equipment and its cost. These costs are summarized in Table 4-2. The cost of the major equipment is used to estimate the overall capital costs for the Option A process.

Table 4-2. Major Equipment for the Option A Process

Component	Price	Reference	Comments
Sulfur Polymer Cement Feeders	$44,100	RES (2002) account 100-55, page 2	Conveyer 20-525 cf/hr
Sulfur Polymer Cement Hopper	$10,650	Perry and Green (1997) Table 9-50	$\$4{,}700 \cdot \left(\frac{4{,}200}{1{,}000}\right)^{0.57} = \$10{,}650$
Sodium Sulfide Pump	$15,000	Bubb (2004a)	Vertical Pump and electric motor. Designed for concentrated acid.
Sodium Sulfide Feed Valves	$330	RES (2002) account 15-47, page 27	Stainless Steel Gate Valves, 200#, Socket Weld, ¾ -inch Sch 40.
Sodium Sulfide Tank	$557	MSC (2004)	Polyethylene Double-Walled Tank 100 gal
Mixer	$180,000	Bubb (2004b)	Vertical Vacuum Blender 35 cubic feet Jacketed Motor, Valves, Controls, Thermocouples
Heater	$26,495	Bubb (2004b)	72 kW
Liquid Nitrogen Tank	$627	LACO (2004)	2L N2 reservoir (16 hour holding time)
Off-gas Ducts	$506.47 per 100 ft^2 = $5,065	RES (2002) account 15-9, page 1	24 GA ductwork (20" diameter), 1000 ft^2
HEPA Filter	$306.50	Grainger (2004) pg 3575	Air Handler HEPA Air Filter 1,100 CFM, 24"x24"x11.5", 99.97% efficient
Carbon Filter	$47.25	Grainger (2004) pg 3571	Activated Carbon Disposable Filters 250 FPM, 24"x24"x2"
Vacuum Pump	Pump $4,800 Electric Motor $1,187 Total: $5,987	RES (2002) account 100-110, page 2 RES (2002) account 100-653, page 2	Assumed similar cost to a fan: Vaneaxial Fan 44-inch diameter 1 – 30 HP 15,000 – 47,000 CFM Electric Motor 7.5 HP AC Motor
Chiller	$5,366	MSC (2004) page 4477	Lytron RC045 20,100 BTU/hr, 4.3 gpm Pump
Condenser	$4,186	MSC (2004) page 4476	Liquid-to-air heat exchanger model 6640 x 2 + $2,000 allotment for vessel and manufacturing
Forklift	$25,000	Solis (2004)	4,000-6,000 lb capacity Electric Drive

Notes: price gives the costs for one piece of equipment. Quantities of equipment required are given in Appendix C.

The key information for the mass components in each treatment batch is as follows:

- 33% weight mercury,
- 65% weight sulfur polymer cement, and
- 2% weight sodium sulfide.
-

Thus, the mass of treated product is approximately 3 kg/kg mercury treated.

For 1,000 MT of mercury processed per year, this sets the amount of reagents required per year. This also means that there are 3,000 MT of waste product for disposal each year. Table 4-3 lists the materials used in the Option A process and their costs. This includes reagents and drums into which treated mercury is placed.

Table 4-3. Material Costs for Option A Process

Component	Price	Reference	Comments
Sulfur Polymer Cement	$0.12 / lb delivered ($0.264/ kg)	Chang (2001)	Martin Resources (Odessa, TX) Chement 2000
Sodium Sulfide	$10.53 / kg delivered	Lab Depot (2004)	Na_2S (36% water of crystallization) 1.5 g/cm^3
55-gallon drums	$33 per barrel delivered	Ten Siethoff (2004c)	

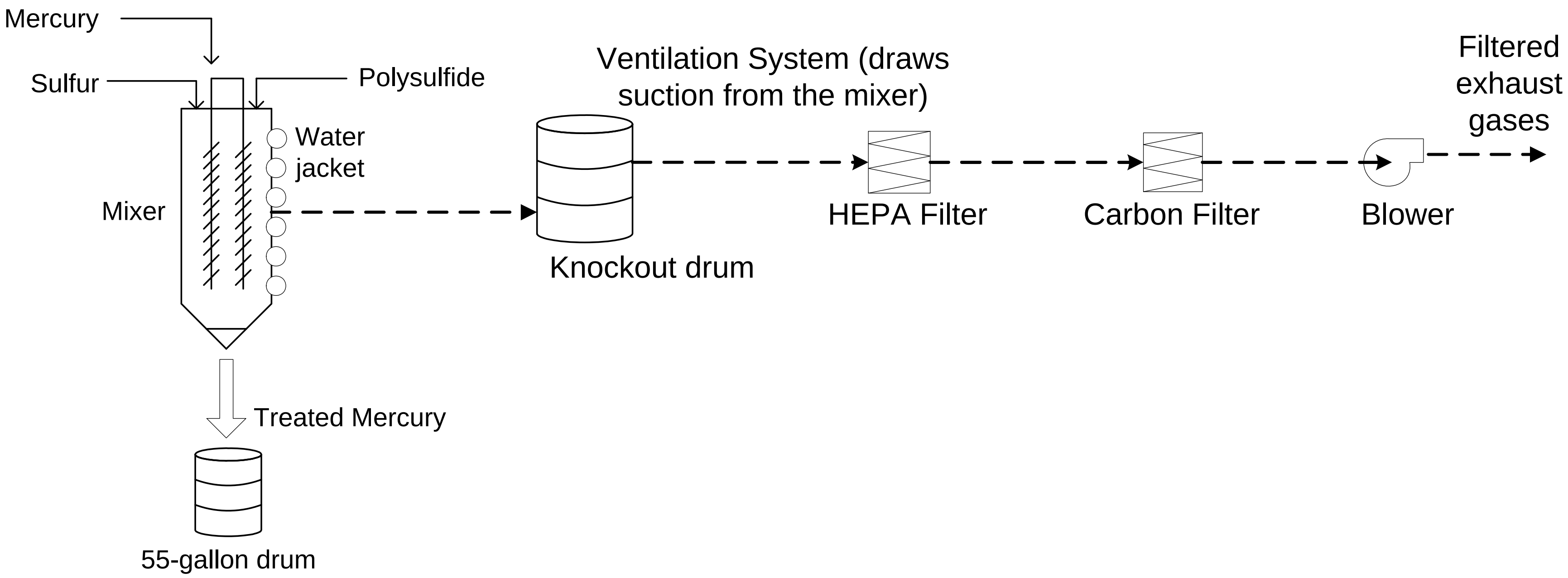
Staff salary costs and utility costs for the Option A treatment process are estimated on the process diagram in Appendix C. These costs are included in the annual O&M costs for the treatment process. Staff salary is based on the Website Salary.com (Salary.com 2004). For all three options, the calculated O&M costs include the assumption that the facility is down 20% of the time for maintenance and repair.

4.1.2.2 Option B

The Option B process treats elemental mercury or mercury containing wastes. A process diagram is shown in Figure 4-2. The process, performed in batches, consists of the following steps:

1. A sulfur-containing compound (otherwise known as the amalgamating agent), preferably elemental sulfur in powdered form, is spread throughout a mixer.
2. The mercury-containing material is added to the mixer and mixed.
3. A polysulfide is added and mixed to activate the reaction between sulfur and mercury. Typically this polysulfide is calcium polysulfide or sodium polysulfide.
4. The resulting granular waste is poured into drums.

Figure 4-2. Option B Sulfide Process



As with the Option A process, a ventilation system with filters is required. Appendix D includes further diagrams for the mercury treatment processes that show the equipment and materials used for the cost estimates. Each of the diagrams shows the sizing for process capacity, reagent consumption, and the major equipment. The assumptions and sources of information shown on the process diagrams are discussed below.

The following is the key information for sizing the Option B process:

- 375 kg of mercury per batch[19],
- 3 batches per mixer-shift, and
- 80% utilization of the equipment.

Using this information, five mixers operating in parallel can process the required mass of mercury per year (1,000 tons). The major equipment necessary to operate these mixers is shown on the process diagram, and Table 4-4 lists the major equipment and its cost. The cost of the major equipment is used to estimate the overall capital costs for the Option B process.

The following is the key information regarding the mass components in each treatment batch:

- 67% mercury,

3% polysulfide, and30% sulfur.Thus, the mass of treated product is approximately 1.5kg/kg mercury treated.

For 1,000 tons of mercury processed per year, this sets the amount of reagents required per year. This means that 1,500 MT of waste product needs to be disposed of each year from the Option B process. Table 4-5 lists the materials used in the process and their costs. This includes reagents and drums into which treated mercury is placed.

Staff salary costs and utility costs for the treatment process are estimated on the process diagram. These costs are included in the annual O&M costs for the treatment process. Staff salary is based on information from Salary.com.

4.1.2.3 Option C

The final product of Option C is a monolithic amalgamated material that is encapsulated in polyethylene-lined steel drums. The process, which is performed in batches in drums, consists of steps to create an amalgam and (if required) additional steps to create a stabilized form. A process diagram is shown in Figure 4-3.

The process steps are as follows:

1. A proprietary powdered reagent is added to elemental mercury in a drum and mixed.
2. Another proprietary powdered reagent is added to the drum and mixed.
3. A proprietary liquid reagent is added to the drum and mixed.
4. The stabilized form is created by mixing in three more proprietary reagents (two powdered, one liquid) and curing.

---

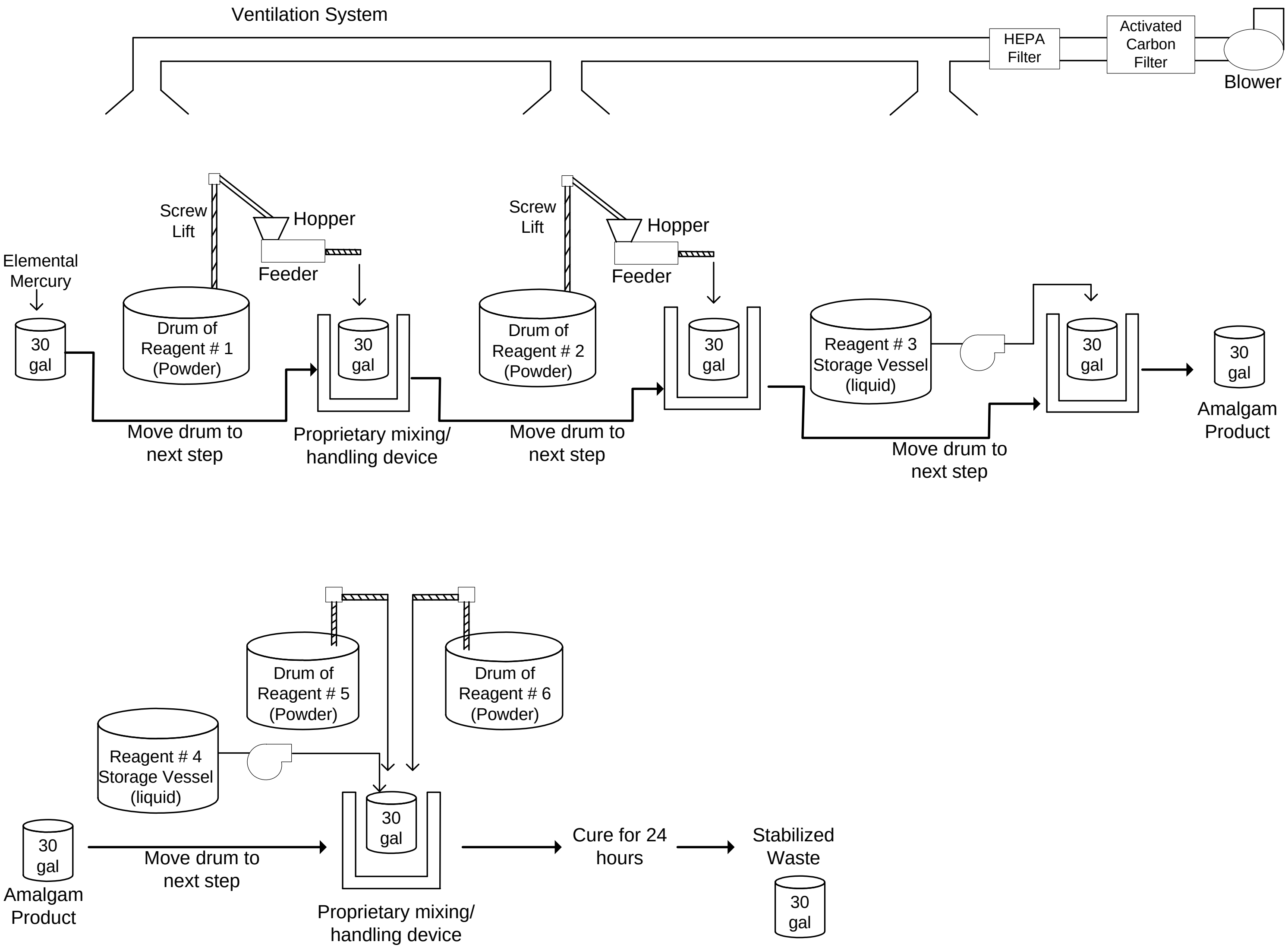
[19] This batch size was confirmed in discussions with Vendor B and represents scaling up by a factor of five from the existing mixer.

Table 4-4. Major Equipment for the Option B Process

Component	Price	Reference	Comments
Mixers	$65,000	Bubb (2004d)	60 cubic foot mixer
Polysulfide Pumps	Pump $2,400 Electric Motor $1,187 Total= 3,587	RES (2002) account 100-280, page 2 RES (2002) account 100-653, page 2	Pump Vertical Split Case Centrifugal Pump Max operating pressure 285 psi 50 gpm and 200 ft of head 7.5 HP Electric Motor 7.5 HP AC Motor
Polysulfide Feed Valves	$760	RES (2002) account 15-47, page 27	Stainless Steel Gate Valves, Screwed 2-inch Sch 40
Sulfur Hoppers	$26,400	RES (2002) account 100-45, page 4	Gravimetric Feeder 720 – 24,000 lb / hr
Crane	$78,000	RES (2002) account 100-495, page 4	Overhead traveling bridge crane, Floor operated 3 ton, 75 foot span
Water Heater	$2,769	RES (2002) account 15-28, page 2	Commercial water heater, gas 50 gallons, 90,000 BTU/hr
Ventilation System Ducts	$506.47 per 100 ft^2 = $5,065	RES (2002) account 15-9, page 1	24 GA ductwork (20” diameter), 1000 ft^2
HEPA Filter	$306.50	Grainger (2004)	Air Handler HEPA Air Filter 1,100 CFM, 24”x24”x11.5”, 99.97% efficient
Carbon Filter	$47.25	Grainger (2004)	Activated Carbon Disposable Filters 250 FPM, 24”x24”x2”
Knockout Drum	$6,300	Perry and Green (1997) page 9-69	Pressure Vessel Horizontal Drum 1,000 gal
Blower	Fan $4,800 Electric Motor $1,187 Total: $5,987	Fan RES (2002) account 100-110, page 2 RES (2002) account 100-653, page 2	Fan Vaneaxial Fan 44-inch diameter 1 – 30 HP 15,000 – 47,000 CFM Electric Motor 7.5 HP AC Motor
Forklift	$25,000	Solis (2004)	4,000-6,000 lb capacity Electric Drive

Notes: price gives the costs for one piece of equipment. Quantities of equipment required are given in Appendix D.

Figure 4-3. Option C Process



As with the other processes, a ventilation system with filters is required.

No Appendix is shown for this process to protect proprietary details. The principal assumptions and sources of information for costing the process are described below.

Two parallel amalgamation process lines and three parallel stabilization process lines can treat 1000 tons of mercury per year. The processes will operate two shifts per day. The major equipment necessary to operate these process lines is shown on the process diagram in Attachment C, and Table 4-6 lists the major equipment and its cost. The cost of the major equipment is used to estimate the overall capital costs for the Option C process.

Table 4-5. Material Costs for Option B Process

Component	Price	Reference	Comments
Polysulfide	$0.31 / lb delivered ($0.682 / kg)	Gragg (2004)	LA Chemical
Sulfur	$0.17 / lb delivered ($0.374 / kg)	Bubb (2004e)	Georgia Gulf Sulfur
55-gallon drums	$33 per barrel delivered	Ten Siethoff (2004c)	

The costs and the chemical forms of the reagents in the Option C Process constitute proprietary information. Table 4-7 lists the materials used in the process and their costs. Note that the drums in which mercury is treated are 22 gallons for this cost estimate. The drum size was reduced so that the treated mercury filled 90% of the container volume, meeting the monofill requirement. The mass of waste product is 5.66 kg/kg of treated Hg.

Staff salary costs and utility costs for the treatment process are estimated on the process diagram. These costs are included in the annual O&M costs for the treatment process. Staff salary is based on information from Salary.com, and the number and type of staff required were provided by the vendor.

4.1.2.4 Cost Input Factors Common to All Treatment Technologies

Total capital costs are estimated as a percentage of the costs for the major equipment; that is, elements of the total capital cost are calculated by multiplying factors that are applied total major equipment costs. The factors used are shown in Table 4-8. The bases for the factors are given in the notes under the table.

4.1.2.5 Operating and Maintenance Costs

Direct operating costs for treatment (and macroencapsulation) are estimated on the Process Diagram sheets included in Attachments C and D (for Options A and B). The costs for Option C were calculated in the same way. Flask disposal costs ($0.44 per kilogram of mercury processed) included in the treatment O&M are based on Bethlehem (2001). Costs, overhead, fees, and contingency are based on factors that are shown in Table 4-9. The bases for the factors are given in the notes under the table.

Table 4-6. Major Equipment for the Option C Process

Component	Price	Reference	Comments
Drum Mixer	$1,404	MSC (2004) pg. 4481	TEXP Mixer 1.5 HP
Drum Truck	$321	MSC (2004) pg. 3196	Steel Deck Platform Truck 2,500 lb 30"x60"x40"
Mixing and Handling Device	$3,725	NA	Use the Mixer and Truck items above plus a $2,000 allowance for customization of the assembly (e.g. frame, brakes, track).
Lift/Hopper/Feeder	$8,385	Flexicon (2004)	Flexicon Stainless Steel, 50 cubic ft / hr 10 ft long, 4.5" OD
Reagent 3 and 4 Pumps	Pump $2,400 Electric Motor $1,187 Total: $3,587	RES (2002) account 100-280, page 2 RES (2002) account 100-653, page 2	Pump Vertical Split Case Centrifugal Pump Max operating pressure 285 psi 50 gpm and 200 ft of head, 7.5 HP Electric Motor 7.5 HP AC Motor
Reagent 3 and 4 Feed Valves	$760	RES (2002) account 15-47, page 27	Stainless Steel Gate Valves, Screwed 2-inch Sch 40
Crane	$78,000	RES (2002) account 100-495, page 4	Overhead traveling bridge crane, Floor operated 3 ton, 75 foot span
Ventilation System Ducts	$506.47 per 100 ft^2. Total= $5,065	RES (2002) account 15-9, page 1	24 GA ductwork (20" diameter), 1000 ft^2
HEPA Filter	$306.50	Grainger (2004)	Air Handler HEPA Air Filter 1,100 CFM, 24"x24"x11.5", 99.97% efficient
Carbon Filter	$47.25	Grainger (2004)	Activated Carbon Disposable Filters 250 FPM, 24"x24"x2"
Blower	Fan $4,800 Electric Motor $1,187 Total: $5,987	Fan RES (2002) account 100-110, page 2 RES (2002) account 100-653, page 2	Fan Vaneaxial Fan 44-inch diameter 1 – 30 HP 15,000 – 47,000 CFM Electric Motor 7.5 HP AC Motor
Forklift	$25,000	Solis (2004)	4,000-6,000 lb capacity Electric Drive

Note: price gives the costs for one piece of equipment.

Table 4-7. Material Costs for the Option C Process

Component	Price	Reference	Comments
Reagents	Proprietary		
22-gallon drums	$33 per barrel delivered	Ten Siethoff (2004c)	Assume, since not a standard barrel size, that the barrels will cost the same as 55-gallon barrels.

Table 4-8. Factors Used to Estimate Fixed Treatment Facility Capital Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Allowance for equipment not yet identified	0.10	0.15	0.20	1
Building site preparation	0.08	0.15	0.22	2
Building construction, services installation	0.26	0.305	0.35	2
Cost to install major equipment	0.39	0.41	0.43	2
Piping	0.30	0.345	0.39	2
Structural foundations (steel, concrete)	0.28	0.28	0.28	3
Electrical	0.08	0.125	0.17	2
Instruments	0.13	0.13	0.13	2
Auxiliaries	0.48	0.515	0.55	2
Other field expenses	0.35	0.39	0.43	2
Engineering	0.35	0.39	0.43	2
Initial start-up costs	0.02	0.13	0.24	4
Fees, overhead, and profit	0.09	0.13	0.17	2
Contingency	0.39	0.39	0.39	2

Notes:

1. Based on guidance in Perry and Green (1997). Minimum and Maximum reflect the range given in the reference, Best is the average of those values. The costs for Major Equipment are multiplied by the factor to make an allowance for equipment not yet identified.
2. From Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
3. From Table 9-51 of Perry and Green (1997) for fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
4. Initial start-up costs are taken from Equation 9-260 of Perry and Green (1997). The Direct Plant costs are multiplied by this factor to estimate start-up costs. Minimum and Maximum values reflect possible ranges for the newness of the process, newness of the equipment, the labor quality, and the interdependency of steps in the process. The Best factor is an average of the Minimum and Maximum.

Table 4-9. Factors Used to Estimate Treatment and Macroencapsulation O&M Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Maintenance and Repair	0.02	0.06	0.10	1
Insurance	0.01	0.01	0.01	1
Property tax	0.02	0.02	0.02	1
Other overhead	0.055	0.055	0.055	2
Fee	0.20	0.20	0.20	3
Contingency	0.39	0.39	0.39	4

Notes:

1. Percentage of the major equipment costs (including the allowance for equipment not yet identified) for the treatment or macroencapsulation facility based on guidance in Perry and Green (1997).
2. Percentage of the direct plus indirect costs based on guidance in Perry and Green (1997).
3. Percentage of the direct plus indirect costs based on vendor information for similar process.
4. Percentage of the direct plus indirect costs based on guidance in Perry and Green (1997) for capital costs.

4.1.3 Macroencapsulation

ARROW-PAK macroencapsulation is a process offered by Boh Environmental that places waste into steel drums that are then sealed inside HDPE pipe (DOE 2002; USEPA 2002d). As part of the three treatment processes considered here, the waste is placed in drums. The macroencapsulation process adds the following steps:

1. The drums are placed into ARROW-PAK tubes (HDPE pipe) using a forklift fitted with a plunger and a purpose-built loading rack.
2. The ARROW-PAK tubes are sealed at both ends with HDPE endcaps that are fused to the pipe.

Attachments C and D (for Options A and B respectively) each include a diagram for the macroencapsulation process that shows the equipment and materials used for the macroencapsulation cost estimates . The macroencapsulation costs for Option C were calculated similarly. While the major equipment used for the macroencapsulation process is the same for every mercury treatment process, the material quantities vary with the amount of waste produced by each process. This section describes the assumptions and sources of information shown on the macroencapsulation process diagram.

Table 4-10 lists the major equipment and costs for the macroencapsulation process. The cost of the major equipment is used to estimate the overall capital costs for the macroencapsulation process. The materials' costs for macroencapsulation are listed in Table 4-11.

Table 4-10. Major Equipment for Macroencapsulation

Component	Price	Reference	Comments
Crane	$78,000	RES (2002) account 100-495, page 4	Overhead traveling bridge crane, Floor operated 3 ton, 75 foot span
Waste loading rack	$2,400	Global Industrial (2004)	Increased costs of commercial pallet racks to account for customization required for this application.
Fusion equipment	$3,500	MSC (2004) pg 962	Assume capital required is similar to arc welding machine
Chocks	$43	Grainger (2004) pg 2346	
Forklift	$25,000	Solis (2004)	4,000-6,000 lb capacity Electric Drive

Note: price gives the costs for one piece of equipment.

Table 4-11. Material Costs for Macroencapsulation Process

Component	Price	Reference	Comments
Arrow-Pak tubes	$45/foot	Bubb (2004f)	Estimated as HDPE pipe
Arrow-Pak endcaps	$250 per endcap	Ten Siethoff (2004d)	Estimated as HDPE endcaps

As with the treatment facility capital costs, total capital costs are estimated as a percentage of the costs for the major equipment. The factors used for a macroencapsulation facility at a fixed site are shown in Table 4-12. The bases for the factors are given in the notes under the table.

Staff salary costs and utility costs for the macroencapsulation process in Options A and B are estimated on the process diagrams in Appendices C and D. These costs are included in the annual O&M costs for macroencapsulation. The costs for Option C are calculated similarly. Staff salary is based on information from Salary.com.

4.1.4 Mobile Treatment

The size of the treatment facilities for the centralized alternative is such that it is perfectly feasible to skid mount them and transport them from site to site. The base case alternative is one in which there is a single mobile facility capable of treating 1,000 MT per year that is moved from site to site as needed. Potential alternatives are ones with somewhat smaller capability (say 500 MT/year or 330 MT/year) so that mercury can be treated at more than one site at once.

Facility relocation costs are estimated as the sum of the following: transportation of equipment, assembling the treatment facility, start-up, and contingency. The sum is the cost for one move. Total costs over the span of processing will depend on the number of facility relocations that occur.

Table 4-12. Factors Used to Estimate Fixed Macroencapsulation Facility Capital Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Allowance for equipment not yet identified	0.10	0.15	0.20	1
Building site preparation	0.08	0.15	0.22	2
Building construction, services installation	0.26	0.305	0.35	2
Cost to install major equipment	0.19	0.21	0.23	3
Other field expenses	0.10	0.11	0.12	3
Engineering	0.35	0.39	0.43	4
Initial start-up costs	0.02	0.13	0.24	5
Fees, overhead, and profit	0.30	0.315	0.33	3
Contingency	0.26	0.26	0.26	3

Notes:

1. Based on guidance in Perry and Green (1997). Minimum and Maximum reflect the range given in the reference, Best is the average of those values. The costs for Major Equipment are multiplied by this factor to make an allowance for equipment not yet identified.
2. Considered as additional space that would be added to the building used for treatment. Factor is from Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
3. Used factors from Table 9-51 of Perry and Green (1997) for solids processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
4. Used factors from Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
5. Initial start-up costs are taken from Equation 9-260 of Perry and Green (1997). The Direct Plant costs are multiplied by this factor to estimate start-up costs. Minimum and Maximum values reflect possible ranges for the newness of the process, newness of the equipment, the labor quality, and the interdependency of steps in the process. The Best factor is an average of the Minimum and Maximum.

As with the fixed facility capital costs, total capital costs for mobile treatment are estimated as a percentage of the costs for the major equipment. The Factors used are shown in Table 4-13. The bases for the Factors are given in the notes under the table. The category for Other Field Expenses, which was included in capital costs for the fixed facility, has been deleted since those costs are associated with construction of a fixed facility. Costs for transportation of equipment between locations for mercury treatment have not been estimated. They are assumed to be contained within the uncertainty bands on the O&M cost estimates (see Section 4.2).

Assembling the treatment process lines is estimated to cost 1/3 as much as installing equipment in a fixed facility. The cost to install equipment in a fixed facility is based on a percentage of the major equipment costs. Costs for macroencapsulation facility assembly following moves are assumed to be negligible.

Start-up of the facility is estimated to cost 1/10 as much as the initial start-up costs for the mobile facility, which are given as part of the capital costs.

Contingency is estimated as a percentage of the rest of the facility relocation costs (the factor is 0.39) based on guidance in Perry and Green (1997) for capital costs.

Table 4-13. Factors Used to Estimate Mobile Treatment Facility Capital Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Allowance for equipment not yet identified	0.10	0.15	0.20	1
Steel for skids	0.28	0.28	0.28	2
Cost to assemble major equipment skids	0.26	0.273	0.287	3
Piping	0.30	0.345	0.39	4
Electrical	0.08	0.125	0.17	4
Instruments	0.13	0.13	0.13	4
Auxiliaries	0.48	0.515	0.55	4
Engineering	0.70	0.78	0.86	5
Initial start-up costs	0.02	0.13	0.24	6
Fees, overhead, and profit	0.09	0.13	0.17	4
Contingency	0.39	0.39	0.39	4

Notes:

1. Based on guidance in Perry and Green (1997). Minimum and Maximum reflect the range given in the reference, Best is the average of those values. The costs for Major Equipment are multiplied by the factor to make an allowance for equipment not yet identified.
2. From Table 9-51 of Perry and Green (1997). Used the factor for structural steel foundations for fluid processing plant. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
3. 2/3 of the factor used for installation of equipment for a fixed solids-fluid facility. Assembly of plant following relocations is accounted for in Facility Relocation table. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
4. From Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values.
5. Double the factor used for engineering for a fixed facility. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
6. Initial start-up costs are taken from Equation 9-260 of Perry and Green (1997). The Direct Plant costs are multiplied by this factor to estimate start-up costs. Minimum and Maximum values reflect possible ranges for the newness of the process, newness of the equipment, the labor quality, and the interdependency of steps in the process. The Best factor is an average of the Minimum and Maximum.

For the mobile treatment alternative, the macroencapsulation module is also mobile. As with the treatment facility capital costs, total capital costs are estimated as a percentage of the costs for the major equipment. The factors used are shown in Table 4-14. The bases for the factors are given in the notes under the table.

4.1.5 Content of Appendices C and D

Appendices C and D contain detailed input to the cost estimates for two of the three treatment technologies: Option A and Option B. There is a similar Appendix for Option C but, since it contains proprietary information, it is not included here. Each Appendix contains:

- Treatment Process Diagrams that also double as worksheets that estimate cost of equipment, costs of reagents, waste volume, staff, etc.
- A table of treatment capital costs for fixed facilities
- A table of treatment capital costs for mobile facilities
- A table of treatment O&M costs
- A table of facility relocation costs
- Macroencapsulation diagrams that also double as worksheets
- A table of macroencapsulation capital costs for fixed facilities
- A table of macroencapsulation capital costs for mobile facilities
- A table of macroencapsulation O&M costs

Table 4-14. Factors Used to Estimate Mobile Macroencapsulation Facility Capital Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Allowance for equipment not yet identified	0.10	0.15	0.20	1
Cost to assemble major equipment skids	0.127	0.14	0.153	2
Other field expenses	0.10	0.11	0.12	3
Engineering	0.35	0.39	0.43	4
Initial start-up costs	0.02	0.13	0.24	5
Fees, overhead, and profit	0.30	0.315	0.33	3
Contingency	0.26	0.26	0.26	3

Notes:

1. Based on guidance in Perry and Green (1997). Minimum and Maximum reflect the range given in the reference, Best is the average of those values. The costs for Major Equipment are multiplied by this factor to make an allowance for equipment not yet identified.
2. 2/3 of the factor used for installation of equipment for a fixed solids processing facility. Assembly of plant following relocations is accounted for in Facility Relocation table. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
3. Used Factors from Table 9-51 of Perry and Green for solids processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
4. Used factors from Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
5. Initial start-up costs are taken from Equation 9-260 of Perry and Green. The Direct Plant costs are multiplied by this factor to estimate start-up costs. Minimum and Maximum values reflect possible ranges for the newness of the process, newness of the equipment, the labor quality, and the interdependency of steps in the process. The Best factor is an average of the Minimum and Maximum.

4.2 Monofill

For all scenarios in this cost estimate except long-term storage, treated mercury will be disposed of in a monofill. The monofill is a single purpose landfill: only treated mercury will be placed in it. Since it will hold waste containing mercury, the monofill will be designed, constructed, and operated as a hazardous waste disposal facility.

4.2.1 Monofill Requirements per Code of Federal Regulations

The bases for requirements that will affect the monofill are taken from 40 CFR Part 264 (CFR 2004). These requirements are summarized below.

Design Features

The monofill will require a double liner on the bottom, a final cover that includes a top liner, a leachate collection and removal system, and a leak detection system (§264.301). The secondary part of the bottom liner must be composite (soil or clay plus a membrane), with a three foot thick soil/clay component. The top liner is installed upon closure of each fill cell. The top liner must minimize liquids that migrate into the landfill, promote drainage away from the sealed landfill, and include cover to protect the liner (§264.310).

The monofill must have a run-on control system that prevents water from flowing onto the active portion of the fill during a storm. The monofill also must have a run-off control system to collect water that falls into the fill during storms. Both systems require facilities to empty water out following storms.

Construction Quality Assurance

A Construction Quality Assurance (CQA) program will be required (§264.19). This entails preparing a written CQA plan developed and implemented by a registered Professional Engineer. Testing and inspections are required to ensure that construction materials and installed unit components meet the design specifications. Sufficient observations, testing, measurement, and inspections are required to ensure:

- Structural integrity of foundations, dikes, soil liners, geomembranes, leachate collection and removal systems, and leak detection systems;
- Proper construction according to design specifications and permits; and
- Conformity of materials with design and material specifications.

The CQA program will also require test fills for compacted soil liners to ensure the liners meet requirements, or data showing the liner will work in the site conditions.

Special Requirements for Containers

Containers must be at least 90% full when placed in the landfill (§264.315).

Waste Analysis

If the landfill is located at a different site than is the waste treatment facility, the landfill operator must inspect or analyze each shipment to ensure it matches the manifest (§264.13).

Security

The facility must be secured with 24-hour surveillance or a fence and gate attendant (§264.14).

Personnel Training

Personnel who work at the landfill must undergo hazardous waste handling training (§264.16).

Monitoring and Inspection

During construction, the liners must be inspected to ensure their integrity (§264.303). While in operation (filling), the landfill must be inspected weekly and after storms to detect:

- Problems with the run-on and run-off control systems,
- Problems with the leachate collection and removal system, and
- Leaks as shown in the leak detection system.

If leakage rates increase above the “actionable level”, then a response is required (§264.304).

Post-Closure Care

The final cover will have to be maintained to ensure its integrity and effectiveness. Repairs may be necessary to correct the effects of settling, erosion, or other events (§264.310).

The leachate collection and removal system must be operated until leachate is no longer detected. Once the final cover is installed, the leak detection system will have to be checked monthly to ensure that no leaks are occurring. If leak rates are slow enough, the interval can eventually be increased to semi-annual inspections. If leakage rates increase above the “actionable level”, then response is required (§264.303).

A groundwater monitoring system must be maintained and monitored.

Post-closure care must continue for thirty years after the monofill is closed (§264.117).

4.2.2 Monofill Cost Bases

Monofill costs are estimated for the various treatment scenarios. Costs are estimated based on a disposal cell that is sized to hold five years’ worth of treated mercury. Since the processes assumed for these cost estimates treat 1,000 tons of mercury per year, each cell holds 5,000 tons. Consequently, the cost estimates for 25,000 ton scenarios have five monofill cells.

For centralized treatment, it is assumed that the treatment facility and monofill are located at a commercial site that already has landfills. Thus, the operator of the existing landfill can readily apply for expansion to include the monofill. Similarly, for the mobile treatment case, the waste (in drums or tubes) is transported to a centralized monofill at a site where the operator already has landfills. In both cases, existing buildings are assumed to be available for administrative and other uses associated with the disposal cells for treated mercury.

The monofill design, construction, operation, and post-closure care are based on the requirements of 40 CFR Part 264 which are listed in Section 4.2.1. How the requirements are incorporated in the landfill design envisioned for the cost estimate is discussed below.

General Design Features

For the fixed treatment facility alternative, it is assumed that a monofill will be located at the treatment site. For the mobile facility alternative, it is assumed that material will be transported to a centralized monofill following treatment.

For the purposes of the estimate, it is assumed that the monofill will be divided into cells that are large enough to hold five years' worth of treated waste. The size of the cells will vary depending on whether the waste is placed in drums or macroencapsulated in Arrow-Pak tubes. The number of drums or tubes per year (and thus the size of the cell) is calculated based on the assumptions for each scaled-up treatment process. Figure 4-4 shows a plan and cross-section view for a monofill cell.

The exact design requirements will depend on Factors such as the weather, hydrology, soil conditions, and topography of the landfill site. The design used for this cost estimate includes features identified for a hazardous waste landfill by USEPA (2003), Geoengineers (2004), Jones (2003), Rocky Mountain Arsenal (2004), and DPRA (1998). This design meets the CFR requirements discussed in Section 4.1.5.1. As required by the CFR, each monofill cell will have the following features:

- Run-on controls in the form of a 6-foot high berm,
- Run-off controls in the form of a 6-foot deep drainage ditch,
- A two layer bottom liner,
- A top liner once the cell is closed, and
- Groundwater monitoring wells.

Disposal Volume Excavation

The landfill is constructed such that half the waste volume is below existing grade, and the remainder is built-up in a mound above grade. The required volume of material to be excavated for each cell is based on the assumed depth and required cell area.

Run-on and Run-off Controls

Each monofill cell will be surrounded by a run-on control berm and run-off control ditch. The excavation volume is based on a 6-foot deep, trapezoidally shaped ditch with a 1-foot wide base. The berm is assumed to be 6-feet high.

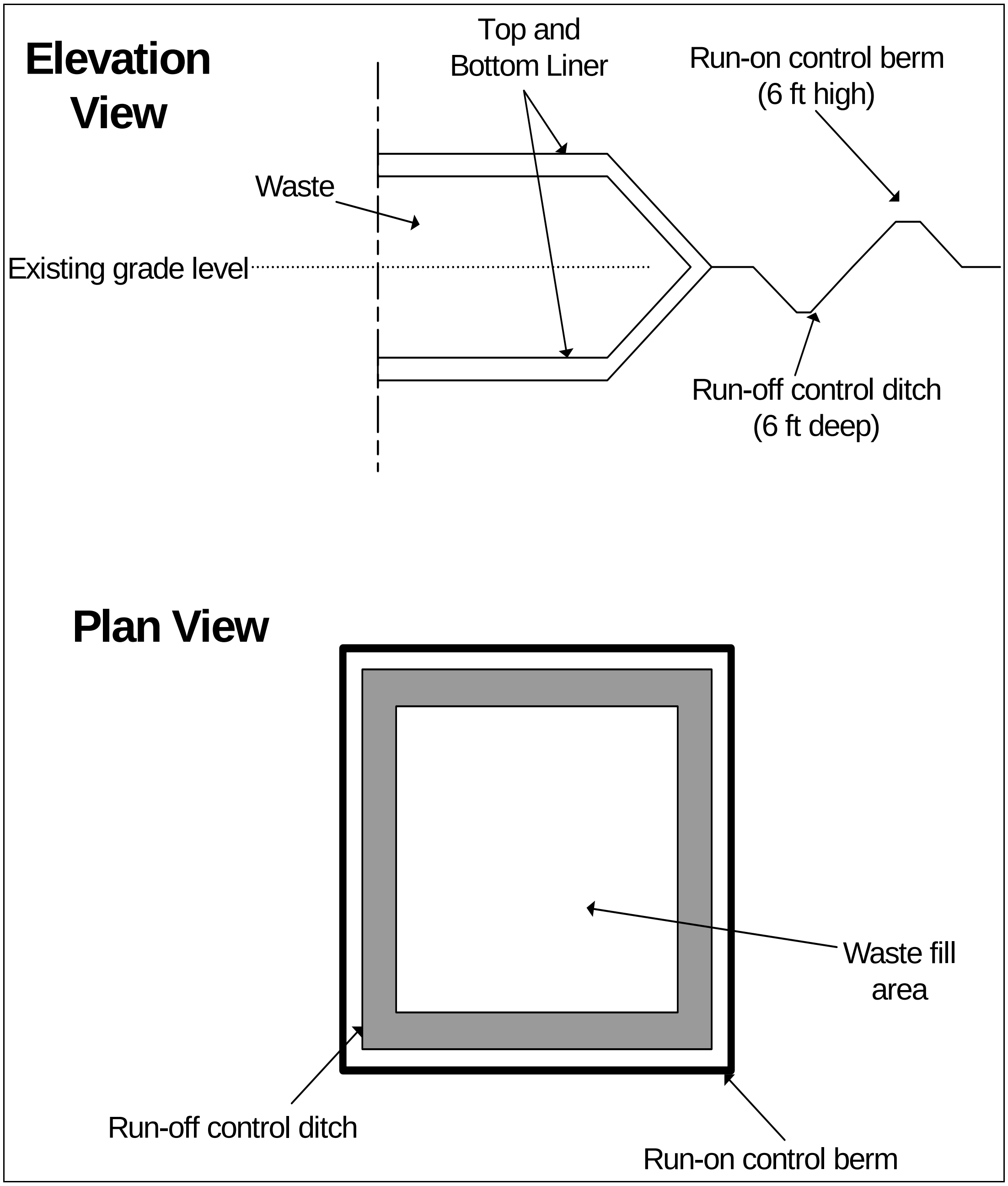


Figure 4-4. Landfill Cross-Section and Plan Design

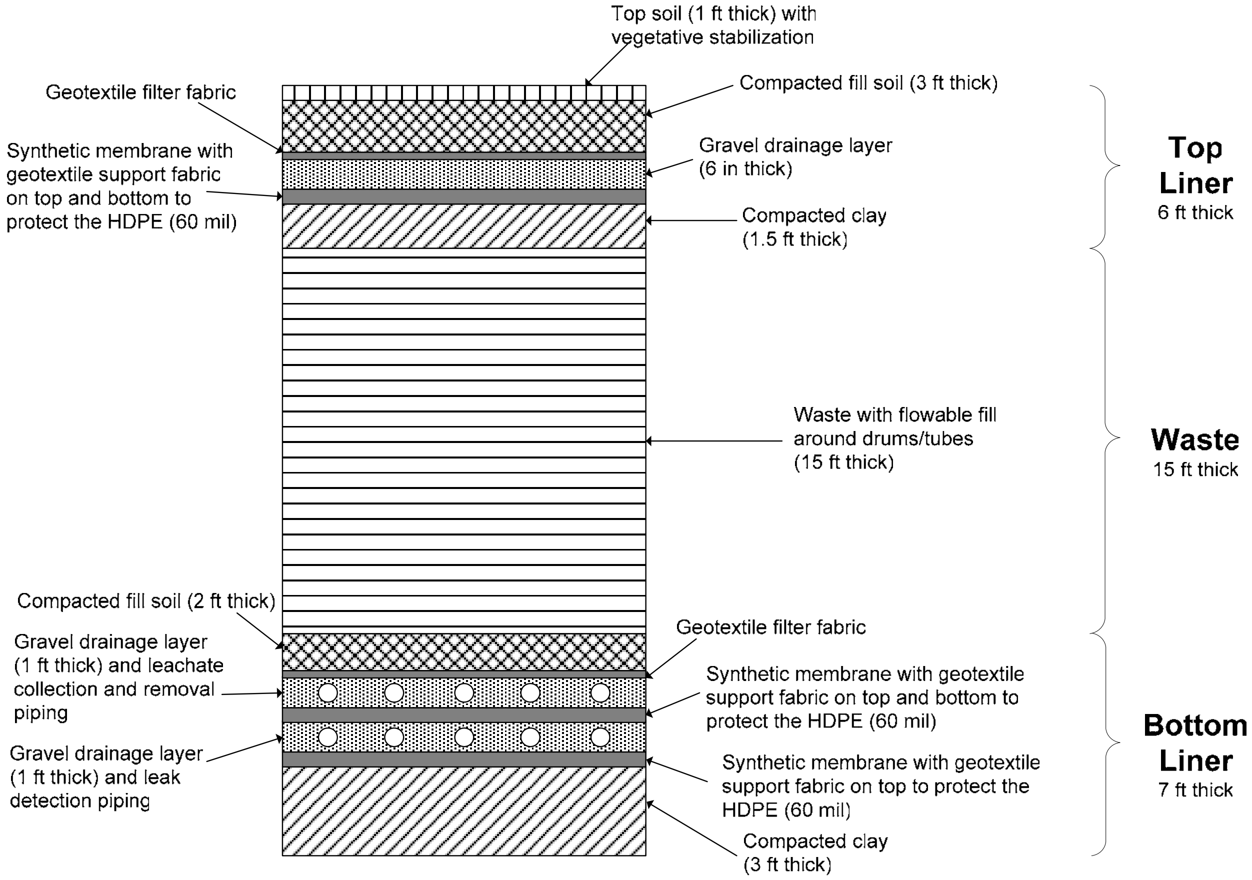


Figure 4-5. Landfill Liner Cross-Section

Waste and Fill Layer

Two feet of compacted fill soil will protect the primary bottom liner from damage during placement of the waste containers. As waste is placed in the monofill, a flowable fill will be placed around the drums or tubes. The fill will be treated to the desired pH for the waste. The waste layer will be fifteen feet thick.

It is assumed that 10% of the disposal volume will be filled with flowable fill. The flowable fill unit cost is based on the value for compacted clay.

Top Liner

Once the waste layer is full, a cover will be placed to close the cell. This top cover will consist of a composite liner with 1.5 feet of compacted clay and a HDPE membrane. Geotextile support fabric will sandwich the HDPE to protect it. A gravel drainage layer will promote drainage of rain away from the sealed fill cell. Geotextile filter fabric will prevent fill soil from clogging the drainage layer. Top soil will be placed above compacted fill soil that will protect the top cover. Vegetation will be planted to prevent erosion of the top soil and fill soil.

Groundwater Monitoring Wells

Each fill cell will have four groundwater monitoring clusters (one upgradient cluster and three downgradient based on the design in DPRA (1998). Each cluster consists of three wells.

Construction Quality Assurance

For the cost estimate, the CQA Program will add to construction expenses. This additional cost is meant to cover all observations, tests, measurements, and inspections required during construction to assure quality.

Special Requirements for Containers

All three treatment processes considered in this estimate will fill containers at least 90% full, so the CFR requirement will be met.

Waste Analysis

It is assumed that the operator of the landfill will be able to inspect markings on the outside of the drums or tubes to verify the contents of the containers. Quantities of these barrels or tubes will easily be checked by the logistics personnel when shipments of waste arrive. The chemical analysis of the waste that occurs at the treatment facility will serve as the analysis for the landfill also.

Equipment

Since the monofill is located at an operating landfill site, all equipment necessary for handling waste and fill is assumed to be available. This equipment may include cranes, front end loaders, and flowable fill equipment. No costs are charged to the monofill to purchase, operate, or maintain this equipment.

Security and Personnel Training

It is assumed that the landfill will be constructed at a site that already has a security system, so this cost will not be included in the estimate. It is also assumed that the personnel who work the new landfill will already have hazardous waste training.

Staffing

Since the monofill will be located at a site that already has landfills, the staff available at the site will be utilized for monofill operations (during filling). The charges for landfill site staff time will depend on the volume of waste delivered from the treatment process and the frequency that waste is shipped to the monofill. The staff that will be utilized is assumed to consist of:

- Four Operators,
- One Maintenance Technician,

- One Logistics and Shipping Clerk,
- One Operations Supervisor,
- One Administrative Assistant,
- One Plant Manager,
- One QA/Health/Safety Coordinator.

Monitoring and Inspection

During construction, the liners will be inspected as part of the CQA Program. The run-off, run-on, LCRS, and LDS will be inspected weekly during operations (filling). The cost of these inspections is included in the charges for the QA, Health, and Safety Coordinator.

Leachate Treatment

While in operation (filling), the LCRS will collect rain water that falls in the open cell. It is assumed that this leachate will not require treatment.

Utilities

Utilities are assumed to be an annual cost for each cell during filling operations. Once cells are closed, the utilities are assumed to be negligible.

Post-Closure Care

The post-closure care period will be 30 years following closure of each landfill cell.

It is assumed that the LCRS will require monthly inspections for five years following closure. Five years after cell closure, it is assumed that no more leachate will appear and that inspections are not required. Each inspection is assumed to require a day of an operator's time.

The LDS is assumed to require monthly inspections until 5 years after closure, then semi-annual inspections for the remainder of the 30-year post-closure care period. Each inspection is assumed to require a day of an operator's time.

It is assumed that ground water samples will be required monthly from each well while cells are being filled, and then semi-annually for the 30-year post-closure care period.

Permits and Bonding

Permits are assumed to be an annual cost for the entire operation and post-closure period for each landfill cell.

Bonding is assumed to be an annual cost for the entire operation and post-closure period for each landfill cell.

Assumptions on Failures, Leakage Rates, and Corrective Actions

Since the costs for catastrophic failures and corrective actions are difficult to estimate and could be high, the following assumptions will be made:

- It is assumed that no problems will be found during operation (filling) that require repairs or remediation.
- Leakage rates are assumed to remain below "actionable levels", so that repair and remediation is not required during the life of the monofill.
- It is assumed that no ground water problems occur that require repair of the monofill.
- It is assumed that no catastrophic failure of the containment system occurs that requires emergency repair.

4.2.3 Monofill Costs

Tables showing the build up of the cost estimates are provided in Appendices E, F, and G for monofills that take treated mercury from the Option A, Option B, and Option C processes, respectively. Each of the Appendices contain the following:

- A table of monofill dimensions
- A table of labor and materials costs during construction
- A table of O&M costs during filling
- A table of post-closure O&M costs

Engineering

Engineering costs are estimated as being 10% of the Construction costs (DPRA 1998).

Construction

Construction costs are the sum of Labor and Materials, Inspection and Testing, Quality Assurance, Other Field Expenses, Fee, and Contingency. Inspection and Testing, Quality Assurance, and Other Field Expenses are estimated as percentages of the labor and material costs. The Fee and Contingency are estimated as percentages of the sum of all other Construction costs. The factors, taken from DPRA (1998), are shown in Table 4-15.

Table 4-15. Factors Used to Estimate Monofill Construction Costs

Cost Element	Factor Used in Cost Estimate
Inspection and Testing	0.05
Quality Assurance	0.15
Other Field Expenses	0.05
Fee	0.15
Contingency	0.10

Operating and Maintenance During Filling

Operations and Maintenance costs during filling are assumed to be made up of the following categories: Permits, Bonding Insurance, Direct O&M Costs, and Contingency. Permits cost $10,000 per year (DPRA 1998). Bonding Insurance is assumed to cost $10,000 per year. Direct O&M Costs are calculated in a separate table; the subtotal is given in the Summary table. Per DPRA (1998) Contingency is 10% of the other O&M costs.

An annual total is given for O&M during filling. The subtotal for O&M during filling sums the annual total for the number of years treated mercury is sent to the monofill: 5 years for 5,000 tons, 12 years for 12,000 tons, and 25 years for 25,000 tons.

Operating and Maintenance Post-Closure

Operating and Maintenance costs for the 30 years after each monofill cell is closed are given in Appendices E, F, and G. Details of the estimate are given in the O&M (post-closure) table. The O&M (post-closure) table gives the costs for one cell. Consequently, the summary table results for scenarios that require more than one cell are multiples of the O&M (post-closure) table total.

Miscellaneous

The size of the monofill cell is a key parameter for estimation of labor and materials costs. The Dimension tables in Appendices E, F, and G give the size of a five year monofill cell for each treatment process. The size of the cell is set by the number of barrels of treated mercury the five year cell must accept. Dimensions are calculated for disposal of treated mercury in barrels and in Arrow-Pak tubes.

The monofill is assumed to be shaped as shown in Figure 4-4, with a square or rectangular plan. The cross-sections at the edges of the cells have 45-degree slopes. Volumes and areas for cost estimation are approximated using these shapes and the lengths of the cell sides.

The cost estimates for labor and materials are based on the size of the five year cell and the unit costs for the materials and construction activities. All unit costs are installed costs based on DPRA 1998. Since this reference has 1998 prices, the costs have been escalated 12%[20] to account for inflation between 1998 and 2004 (USDOL 2004).

Direct Operating and Maintenance costs during filling are calculated in the Direct O&M (filling) tables in Appendices E,F, and G. The total from this table is used in the Summary table. The direct costs are composed of the following: salary for staff, costs for groundwater monitoring tests, utilities, and the fee. Salary for staff is based on an estimate of the time required to accept shipments of treated mercury. The number of shipments is calculated based on the amount of waste produced per year, the weight each truck can transport, and the amount of room available on each truck. The number of shipments is calculated for treated mercury in barrels and for waste macroencapsulated in Arrow-Pak tubes. Annual utilization of the staff is calculated as the ratio of shipments to shifts the staff works (based on a five-day work week). The burdened salary for staff is taken from Salary.com.

The cost for groundwater monitoring tests is based on costs given in DPRA (1998). The costs have been inflated 12% to account for inflation between 1998 and 2004 (USDOL 2004).

Utilities are assumed to cost $10,000 per year while the monofill is in operation (being filled).

The fee is 15% of the sum of the other operating and maintenance costs.

The O&M (post-closure) sheets in Appendices E, F, and G gives the total costs for operating and maintenance for a 30-year post-closure period. These costs are made up of the following parts: LCRS monitoring, LDS monitoring, ground water sample analysis, utilities, contingency, license and bonding costs, and the fee.

LCRS and LDS monitoring costs are a function of the time spent monitoring the systems per year and the costs for operators' time to perform the monitoring. Each inspection is assumed to take one day of an operator's time. The cost for a day of an operator's time is estimated as a function of the burdened salary for the operator.

The cost for groundwater monitoring tests is based on costs given by DPRA (1998). The costs have been inflated 12% to account for inflation between 1998 and 2004 (USDOL 2004).

Utilities are assumed to cost $1,000 per year after the monofill cell is closed. License and bonding fees are assumed to cost $10,000 per year after the monofill cell is closed.

The fee is 15% of the sum of the post-closure operating and maintenance costs. Contingency is calculated as 10% of the post-closure operating and maintenance costs plus fee.

4.3 Storage

This section first lays out assumptions for calculating the costs of the long-term storage alternative, and then describes assumptions for the costs associated with the treatment alternatives. The basic input data are derived from Appendix D of the MMEIS (DLA 2004). For example, the MMEIS estimates the annual cost of storing 2,617 MT of elemental mercury at the Somerville Depot to be $404,495. This is made up of two parts, utility costs of $4,945 and rental of $400,000, based on 43,200 ft^2 at an annual rent of $1.76/$ft^2$. Routine maintenance of the warehouse is assumed to be included in the rent. Other labor, such as walking down the stockpile and taking occasional mercury vapor concentration measurements, is assumed to be negligible. Thus, the cost of storage of 1 MT at Somerville for 1 year is $404,495/2617 = $154. The average cost of storage at all DLA facilities (except the Y-12 facility) is $147/MT/yr. In the calculations reported below, the cost of storage is simply calculated by multiplying the amount of elemental mercury in storage in a particular year by $147, discounting to obtain NPV, and summing over all years of storage.

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[20] Using Producer Price Index average for 1998 versus the average through August 2004.

4.3.1 Long-Term Storage

This subsection describes the bases and assumptions for long-term storage of elemental mercury for the three mass alternatives.

Alternative 1 – 5,000 MT

Alternative 1 is quite close to the status quo at DNSC locations. Therefore, Alternative 1 is costed as if storage will continue there for 35 years. On a non-discounted basis, 5,000 MT would therefore cost 5,000x147 = $735,000/year.

Alternative 2 – 12,000 MT

For this alternative, it is assumed, as for Alternative 1, that there is 5,000 MT of elemental mercury in existing storage. The remaining 7,000 MT becomes available at a uniform rate over a period of 12 years, i.e., at a rate of 583 MT/yr[21]. For the storage alternative, therefore, the amount in the stockpile will increase by this amount each year, and additional (non-discounted costs) accrue at a rate of 583×147 = $85,700/yr. This is in addition to the costs incurred for storing the original 5,000 MT.

Alternative 3 – 25,000 MT

For this alternative, it is assumed, as for Alternative 1, that there is 5,000 MT of elemental mercury in existing storage. The remaining 20,000 MT becomes available at a uniform rate over a period of 25 years, i.e., at a rate of 800 MT/yr. For the storage alternative, therefore, the amount in the stockpile will increase by this amount each year, and additional costs will accrue at a non-discounted rate of 800×147 = $117,600/yr.

4.3.2 Storage Costs Associated with Treatment and Disposal Alternatives

The need for storage will not vanish immediately even if the waste is treated.

Alternative 1 – 5,000 MT

For the centralized treatment location, it is assumed that elemental mercury will be transported from the current storage locations to the treatment facility at a rate of 1,000 MT per year for five years. Each 1,000 MT occupies 45,000 ft^2 (~ 4,200 m^2). It is assumed that storage space will be decommissioned at a rate of 45,000 ft^2 (4,200 m^2) per year, and that storage costs will decrease by 1,000x147 = $147,000/yr until all the mercury has been treated. The same rate of depletion of the existing stockpile is assumed for the mobile treatment alternative.

Alternative 2 – 12,000 MT

When the mercury is treated at a centralized facility, it is assumed that the 583 MT/yr of "new" elemental mercury is transported directly to the treatment facility, thus obviating the need for intermediate storage. The remaining 417 MT/yr required to make up the assumed treatment rate of 1,000 MT/yr is drawn down from storage. Each year, therefore, the non-discounted costs of storing elemental mercury decrease by 417x147 = $61,300/yr for 12 years. The same rate of depletion of the existing stockpile is assumed for the mobile treatment alternative.

Alternative 3 – 25,000 MT

When the mercury is treated at a centralized facility, it is assumed that the 800 MT/yr is transported directly to the treatment facility, thus obviating the need for intermediate storage. The remaining

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[21] Note that the assumption that there is about 5,000 MT in existing storage and that additional elemental mercury becomes available at a rate of a few hundred MT per year is consistent with data in Appendix D of the MMEIS.

200 MT/yr required to make up the assumed treatment rate of 1,000 MT/yr is drawn down from storage. Each year, therefore, the non-discounted costs of storing elemental mercury decrease by 200x147 = $29,400 for 25 years. The same rate of depletion of the existing stockpile is assumed for the mobile treatment alternative.

4.4 Transportation

This section describes the assumptions and bases for transportation costs associated with the various treatment and storage alternatives.

4.4.1 Centralized Treatment

In the case of centralized treatment, in all scenarios elemental mercury needs to be transported to the centralized facility at a rate of 1,000 MT per year. As noted above, it is assumed that elemental mercury will be transported in drums (six 76 lb (34 kg) flasks to a drum) with five drums to a pallet. Each pallet carries almost exactly 1 MT of elemental Hg: therefore 1,000 pallets will be transported each year. If the material is transported by road, each truck can carry up to 14 pallets or 14 MT (DLA 2004), so that there will be 71.4 truckloads per year. If the material is transported by rail, each railcar can carry up to 28 pallets or 28 MT (DLA 2004), so there will be ~ 36 railcar shipments per year. For the purposes of the current analysis, only full trucks or railcars will be considered. In practice, the exact number of pallets per truck or railcar is not critical because the authors used the MMEIS (DLA 2004) to calculate a cost per ton-mile of elemental mercury transport. These costs lie in the range $0.025-$0.038/MT-mile for rail and $0.039- 0.064/MT-mile for road. In addition to the cost per ton-mile, there is a preparation cost per ton that covers such items as overpacking, amounting to ~ $96/MT for truck transportation and ~ $111/MT for rail transportation.

The required transportation distances are not known because the location of the treatment facility has not yet been identified. To gain insight into the magnitude of mercury transport costs, three “proxy” and three existing storage depot locations were incorporated as candidate treatment facility locations. Transit distances were then calculated to the candidate treatment sites and unit transport costs derived from the MMEIS (DLA 2004) were applied to arrive at total transport costs. The six candidate site locations were chosen to provide a range of potential transport distances of 150 to 2,800 miles for “legacy” mercury stocks. Another basic assumption is be that the average transportation distance for “new” mercury is 1,000 miles and uncertainty will be accommodated by assuming that the range is 500 to 1,500 miles.

Examples of how transportation costs are calculated for the centralized treatment alternatives follow:

5,000 MT

For the 5,000 MT case the elemental mercury is all “legacy” mercury and therefore travels 150 to 2800 miles. The minimum non-discounted cost per year is to move 1,000 MT 150 miles by rail at a cost of $0.025 per MT-mile plus $111/MT preparation costs = 1,000x150x0.025+1,000x111 = $114,750/yr. The maximum cost is to move 1,000 MT 2,800 miles by truck at a cost of $0.064 per MT-mile and an initial preparation cost of $96/MT = 1,000x2,800x0.064 + 1,000x96 = $275,200/yr.

12,000 MT

For the 12,000 MT alternative, there is a need to transport 417 MT of “legacy” mercury and 583 MT of “new” mercury/year. The non-discounted annual costs for the legacy mercury are obtained by scaling the results from the previous paragraph by 0.417 to give a range from $47,900 to $114,800/yr. The minimum cost of transporting the “new” mercury is to move it 500 miles by rail at $0.025/MT-mile with $111/MT preparation costs = 500x0.025x583 + 111x583 = $72,700/yr. The maximum cost is to move the “new” mercury 1,500 miles by truck at a cost of 0.064/MT-mile and a preparation cost of $96/MT =

1,500x0.064x583 + 96x583 = $111,900/yr. Combining the estimates for “legacy” and “new” mercury gives a range of $120,600 to $226,700/yr.

For the centralized treatment alternatives, it is assumed that the monofill is collocated with the treatment facility and that transportation costs for the final waste form are negligible.

4.4.2 Mobile Treatment

In the case of mobile treatment, the treatment facility travels to the mercury, so no elemental mercury is transported. Instead, the treated waste (macro-encapsulated or not) is transported to a centralized monofill. If it is not macro-encapsulated, it is assumed that the waste is in 55-gallon drums for the Option A and Option B processes and 22 gallon drums for the Option C process. If it is macro-encapsulated, 55-gallon or 22-gallon drums are placed in sealed polyethylene tubes. The location of the monofill is not specifically known, so as in the centralized treatment scenarios, three “proxy” and three existing storage depot locations were incorporated as candidate monofill locations. Transit distances were then calculated to the candidate monofill sites and unit transport costs derived from the MMEIS (DLA 2004) were applied to arrive at total transport costs. The six candidate site locations were chosen to provide a range of potential transport distances of 150 to 2,800 miles for “legacy” mercury stocks. Again, it is assumed that the average distance to the monofill for waste forms generated from “new” mercury is 1,000 miles, with a range extending from 500 to 1,500 miles. The costs per MT-mile for treated waste are assumed to be the same as those for elemental mercury, so that transportation costs for mobile treatment can be simply scaled from those for centralized treatment. Thus, for example, for Option A, 3 MT of waste are generated for every MT of elemental mercury so, taking the 5,000 MT results from Section 4.4.1 and multiplying by 3 gives a non-discounted cost range from $344,000 to $825,600/yr

4.4.3 Long-Term Storage – Transportation of Elemental Mercury

For the 5,000 MT alternative, it is assumed that there is already 5,000 MT of elemental mercury in storage, so that no further transportation costs are incurred. For the 12,000 MT alternative, 583 MT of “new” elemental mercury is transported to a centralized storage facility each year for 12 years. For the 25,000 MT alternative, 800 MT of “new” elemental mercury is transported to a centralized storage facility each year. As above, the total transportation distance varies from 500 to 1,500 miles. For example, the range of costs for the 12,000 MT alternative (583 MT of “new” mercury per year) has already been calculated in Section 4.4.1 and is from $72,700 /yr to $111,900/yr.

4.4.4 Miscellaneous

There are a number of items that need to be delivered to the various sites and in principle their transportation costs should be calculated:

- Mercury flasks and 30-gallon drums for overpacks
- 22-gallon and 55-gallon drums to contain waste
- Reagents

In practice, the costs of these items are quoted as delivered to the site, so there is no need for explicit calculation of transportation costs.

4.5 Uncertainties

This section contains a simplified assessment of uncertainties in the costs associated with each of the 39 alternatives. The overall costs are broken down into the following categories:

As noted at the beginning of Chapter 4, each of the thirty-six cost estimates for treatment and disposal includes the following elements:

- Capital costs for the treatment facility,
- Capital costs for the macroencapsulation facility (if part of the alternative)
- Operating and maintenance costs for the treatment process,
- Operating and maintenance costs for the macroencapsulation process (if part of the alternative),
- Costs associated with the mobile treatment alternative,
- Transportation costs associated with each alternative,
- Costs of storing elemental mercury prior to treatment
- Decommissioning costs for the treatment facilities,
- Monofill engineering and construction costs,
- Monofill operating costs, and
- Costs of maintaining and monitoring the monofill for a thirty-year period following its closure.

Each of the three storage alternatives contains the costs of maintaining the existing stockpile (assumed to be 5,000 MT) in storage, adding to storage space for the 12,000 MT and 25,000 MT cases, and transporting elemental mercury to the storage facility(ies).

Initially, it was hoped that the uncertainties in each of these elements could be built up from uncertainties in the costs of individual components or activities. This did prove possible for the capital costs for fixed treatment and fixed macroencapsulation facilities. However, with the information that the team was able to collect within the budget available for this project, this did not prove possible for the remaining elements. Therefore, the authors adopted some simplifications, as will become clear after first considering some relevant background information.

4.5.1 Background Information on Uncertainties in Capital Costs and Life Cycle Cost Estimates

This section provides information on construction cost uncertainties from a commercial source and on life cycle cost estimate uncertainties from EPA.

4.5.1.1 Construction Projects/Capital Costs

Broadly speaking, there are five types of cost estimate for construction projects (Industrial Cost Engineering 2003)

- Conceptual or order of magnitude
- Factored
- Study or preliminary
- Basis of budget
- Detailed or Firm Price Construction

Conceptual: A minimum of information is used to develop this type of "Ball Park Estimate." The estimate is prepared from in house data available from past jobs on similar plants. A cost estimate determined this way is only valid for a similar plant. This estimate has a probable accuracy of -50% to +50% or worse.

A **factored estimate** requires that all process equipment must be priced. A factored estimate is produced by taking the cost of individual types of process equipment, and multiplying it by an "installation factor" to arrive at the Total Direct Process Cost. The accuracy of this type of estimate depends upon the definition of scope, equipment costs, and known process factors. This type of estimate has a probable accuracy of -25% to +30%.

A **study or preliminary estimate** is prepared after the process engineers have completed the conceptual design, made the equipment list by size and category, made preliminary process flow diagrams, and when engineering is from 1% to 10% complete. The following documents serve as the basis for this type of estimate:

- Reasonably defined equipment list by size and category, including onsite and offsite equipment.
- Preliminary overall plot-plans.
- Know general site conditions such as location, utility requirements, site survey, utility distribution (sewers, power feeders, etc.) labor productivity availability of skilled workmen, and availability of construction materials.
- Overall process flow diagrams.

The probable accuracy of this type of estimate is -15% to +20%.

A **basis of budget estimate** is prepared after the process engineers have completed the conceptual design, made an equipment list by size and category, made process flow diagrams, and the detail engineering is from 25% to 50% complete. The probable accuracy of this type of estimate is -10% to +15%.

In a **detailed estimate** each item is costed in a thorough manner without "eyeballing", "percentaging", or other forms of educated guesses. This estimate is prepared after the process design has been completed and when the detail design is 70% - 90% complete. The probable accuracy of this type of estimate is -5% to +10%.

4.5.1.2 EPA Guidance on Uncertainty in Life Cycle Cost Estimates

EPA has produced some guidance for Life Cycle Cost Estimates for Superfund remediation activities (USEPA 2000) – see Figure 4-6. This displays a similar pattern of declining uncertainty as the design becomes more complete and the project moves into construction and then O&M.

4.5.2 Uncertainties in Costs of Elements of the Long-Term Disposal of Elemental Mercury

Various parts of the cost estimate for the 39 alternatives for long-term disposal of mercury are at different stages with respect to the level of cost uncertainty.

Capital Costs for the Fixed Treatment Facilities: per the information above from the Industrial Cost Engineering Web site, it would appear that a study or preliminary estimate is feasible because overall process flow diagrams are available as is a reasonably defined equipment list. General site conditions may not be known, but it is assumed that the facility will be constructed at an existing site and that adequate utilities, labor and materials will be available. In addition, these facilities are quite simple and it is not expected that there will be very large cost over or underestimates. Therefore, a probable accuracy in the range –15% to + 20% is expected.

Capital Costs for Fixed Macroencapsulation Facilities: It is also expected that a study or preliminary estimate is possible for these facilities so that a predicted range of –15% to +20% is reasonably in accord with expectations.

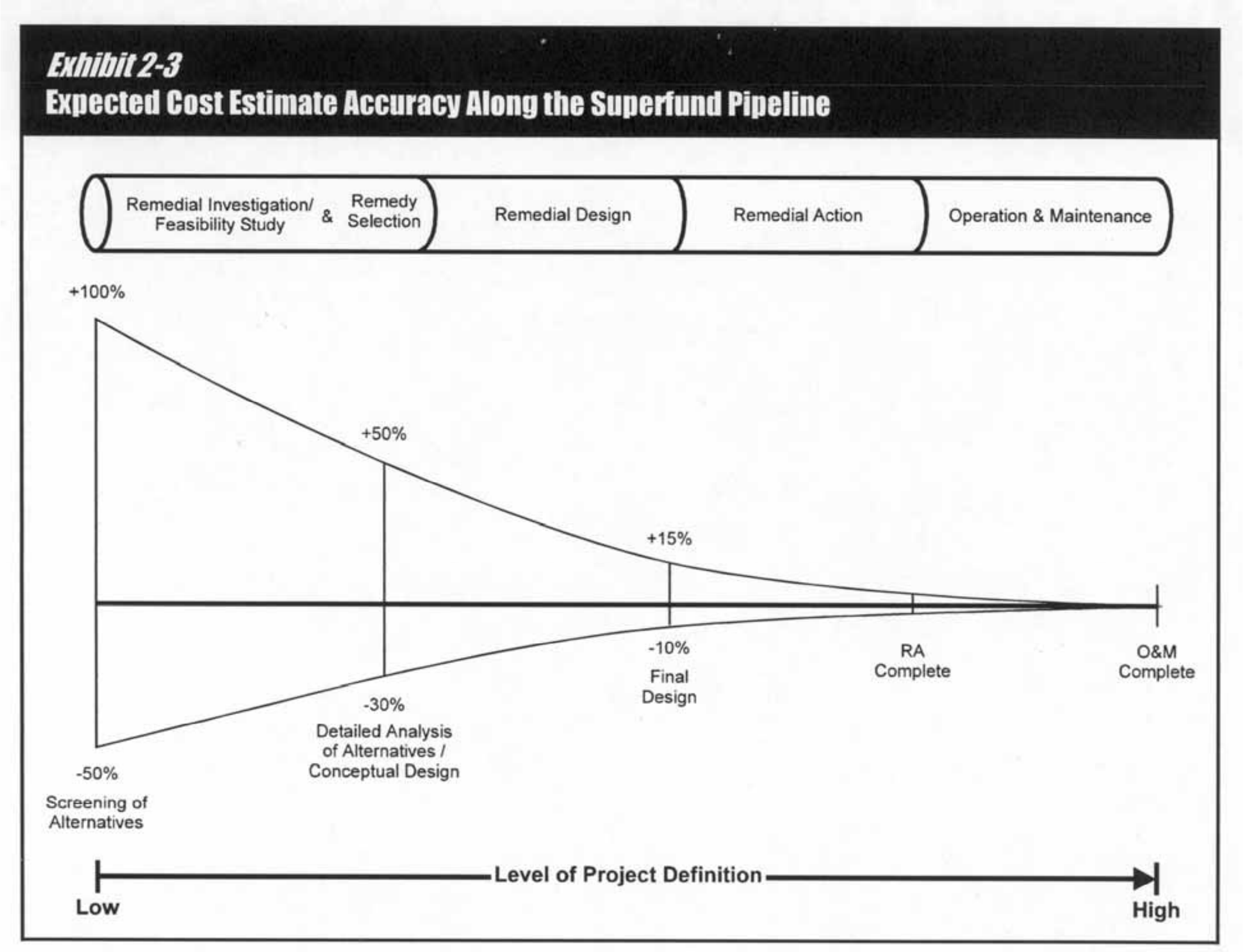

Figure 4-6. Expected Cost Accuracy Along the Superfund Pipeline: Exhibit 2-3 from EPA (2000)

Capital Costs for Mobile Treatment Facilities: this is an area of greater uncertainty. The cost of a single mobile unit can be confidently estimated to within –15 to +20%, as for the fixed case, but what is unknown is whether there would be a single large unit, two half-size units, or several smaller ones. The actual cost estimates in Appendices C and D are for one large facility. One could easily envisage the construction costs doubling or tripling if several smaller units were constructed. Therefore, the cost range is taken to be –15% to +200%.

Capital Costs for Mobile Encapsulation Facilities: these suffer from the same uncertainties as do the costs for the mobile treatment facilities and a similar range is assumed, -15% to +200%.

O&M Costs for Fixed Treatment and Macroencapsulation Facilities: referring to Figure 4-2 above, the fixed treatment and macroencapsulation facilities are beyond the conceptual design phase but clearly not at the final design phase. Interpolating between these two points on Figure 4-2 suggests that a range in these cost between – 15% and + 20% is reasonable.

O&M Costs for Mobile Treatment and Macroencapsulation Facilities: this alternative is really still at the pre-conceptual phase and per Figure 4-2. the range of uncertainty in costs is –50% to + 100%.

Decontamination Costs for the Treatment and Macroencapsulation Facilities: 50% of capital costs with same percentage uncertainty range.

Construction and O&M Costs for the Monofill: monofills are relatively well understood. Referring again to Figure 4-2, the monofill is between conceptual and final design so here again a range of cost uncertainty between –15% and + 20% is reasonable for the total Life Cycle Cost Estimate for the monofill.

Transportation Costs: the largest uncertainty in transportation costs is not knowing how far the mercury or the waste product will be transported. Other transportation costs are well documented in the Mercury Management Environmental Impact Statement (DLA 2004). Transportation cost estimates and uncertainty ranges are discussed in Section 4.4

Storage Costs: storage of elemental mercury has been studied in considerable detail in the MMEIS and is well known. Uncertainties should be small. The authors assigned a small range from –10% to +10%.

4.5.3 Calculation of Uncertainties

In summary, the input cost ranges for the uncertainty analysis are as follows:

- Capital costs for the fixed treatment facility and the fixed macroencapsulation facility: bottom-up calculation (see Appendices C, D, and E) – approximately –15% to + 20%
- Capital costs for the mobile treatment facility and the mobile macroencapsulation treatment facility: -15% to + 200%
- Operating and maintenance costs for the fixed treatment process and the fixed macroencapsulation process: -15% to + 20%
- Operating and maintenance costs for the mobile treatment facility and the mobile macroencapsulation facility: -50% to + 100%
- Transportation costs associated with each alternative: see Section 4.4
- Costs of storing elemental mercury prior to treatment (or for the storage alternative): -10% to + 10%
- Decommissioning costs for the treatment and macroencapsulation facilities: 50% of capital costs with same percentage uncertainty range
- Monofill Life Cycle Cost Estimate: -15% to + 20%.

These costs were assigned triangular probability distributions and were input into the Crystal Ball® computer model for Monte Carlo simulation (Decisioneering 2004), leading to estimates of uncertainty on the total costs of each alternative.

4.6 Results and Interpretation

The results of the economic analysis are summarized in Tables 4-16 and 4-17. Note that the "best" estimates are the means that result from the Monte Carlo analysis and are not necessarily exactly the same as would result from a sum of point estimates without uncertainty distributions. Tables 4-16 and 4-17 prompt a number of observations and conclusions.

Importance of Costs of Reagents

The most striking result is that the Option C alternatives cost far more than do the others. Analysis of the calculations reveals that there is one parameter that drives almost the whole of this difference – the cost of reagents. For Option C, the NPV of reagent costs alone over five years is approximately $123M. By contrast, the five-year NPV of reagents for the Option A process are approximately $8M over 5 years. For the Option B process, NPV of reagent costs over 5 years is approximately $1.4 M. Therefore, for the alternatives that treat 5,000MT, the reagent costs alone account for more than $100M difference between the costs of Option C process and those of the Option A or Option B processes, with correspondingly larger differences for the 12,000 MT and 25,000 MT alternatives.

The composition of the Option C reagents is proprietary. In any future decisionmaking process, the cost per kg of treated Hg will need to be examined in more detail.

Option B – Lowest Cost

The Option B process consistently exhibits the lowest costs. As noted above, it has the lowest reagent cost. In addition, it has the least mass increase of the three technologies – the mass multipliers for waste form production are 1.63 (Option B), 3.26 (Option A), and 5.66 (Option C). This affects other items such as transportation costs.

Mobile Treatment More Costly and More Uncertain

The best estimates for the NPV of alternatives that include mobile treatment are somewhat higher than those for alternatives that include treatment at fixed facilities. In addition, the uncertainty ranges are much wider. Both of these principally result from the wide uncertainty bands on mobile treatment alternatives: -15% to +200% for capital costs and –50% to + 100% for O&M costs. There are also extra costs associated with assembling and disassembling the equipment and moving it from site to site.

Narrow Range of Uncertainties for Fixed Facility Alternatives

In Table 4-16, the range of NPV numbers for fixed-facility alternatives appears to be quite narrow, -10% to +10% or even less. The reader may fairly ask whether these ranges are too small.

To a certain extent, these narrow ranges are an artifact of the Monte Carlo analysis. The input ranges of uncertainties are discussed in Section 4.5 and summarized in Section 4.5.3. There, the ranges chosen for most of the inputs to the Crystal Ball® uncertainty analysis of fixed facility alternatives are in the range –15% to +20%. It is a feature of Monte Carlo analyses that, at a given percentile level (e,g., 95th), the 95th percentile of a sum is less than the sum of the 95th percentiles of the inputs. The more a sum is broken down into its components, the more its 5th to 95th range of confidence is narrowed. Hence we see in Table 4-16 (again excluding the mobile treatment cases) the predicted percentage range has been narrowed to less than the input ranges of from –15% to + 20%.

One possible way of dealing with this would be to default to Figure 4-6. The project as a whole lies somewhere between the "Detailed Analysis of Alternatives/ Conceptual Design" and the "Final Design" which means that the uncertainty range could be as much as –30% to +50%, or as little as –10% to + 15%. The reader can then make a subjective choice as to exactly where in this range of ranges the project actually lies. Similarly, the reader might conclude that the authors have overestimated the maturity of the input items summarized in Section 4.5.3 and that the input ranges of uncertainties should be larger. In summary, there is a great deal of subjectivity in the uncertainty analysis and the reader is entitled to use his or her own judgment to conclude that the ranges might well be larger.

Modest Long-Term Storage Costs

The cost of storage is relatively modest. Note that these storage costs were derived from data in the MMEIS. For example, for continued storage of 5,000 MT for up to 35 years, the NPV is $11.6M. Continuing to store elemental mercury for years or even decades is a reasonable course of action.

It is pertinent to reiterate that, as far as possible, the long-term storage and disposal alternatives are treated on a comparable basis. All of the alternatives have storage requirements and these have been consistently costed by taking data on storage from the MMEIS. Transportation costs have also been treated consistently with data taken from the MMEIS. The periods of time considered are also consistent. For example, the treatment and disposal alternatives include the time taken to fill the monofill and thirty subsequent years of monitoring. Thus, for the 5,000 MT alternatives, costs for treatment and disposal are taken out to 35 years (5 years to fill the monofill and 30 years of monitoring). The costs for long-term storage of 5,000 MT of elemental mercury are also taken out to 35 years. For all alternatives, the NPV is calculated using the same discount rate, as provided by OMB.

Table 4-16. Net Present Value Estimates

Treatment Scenario			Net Present Value Estimates in Millions of Dollars								
			5,000 Metric Tons			12,000 Metric Tons			25,000 Metric Tons		
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Min.**[a]	**Best**[b]	**Max.**[c]	**Min.**[a]	**Best**[b]	**Max.**[c]	**Min.**[a]	**Best**[b]	**Max.**[c]
Option A	With	Fixed	77.1	82.7	89.0	149	161	174	245	265	287
Option A	With	Mobile	75.8	99.2	128	143	191	251	232	315	415
Option A	Without	Fixed	60.2	65.4	71.3	117	128	141	184	203	224
Option A	Without	Mobile	57.7	79.8	107	105	150	207	169	242	341
Option B	With	Fixed	32.3	34.3	36.4	62.2	66.2	70.6	102	109	116
Option B	With	Mobile	32.4	40.9	50.7	60.5	78.3	97.5	98.4	127	160
Option B	Without	Fixed	22.7	24.3	26.2	42.8	46.1	49.9	69.6	75.2	81.8
Option B	Without	Mobile	22.3	29.3	38.0	40.9	54.2	71.7	65.1	87.5	118
Option C	With	Fixed	162	178	197	342	378	418	579	639	707
Option C	With	Mobile	138	203	292	290	429	617	490	732	1,040
Option C	Without	Fixed	146	163	181	306	341	381	517	578	647
Option C	Without	Mobile	119	184	270	247	386	573	421	656	967
Long-Term Storage[d,e]			10.4	11.6	12.8	26.1	29.0	31.9	51.3	57.0	62.7

a. Fifth percentile of the distribution derived from the Crystal Ball® analysis

b. Mean of the distribution derived from the Crystal Ball® analysis

c. Ninety fifth percentile of the distribution derived from the Crystal Ball® analysis

d. Not derived from Crystal Ball® analysis – best estimate based on MMEIS data (DLA 2004) with ±10% uncertainties

e. Cost of shipping elemental mercury to the storage location not included. Upper bound transportation costs derived from MMEIS data are $0 (5,000 MT), $1.0M (12,000 MT), and $2.3M (25,000 MT). These are at most small percentages of the total cost of long-term storage.

Table 4-17. Net Present Value Estimates Expressed as Cost per Metric Ton of Treated Mercury

Treatment Scenario			Net Present Value Estimates in Dollars								
			5,000 Metric Tons			12,000 Metric Tons			25,000 Metric Tons		
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Min.**	**Best**	**Max.**	**Min.**	**Best**	**Max.**	**Min.**	**Best**	**Max.**
Option A	With	Fixed	15,400	16,600	17,800	12,400	13,400	14,500	9,800	10,600	11,500
Option A	With	Mobile	15,200	19,800	25,600	11,900	15,900	20,900	9,300	12,600	16,600
Option A	Without	Fixed	12,000	13,100	14,300	9,800	10,700	11,800	7,400	8,100	9,000
Option A	Without	Mobile	11,600	16,000	21,400	8,800	12,500	17,300	6,800	9,700	13,600
Option B	With	Fixed	6,500	6,900	7,200	5,000	5,500	5,900	4,100	4,400	4,600
Option B	With	Mobile	6,500	8,200	10,100	5,100	6,500	8,100	3,900	5,100	6,400
Option B	Without	Fixed	4,500	4,900	5,200	3,600	3,800	4,200	2,800	3,000	3,300
Option B	Without	Mobile	4,500	5,900	7,600	3,400	4,500	6,000	2,600	3,500	4,700
Option C	With	Fixed	32,400	35,600	39,400	28,500	31,500	34,800	23,000	25,600	28,300
Option C	With	Mobile	27,600	40,600	58,400	24,200	35,800	51,400	19,600	29,300	41,600
Option C	Without	Fixed	29,200	32,600	36,200	25,500	28,400	31,800	20,700	23,100	25,900
Option C	Without	Mobile	23,800	36,800	54,000	20,600	32,200	47,800	16,800	26,200	38,900
Long-Term Storage			2,100	2,300	2,600	2,200	2,400	2,700	2,100	2,300	2,500

One difference between the treatment and disposal alternatives and the long-term storage alternatives is that permitting costs were only considered for the former. This is because the current stockpile of elemental mercury is not regarded as hazardous waste, and therefore hazardous waste permits are not required. For the treatment and disposal alternatives, costs accounted for non-discounted contributions of $10,000 per year for permitting (based on DPRA 1998) and an assumed $10,000 per year for Bonding Insurance. If it should become the case that storage of elemental mercury requires hazardous waste permitting and Bonding Insurance, a non-discounted amount of $20,000 per year should be added to the long-term storage costs. The additional 5-year NPV would be approximately $90,000, a small fraction of the $11.6M presented in Table 4-17.

In conclusion, all steps have been taken to develop costs for the alternatives on the same basis and for this reason it is a valid observation that long-term storage costs are modest relative to the costs of treatment and disposal.

5.0 REFERENCES

This chapter is divided into two parts. Section 5.1 provides a complete list of references. Section 5.2 lists those that were used in comparative analyses of Option Technologies A-F.

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USEPA 2002a, 2002b, 2002c, 2002d
Zhang and Bishop 2003

APPENDIX A

DESCRIPTION OF THE ANALYTIC HIERARCHY PROCESS

Table of Contents

List of Figures

APPENDIX A
DESCRIPTION OF THE ANALYTIC HIERARCHY PROCESS

A.1. Analytic Hierarchy Process (AHP) and Expert Choice®

The Analytic Hierarchy Process (AHP), developed at the Wharton School of Business by Thomas Saaty, allows decision makers to model complex problems in hierarchical structures showing the relationships between the goals, criteria (first- and second-level), and alternatives as shown in Figure A-1. Uncertainties and other influencing factors can also be included in AHP to model complex problems.

AHP is a mathematically rigorous and proven process that supports informed and independent decisions involving multiple criteria. AHP provides a formal structure that decomposes complex problems into sets of smaller, simpler ones. As the smaller problem sets are solved, the reasons for each choice are weighted and documented to determine the solution of the overall problem.

AHP reduces complex decisions to a series of pair-wise comparisons and then synthesizes the results to arrive at the best decision based on a structured decision-making process. The implementation of AHP requires decision makers to choose between first-level criteria, second-level criteria, and alternatives sequentially at each split in the hierarchy. For example in Figure A-1, which includes 3 first-level criteria, the first criterion is compared to the second, the second is compared to the third, and the third is compared to the first. Using this example, assume that decision makers determine that the first criterion is twice as important as the second ($\text{Crit}_1 = 2 * \text{Crit}_2$), the second is three times as important as the third ($\text{Crit}_2 = 3 * \text{Crit}_3$), and the first is six times as important as the third ($\text{Crit}_1 = 6 * \text{Crit}_3$). In evaluating the comparison of the first criterion to the third, AHP can be used to confirm the final pair-wise comparison by using the transitive property of algebra (if $\text{Crit}_1 > \text{Crit}_2$ and $\text{Crit}_2 > \text{Crit}_3$, then $\text{Crit}_1 > \text{Crit}_3$). In this case, the pair-wise comparison and confirmation agree, which would result in a low “inconsistency index.” This index is a measure of the difference between expected and scored relationships resulting from the pair-wise comparisons. It is a signal to decision makers to reflect on particular choices that appear to contradict.

Using AHP, the numbers of pair-wise comparisons can become quite large. However, the Expert Choice® software tool includes a “data grid” or “intensity scale” mode to evaluate alternatives. Pair-wise comparisons are conducted for the first- and second-level criteria, but intensity scales (e.g., “low,” “medium,” and “high”) are used to evaluate each technology alternative individually. Pair-wise comparisons are conducted for each scale to develop weightings of each scale unit. Intensities then are derived from (1) ratings, (2), increasing utility curves, (3), decreasing utility curves, (4) step functions, or (5) direct entries of priorities. Only the “ratings” approach, which uses criterion-specific scales such as low-medium-high, was used to evaluate intensities for this AHP analysis. The ratings for each criterion are discussed later in this appendix and in Appendix B.

Additional information about AHP, including an example that illustrates the mathematical foundation of AHP, is provided in EPA/600/R-03/048, *Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* (USEPA 2002c). This appendix focuses on the process for using Expert Choice® to conduct the environmental analysis of technologies to treat mercury and dispose in a waste containment facility and the related sensitivity and uncertainty analyses.

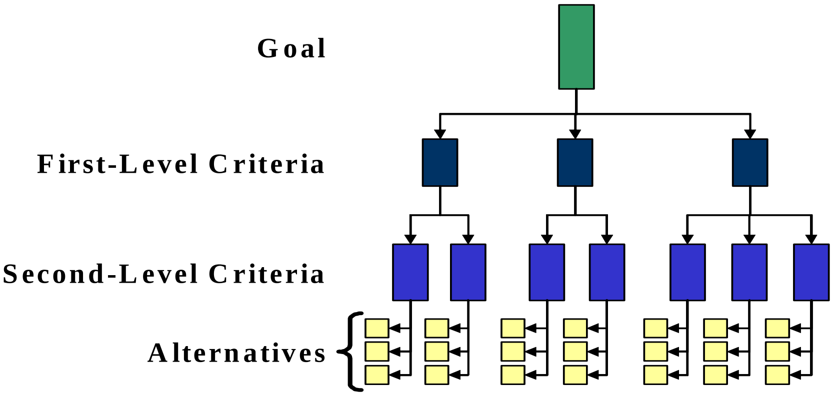


Figure A-1. Decision Hierarchy

A.2. Expert Choice® in the Environmental Analysis of Technologies to Treat Mercury and Dispose in a Waste Containment Facility

To facilitate the pair-wise comparisons and effectively implement the underlying mathematical framework, Thomas Saaty developed the Expert Choice® software tool. Expert Choice® version 11 was used to support the environmental analysis of technologies to treat mercury and dispose of the waste in a containment facility. It was also used to conduct the sensitivity and uncertainty analyses.

The analysis using Expert Choice® includes a seven-step process.

- Step 1: Problem identification and research
- Step 2: Eliminate the infeasible alternatives
- Step 3: Structure a decision model
- Step 4: Evaluate the factors in the model by making pair-wise relative comparisons
- Step 5: Synthesize to identify the "best" alternative.
- Step 6: Examine and verify the decision, iterate as required
- Step 7: Document the decision for justification and control

The first four steps were initiated prior to and completed during a meeting between several experts in elemental mercury treatment and disposal technologies from the U.S. Environmental Protection Agency (EPA) and Science Applications International Corporation (SAIC) on 17 and 18 June 2004. The information gathered during the first four steps was used to complete the fifth and sixth steps. This report represents completion of the seventh step, which is to document the decision for justification and control. The following sections describe the steps used to apply AHP and Expert Choice®.

Step 1: Problem Identification and Research

This step includes the following three sub-steps:

- **Sub-step 1a:** Identify the problem
- **Sub-step 1b:** Identify objectives and alternatives
- **Sub-step 1c:** Research the alternatives.

Sub-Step 1a: The problem identified for AHP analysis using Expert Choice® was determined at the conclusion of the *Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* (USEPA 2002c) and in EPA's statement of work (SOW) to SAIC. Specifically, it was to conduct the environmental analysis of technologies to treat mercury and dispose of the waste in a containment facility.

Sub-Step 1b: During the 17 and 18 June 2004 meeting between EPA and SAIC, the choices of the alternatives listed below were finalized and the following goal was established to focus the AHP analysis: "Minimize environmental impacts during life cycle." In addition, the following criteria were established to conduct the AHP analysis using Expert Choice®:

- **First-Level Criterion 1:** Minimize environmental impacts during routine operation of stabilization facility
  - **Second-Level Criterion 1a:** Minimize environmental impacts from solid waste streams (none of the treatment technologies has liquid waste streams)
  - **Second-Level Criterion 1b:** Minimize environmental impacts from atmospheric discharges
- **First-Level Criterion 2:** Minimize environmental impacts during abnormal or accidental operations
  - **Second-Level Criterion 2a:** Minimize environmental impacts from elemental mercury spills
  - **Second-Level Criterion 2b:** Minimize environmental impacts from other spills
- **First-Level Criterion 3:** Minimize environmental impacts during transportation
  - **Second-Level Criterion 3a:** Minimize environmental impacts during transportation of mercury to stabilization facility
  - **Second-Level Criterion 3b:** Minimize environmental impacts during transportation of stabilized waste to monofill
  - **Second-Level Criterion 3c:** Minimize environmental impacts during transportation of reagents
- **First-Level Criterion 4:** Minimize environmental impacts during decommissioning of the treatment unit
- **First-Level Criterion 5:** Minimize environmental impacts during storage in the monofill
  - **Second-Level Criterion 5a:** Expected ease of maintaining environmental conditions (40 years)
  - **Second-Level Criterion 5b:** Expected long-term susceptibility (after 40 years).

The AHP analysis evaluated the following treatment options, macroencapsulation alternatives, and subsequent alternatives:

- **Treatment options:**
  - Option A process
  - Option B process
  - Option C process
- **Macroencapsulation alternatives:**
  - Dispose of the treated mercury with macroencapsulation
  - Dispose of the treated mercury without macroencapsulation
- **Subsequent alternatives:**
  - Build a fixed treatment facility at one site to which all of the bulk elemental mercury is transported and dispose of in a collocated monofill (centralized treatment alternative)
  - Build one or more portable waste treatment facilities and take them to the sites at which the bulk elemental mercury is stored and dispose of the treated waste in a centralized monofill (mobile treatment alternative).

Since the goal of the AHP analysis was to evaluate mercury across the entire treatment and disposal life-cycle, the alternatives listed above were combined to become the 12 Technology Alternatives evaluated using Expert Choice® as follows:

1. Option A+no macroencapsulation+centralized treatment
2. Option A+no macroencapsulation+mobile treatment
3. Option A+macroencapsulation+centralized treatment
4. Option A+macroencapsulation+mobile treatment
5. Option B+no macroencapsulation+centralized treatment
6. Option B+no macroencapsulation+mobile treatment
7. Option B+macroencapsulation+centralized treatment
8. Option B+macroencapsulation+mobile treatment
9. Option C+no macroencapsulation+centralized treatment
10. Option C+no macroencapsulation+mobile treatment
11. Option C+macroencapsulation+centralized treatment
12. Option C+macroencapsulation+mobile treatment.

Sub-Step 1c: Research was initiated using the SOW and conclusions from the *Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* (USEPA 2002c). Additional research also was conducted to complete the evaluation of alternatives. Earlier sections of this report discuss the results of the research.

Step 2: Eliminate the Infeasible Alternatives

This step includes the following two sub-steps:

- **Sub-Step 2a:** Determine the "musts"
- **Sub-Step 2b:** Eliminate the alternatives that do not meet the "musts."

Sub-Step 2a: Step 2 was initiated at the conclusion of the *Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* (USEPA 2002c) and in EPA's SOW to SAIC. During the 12 June 2004 meeting between EPA and SAIC, the following "musts" were finalized:

- The alternatives were limited to those specified above (Sub-Step 1b).
- The intent of the AHP was to address environmental effects, not costs. An economic analysis of the twelve alternatives was performed after completing the AHP analysis.
- Since there are twelve alternatives, the effort required to pair-wise compare these against each criterion would be excessive (i.e., 12 x 10 = 120 pair-wise comparisons per objective). Therefore, the team instead defined a range of "intensities" for each criterion and brainstormed where each alternative lies within the range.
- The environmental ranking arising from the AHP exercise was not expected to be sensitive to the total mass of mercury (5,000, 12,000, or 25,000 tons). Therefore, there was no need to specify a mass for the AHP analysis. [There was some discussion about whether the mass of mercury might affect some of the criteria (e.g., higher transportation risks for higher quantities), but this would not influence the rankings because all alternatives would be affected the same way.]
- "No macroencapsulation" meant that the stabilized waste will be placed in the monofill exactly as it is generated by the stabilization process. If the process ends with the waste solidifying in some form of container, this container was be given no credit for reducing the rate of leaching.

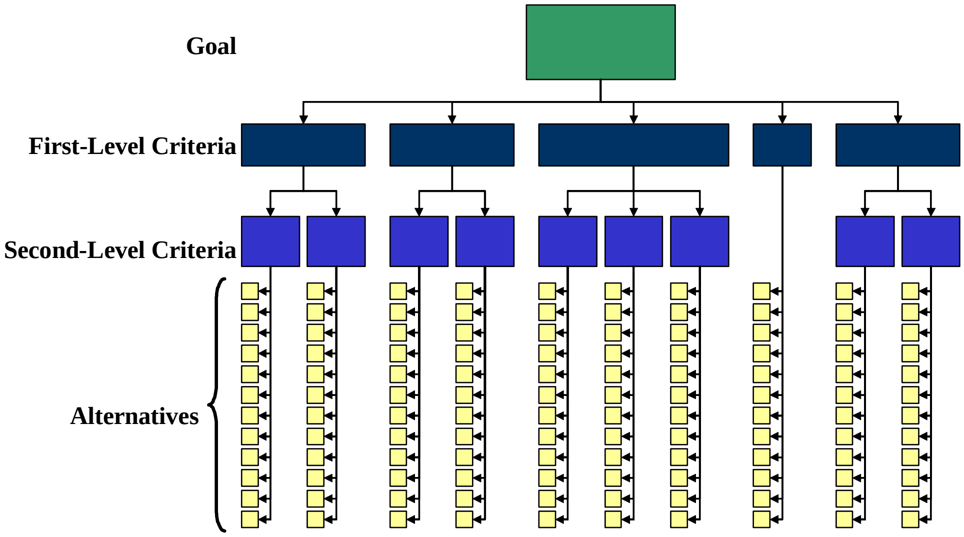


Figure A-2. Full Hierarchical Model

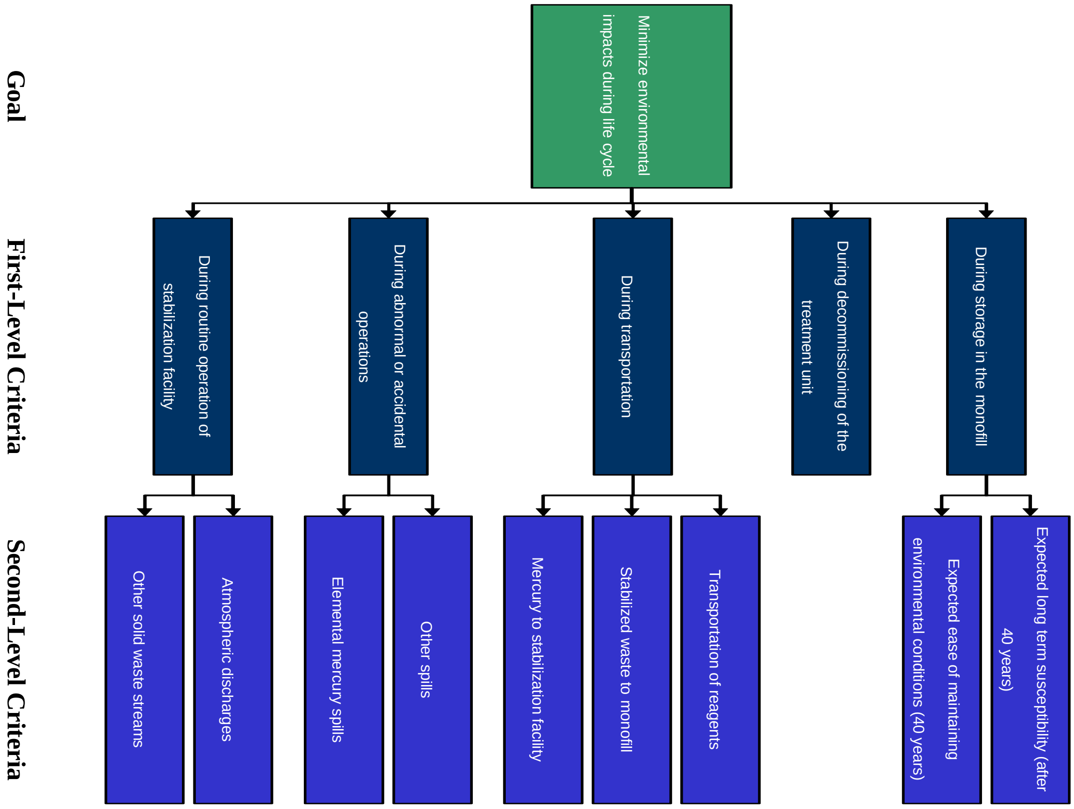


Figure A-3. AHP Goal and Criteria for AHP Analysis

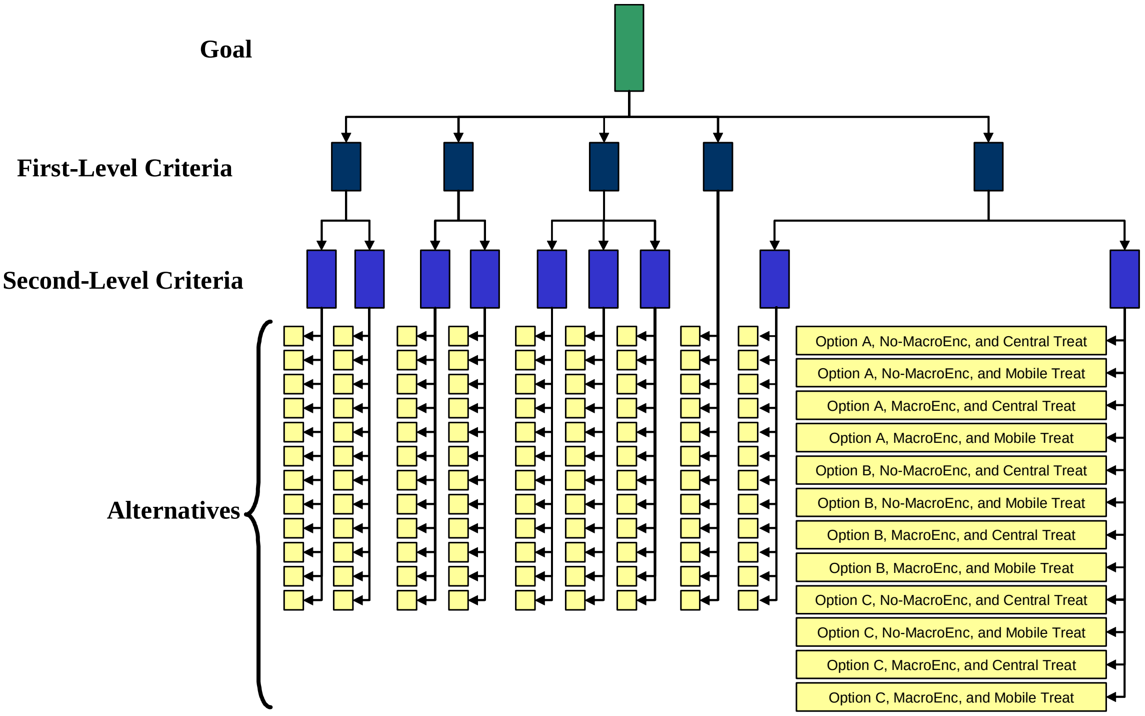


Figure A-4. AHP Alternatives for AHP Analysis

- "Macroencapsulation in the best available medium" means macroencapsulation in a separate step after stabilization. It was agreed that, for the purposes of both the AHP and the cost analyses, the macroencapsulation technology will be the Envirocare ARROW-PAK system, in which waste is sealed in polyethylene containers prior to disposition in a monofill. The already-formed polyethylene containers will be purchased from the manufacturers and filled and sealed at the stabilization site. The ARROW-PAK system is expected to be available in a variety of sizes; the cost and the environmental analyses incorporated appropriate assumptions for container size.
- Initially, SAIC suggested that the design and construction of the monofill will be independent of the stabilization technology. However, after some discussion, it was agreed that, while many elements of the construction will be independent of the disposal alternatives, there might be some features that are technology dependent, such as the composition of the liner and adjustments to the fill material.

Sub-Step 2b: After developing the "musts," none of the alternatives were eliminated.

Step 3: Structure a Decision Model

Step 3 includes developing a structured model in the form of a hierarchy to include the goal, criteria (first- and second-level), and alternatives. This step was completed during the 17 and 18 June 2004 meeting between EPA and SAIC.

Because of the size of the model, it is not practical to enter the information for all of the cells in one figure. Therefore, Figure A-2 illustrates the structure of the full hierarchical model and Figures A-3 and A-4 illustrate components of full model in pieces that are more readable.

Step 4: Evaluate the Factors in the Model by Making Pair-wise Relative Comparisons

This step includes the following two sub-steps:

- **Sub-Step 4a:** Use as much factual data as is available, but interpret the data as it relates to satisfying the objectives
- **Sub-Step 4b:** Use knowledge, experience, and intuition for these qualitative aspects of the problem or when no hard data are available.

Step 4 commenced during the 17 and 18 June 2004 meeting between EPA and SAIC, but because of the detailed information and the copious time needed to evaluate each alternative relative to each criterion, Step 4 was completed subsequent to the meeting through a series of electronic mail messages and telephone conversations. The pair-wise comparisons of the criteria (first- and second-level) were conducted and finalized during the meeting. Rating scales for the evaluation of intensities for the analysis of alternatives were discussed conceptually during the meeting, but the actual analysis was conducted after the meeting.

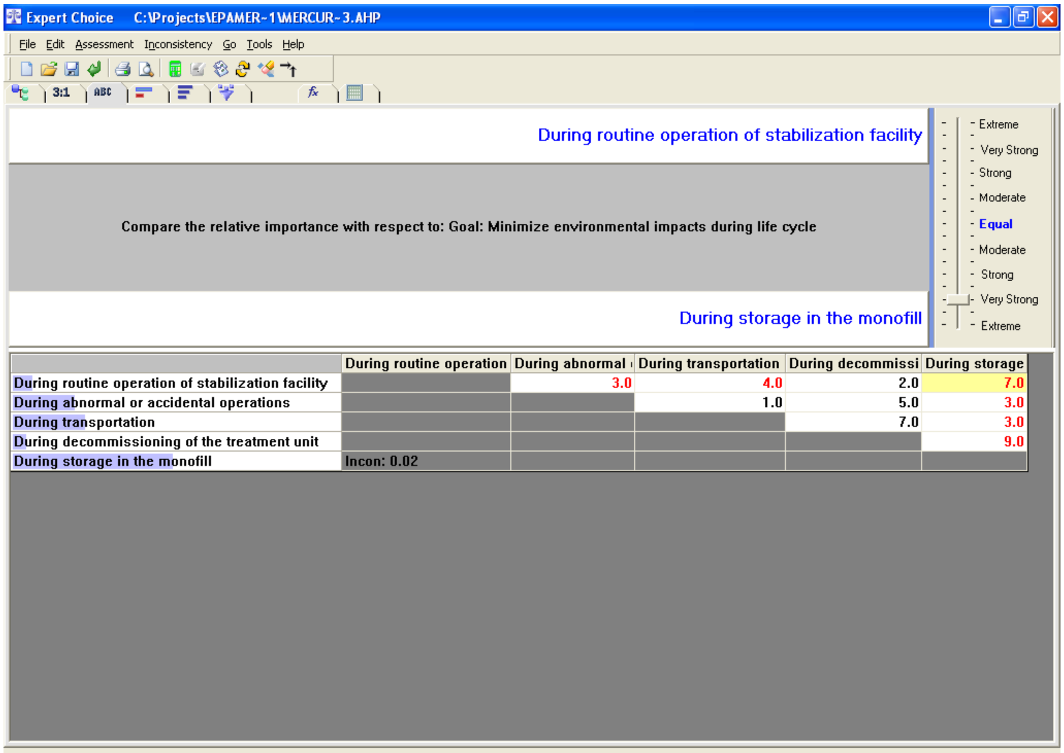
Sub-Step 4a: During the 17 and 18 June 2004 meeting, pair-wise comparisons were conducted for each pair of first-level criteria, then for each pair of second-level criteria. SAIC staff facilitated the pair-wise comparisons by asking questions for each pair such as, “To minimize environmental impacts during the life cycle of operations, are routine operations of the stabilization facility (First-Level Criterion 1) more or less important than abnormal or accidental operations (First-Level Criterion 2)?” Similar questions were asked for each of the remaining pairs of first- and second-level criteria.

In addition, a verbal scale ranging from “equal” to “moderate” to “strong” to “very strong” to “extreme” was used to evaluate the magnitude of the difference in importance between each pair and equate to scores of 1, 3, 5, 7, and 9, respectively. Values for 2, 4, 6, and 8 represented scores between the verbal scale descriptors and non-integer values also could be used, if necessary. The values resulting from the pair-wise comparisons were positive when the first criterion was deemed more important than the second and negative when the first criterion was deemed less important than the second. The following figures illustrate the results of the pair-wise comparisons; values shown in black are positive and values shown in red are negative. The columns on the left side of each matrix identify the first criterion and the row-headings across the tops of each matrix identify the second criterion. For example, Figure A-5 indicates a red “3.0” in the upper left corner of the matrix, which leads to the conclusion that operations during routine operations at the stabilization facility (criterion to left of matrix) are moderately less important than operations during abnormal or accidental operations (criterion listed across top of matrix).

Expert Choice® provides a graphical summary of the priorities of the first-level criteria with respect to the goal and of the second-level criteria with respect to each first-level criterion. For example, Figure A-5 shows that, during the pair-wise comparisons of the criteria, minimizing environmental impacts during storage in the monofill is “very strong[ly]” more important than the is minimizing environmental impacts during routine operations of the stabilization facility. Figures A-5 through A-14 illustrate the results of the pair-wise comparisons and the priorities interpreted from the comparisons.

Sub-Step 4b: As stated previously, pair-wise comparisons were not performed for the technology alternatives because of the large number of comparisons that would have been required to evaluate 12 alternatives against 10 criteria. Instead, a set of rating scales or intensities were developed to evaluate each alternative relative to each criterion.

Qualitative scales were developed for each criterion to measure environmental performance of each alternative. Pair-wise comparisons like the ones described above were conducted for each scale to determine the relative priority of each unit of the scale. The following figures illustrate the results and priorities of pair-wise comparisons of intensity scales for the evaluation of the 12 technology alternatives.



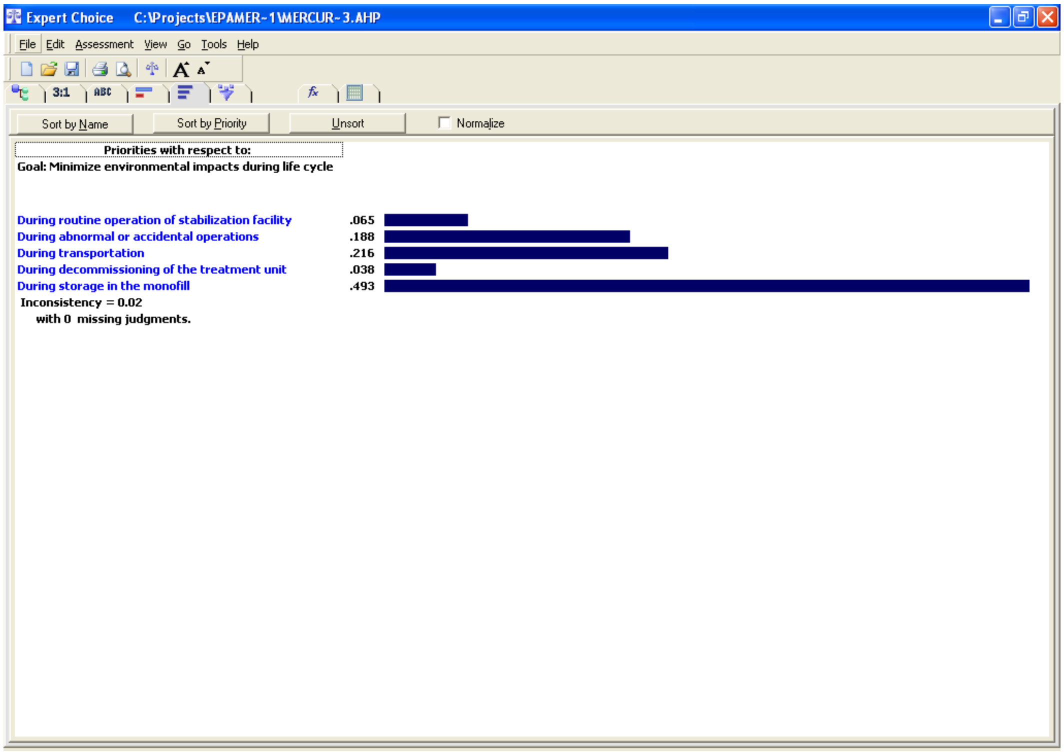
During routine operation of stabilization facility

Compare the relative importance with respect to: Goal: Minimize environmental impacts during life cycle

During storage in the monofill

	During routine operation	During abnormal	During transportation	During decommissi	During storage
During routine operation of stabilization facility		3.0	4.0	2.0	7.0
During abnormal or accidental operations			1.0	5.0	3.0
During transportation				7.0	3.0
During decommissioning of the treatment unit					9.0
During storage in the monofill	Incon: 0.02				

Figure A-5. Results of Pair-wise Comparison of First-Level Criteria

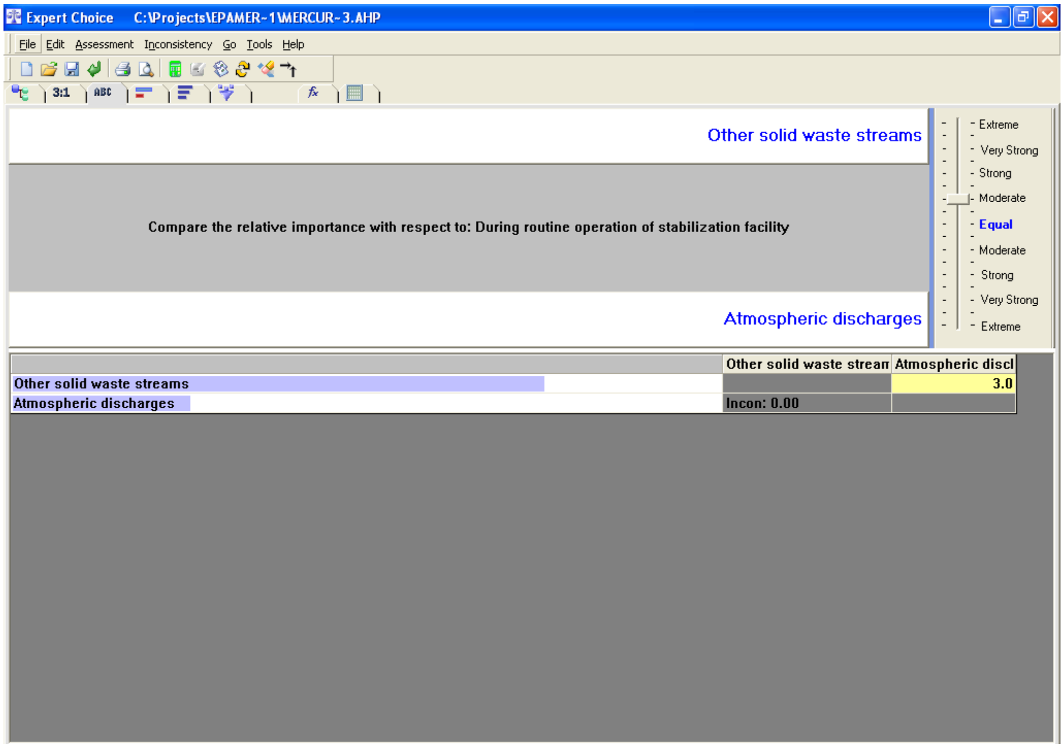


Priorities with respect to:
Goal: Minimize environmental impacts during life cycle

During routine operation of stabilization facility	.065
During abnormal or accidental operations	.188
During transportation	.216
During decommissioning of the treatment unit	.038
During storage in the monofill	.493

Inconsistency = 0.02
with 0 missing judgments.

Figure A-6. Priorities of First-Level Criteria Resulting from Pair-wise Comparisons



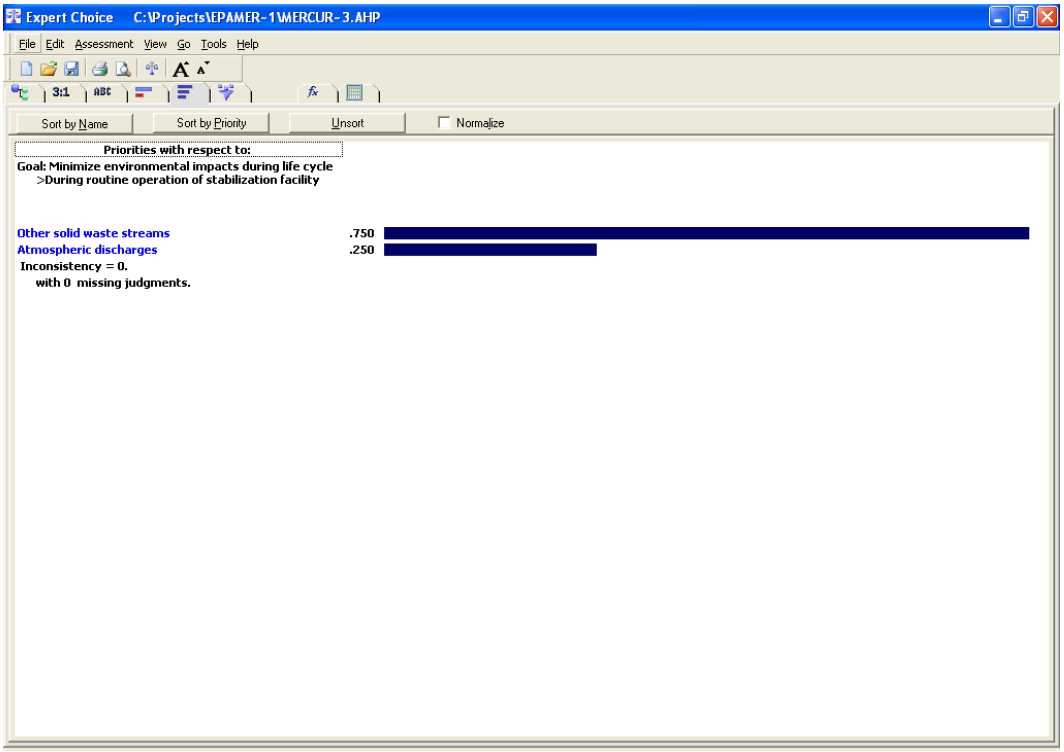
Other solid waste streams

Compare the relative importance with respect to: During routine operation of stabilization facility

Atmospheric discharges

	Other solid waste stream	Atmospheric discl
Other solid waste streams		3.0
Atmospheric discharges	Incon: 0.00	

Figure A-7. Pair-wise Comparison of Second-Level Criteria: During Routine Operations at Stabilization Facility

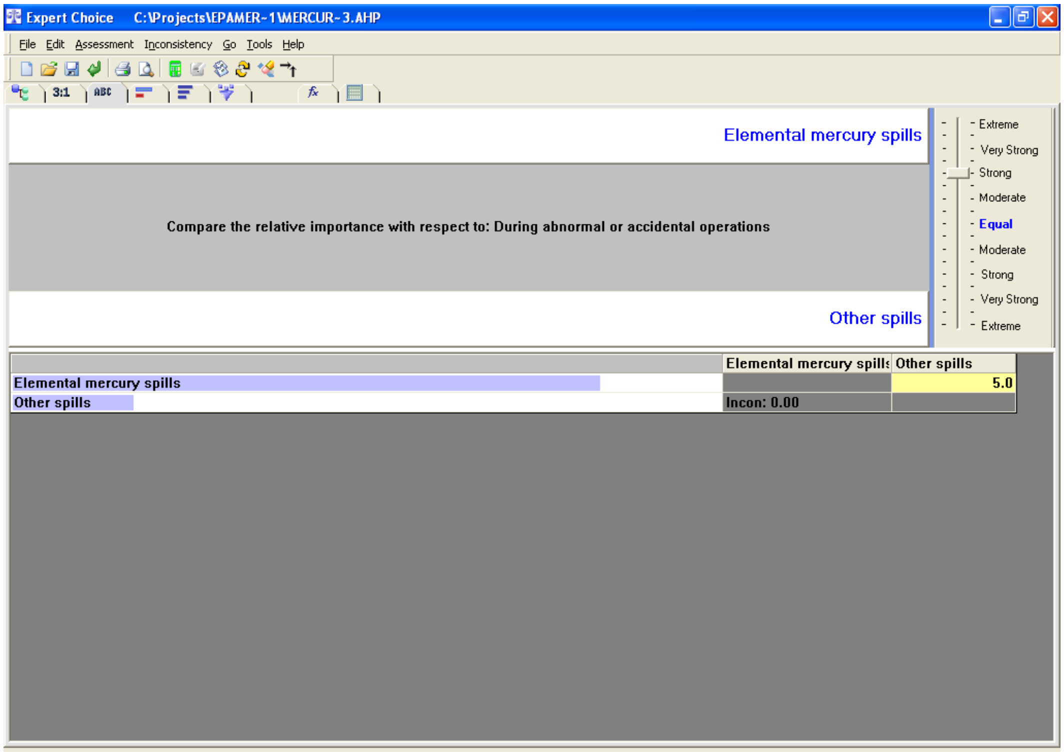


Priorities with respect to:
Goal: Minimize environmental impacts during life cycle
>During routine operation of stabilization facility

Other solid waste streams	.750
Atmospheric discharges	.250

Inconsistency = 0.
with 0 missing judgments.

Figure A-8. Priorities of Second-Level Criteria Resulting from Pair-wise Comparisons: During Routine Operations at Stabilization Facility



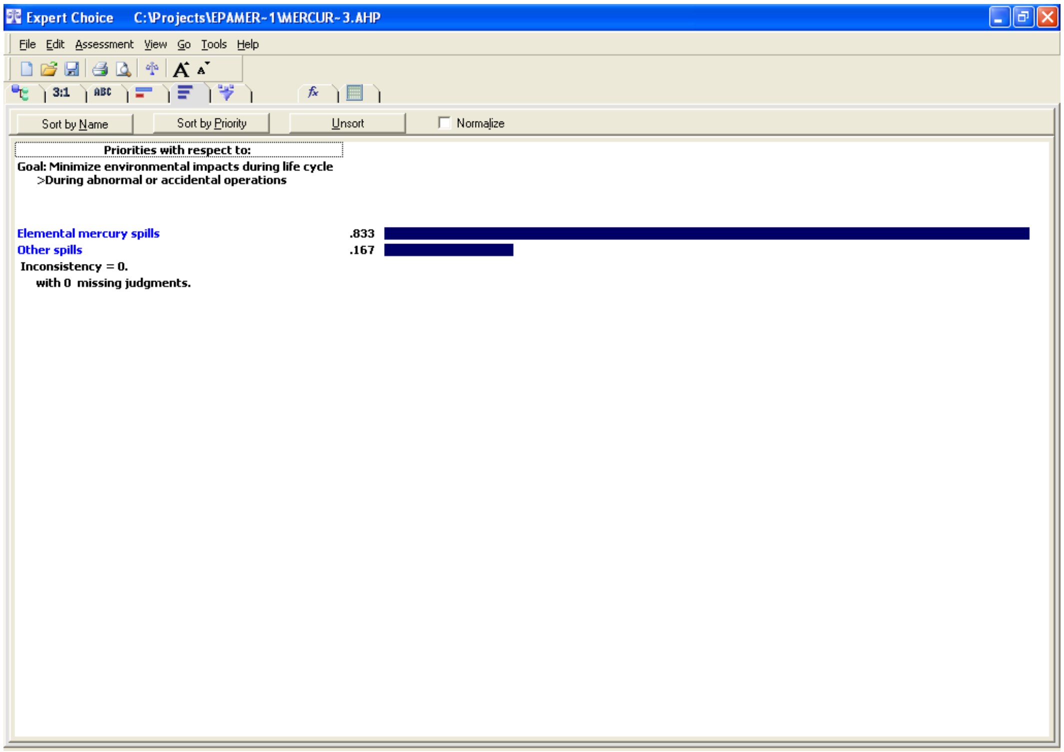
Elemental mercury spills

Compare the relative importance with respect to: During abnormal or accidental operations

Other spills

	Elemental mercury spills	Other spills
Elemental mercury spills		5.0
Other spills	Incon: 0.00	

Figure A-9. Pair-wise Comparison of Second-Level Criteria: During Abnormal or Accidental Operations

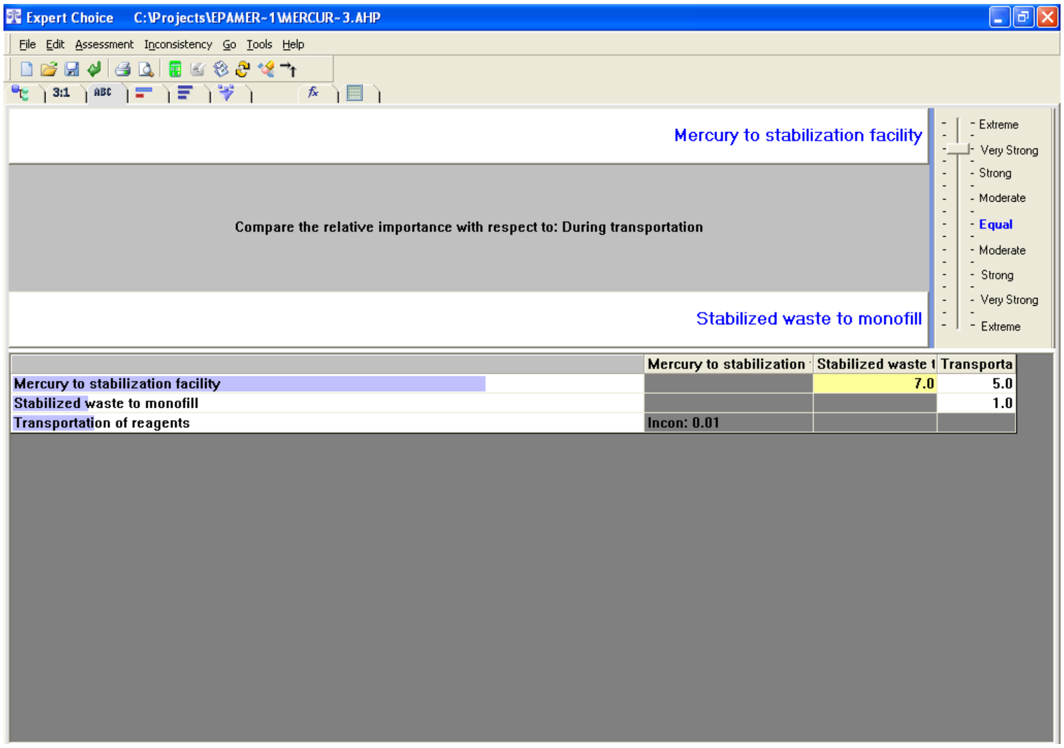


Priorities with respect to:
Goal: Minimize environmental impacts during life cycle
>During abnormal or accidental operations

Elemental mercury spills	.833
Other spills	.167

Inconsistency = 0.
with 0 missing judgments.

Figure A-10. Priorities of Second-Level Criteria Resulting from Pair-wise Comparisons:During Abnormal or Accidental Operations



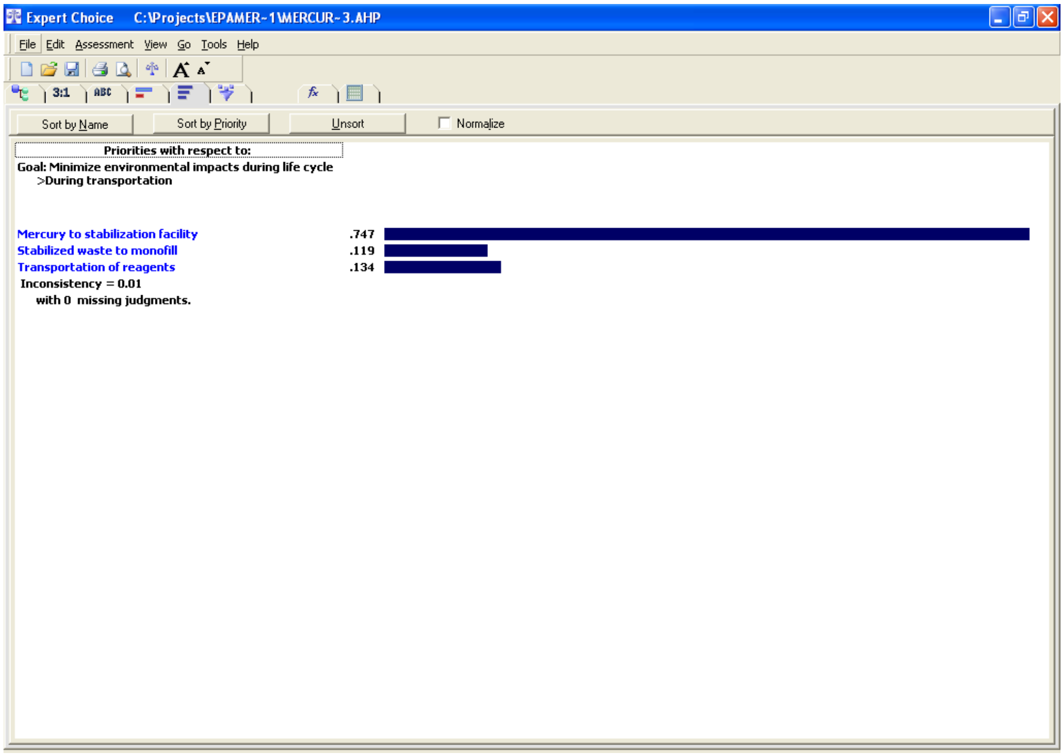
Mercury to stabilization facility

Compare the relative importance with respect to: During transportation

Stabilized waste to monofill

	Mercury to stabilization	Stabilized waste t	Transporta
Mercury to stabilization facility		7.0	5.0
Stabilized waste to monofill			1.0
Transportation of reagents	Incon: 0.01		

Figure A-11. Pair-wise Comparison of Second-Level Criteria: During Transportation

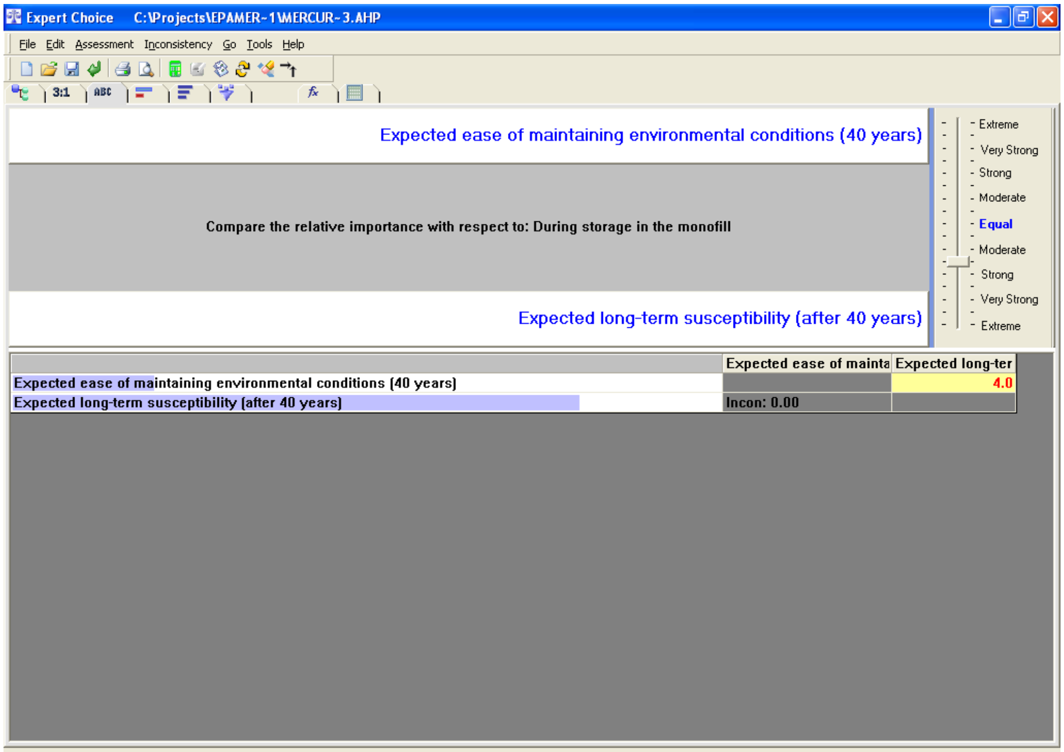


Priorities with respect to:
Goal: Minimize environmental impacts during life cycle
>During transportation

Mercury to stabilization facility	.747
Stabilized waste to monofill	.119
Transportation of reagents	.134

Inconsistency = 0.01
with 0 missing judgments.

Figure A-12. Priorities of Second-Level Criteria Resulting from Pair-wise Comparisons: During Transportation



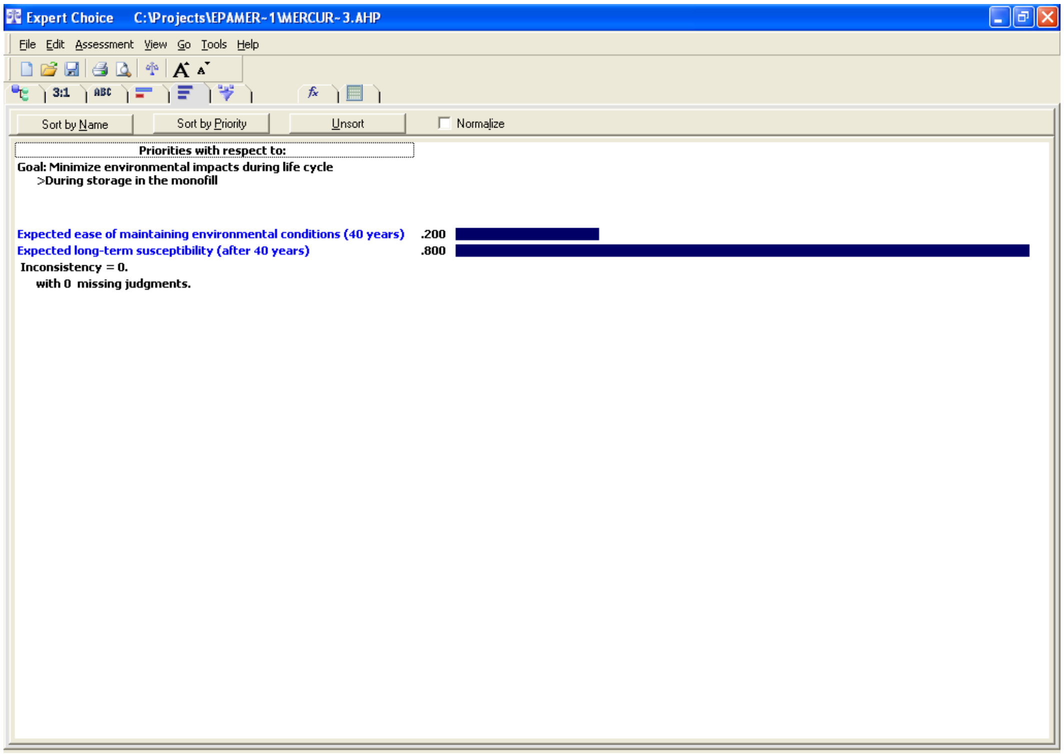
Expected ease of maintaining environmental conditions (40 years)

Compare the relative importance with respect to: During storage in the monofill

Expected long-term susceptibility (after 40 years)

	Expected ease of mainta	Expected long-ter
Expected ease of maintaining environmental conditions (40 years)		4.0
Expected long-term susceptibility (after 40 years)	Incon: 0.00	

Figure A-13. Pair-wise Comparison of Second-Level Criteria: During Storage in the Monofill

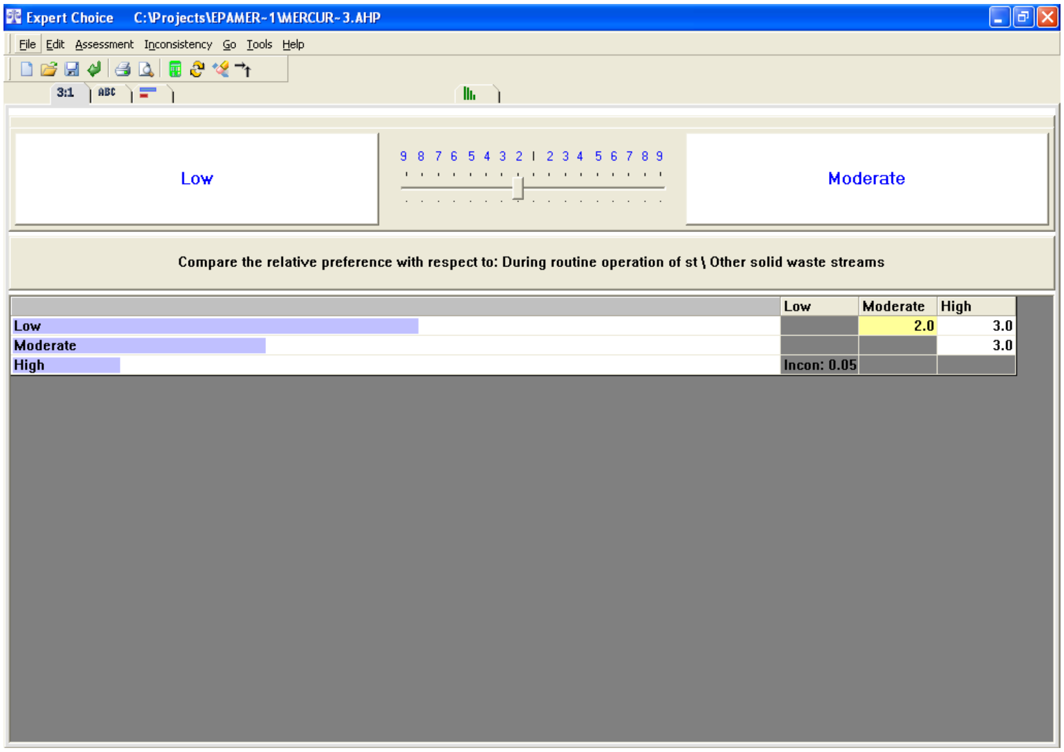


Priorities with respect to:
Goal: Minimize environmental impacts during life cycle
>During storage in the monofill

Expected ease of maintaining environmental conditions (40 years)	.200
Expected long-term susceptibility (after 40 years)	.800

Inconsistency = 0.
with 0 missing judgments.

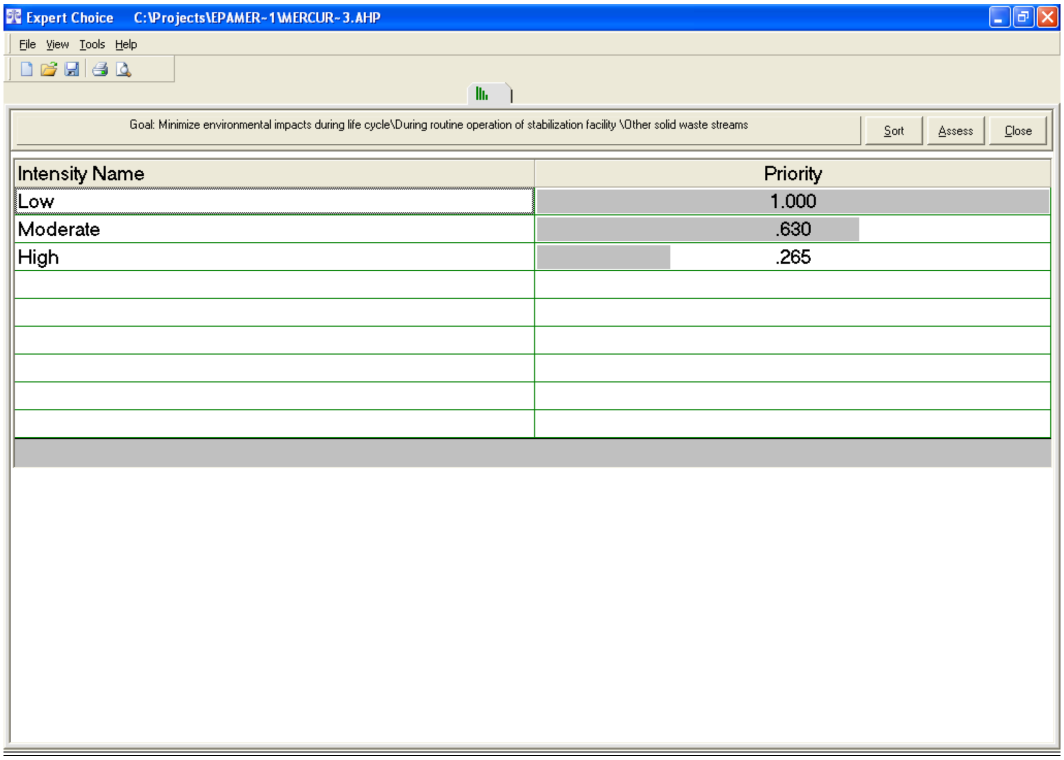
Figure A-14. Priorities of Second-Level Criteria Resulting from Pair-wise Comparisons: During Storage in the Monofill



Compare the relative preference with respect to: During routine operation of st \ Other solid waste streams

	Low	Moderate	High
Low		2.0	3.0
Moderate			3.0
High	Incon: 0.05		

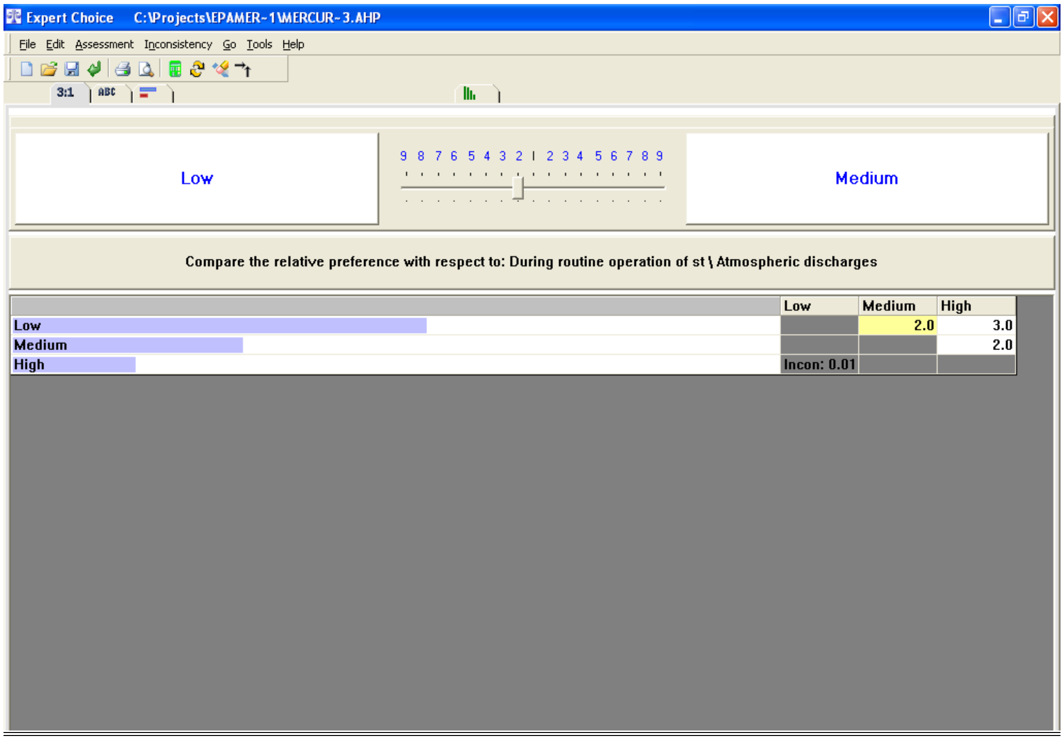
Figure A-15. Assessing Intensities for Low-Moderate-High Scale for Criterion to Minimize Environmental Impacts from Other Solid Waste Streams



Goal: Minimize environmental impacts during life cycle\During routine operation of stabilization facility \Other solid waste streams

Intensity Name	Priority
Low	1.000
Moderate	.630
High	.265

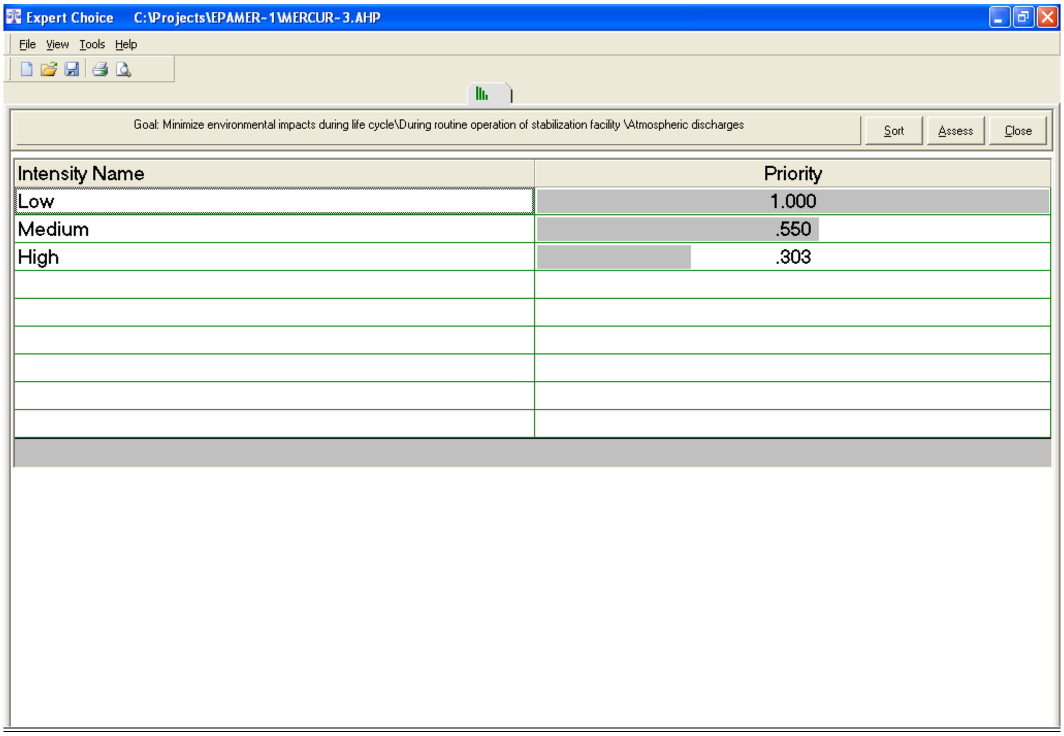
Figure A-16. Priorities for Low-Moderate-High Scale of Criterion to Minimize Environmental Impacts from Other Solid Waste Streams



Compare the relative preference with respect to: During routine operation of st \ Atmospheric discharges

	Low	Medium	High
Low		2.0	3.0
Medium			2.0
High	Incon: 0.01		

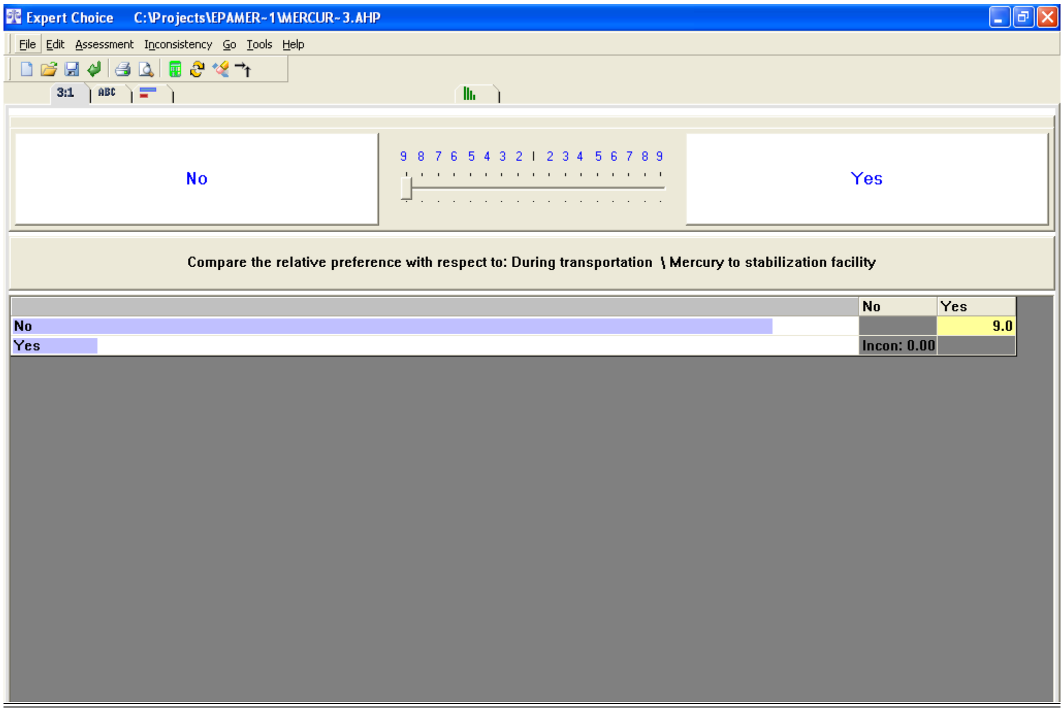
Figure A-17. Assessing Intensities for Low-Moderate-High Scale for Criteria to Minimize Environmental Impacts from Atmospheric Discharges, Elemental Mercury Spills, Other Spills, and During Decommissioning of the Treatment Unit



Goal: Minimize environmental impacts during life cycle\During routine operation of stabilization facility \Atmospheric discharges

Intensity Name	Priority
Low	1.000
Medium	.550
High	.303

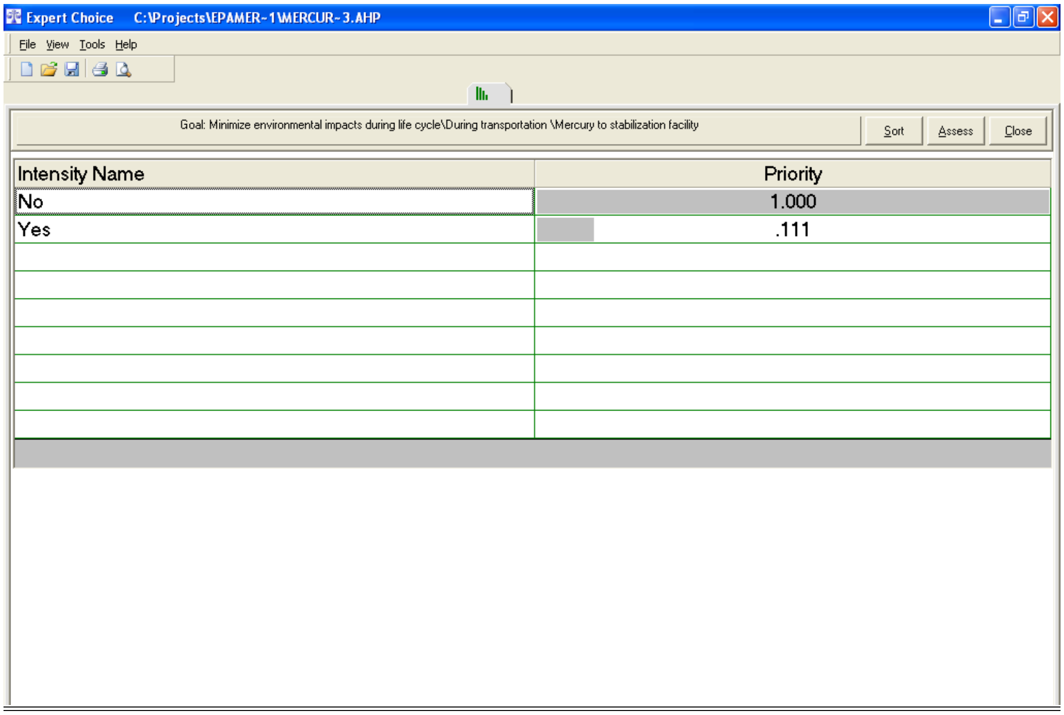
Figure A-18. Priorities for Low-Moderate-High Scale of Criteria to Minimize Environmental Impacts from Atmospheric Discharges, Elemental Mercury Spills, Other Spills, and During Decommissioning of the Treatment Unit



Compare the relative preference with respect to: During transportation \ Mercury to stabilization facility

	No	Yes
No		9.0
Yes	Incon: 0.00	

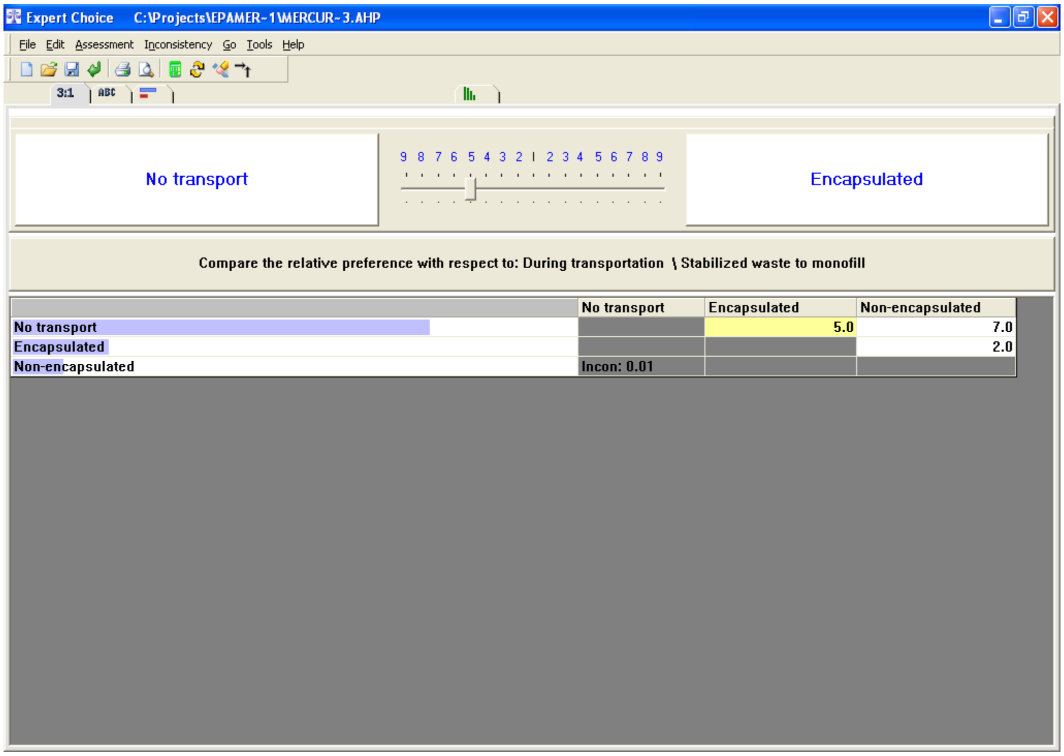
Figure A-19. Assessing Intensities for Yes-No Scale for Criterion to Minimize Environmental Impacts During Transportation of Mercury to Stabilization Facility



Goal: Minimize environmental impacts during life cycle\During transportation \Mercury to stabilization facility

Intensity Name	Priority
No	1.000
Yes	.111

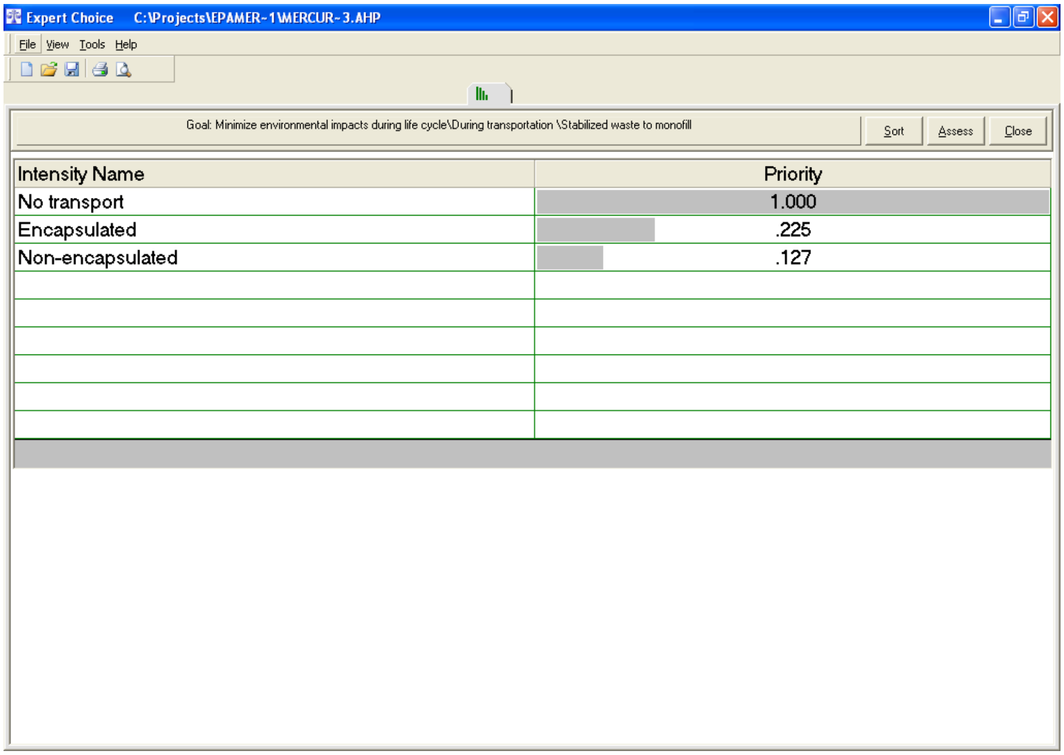
Figure A-20. Priorities for Yes-No Scale of Criterion to Minimize Environmental Impacts During Transportation of Mercury to Stabilization Facility



Compare the relative preference with respect to: During transportation \ Stabilized waste to monofill

	No transport	Encapsulated	Non-encapsulated
No transport		5.0	7.0
Encapsulated			2.0
Non-encapsulated	Incon: 0.01		

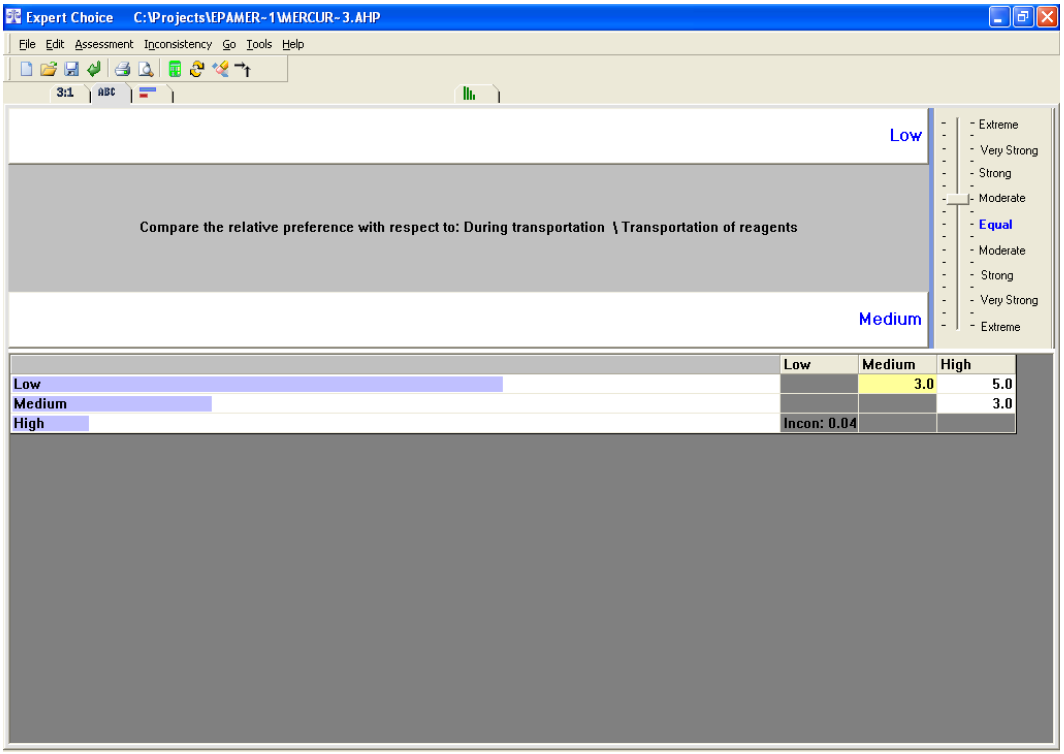
Figure A-21. Assessing Intensities for the Rating Scale for Criterion to Minimize Environmental Impacts During Transportation of Waste to Monofill



Goal: Minimize environmental impacts during life cycle\During transportation \Stabilized waste to monofill

Intensity Name	Priority
No transport	1.000
Encapsulated	.225
Non-encapsulated	.127

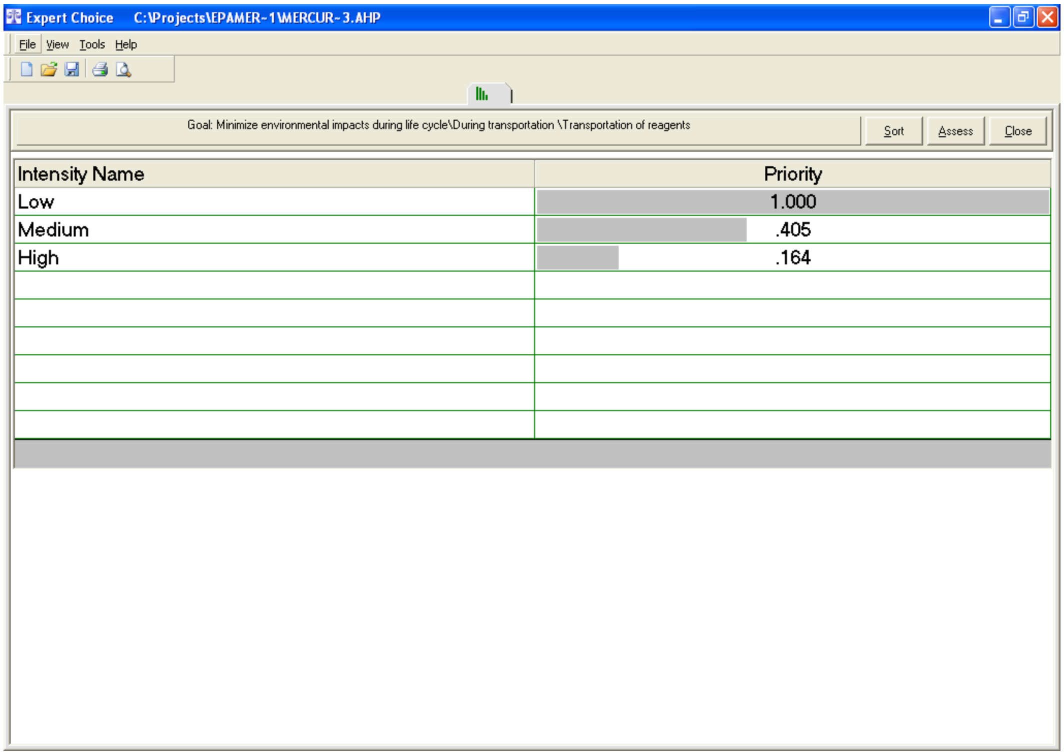
Figure A-22. Priorities for Scale of Criterion to Minimize Environmental Impacts During Transportation of Waste to Monofill



Compare the relative preference with respect to: During transportation \ Transportation of reagents

	Low	Medium	High
Low		3.0	5.0
Medium			3.0
High	Incon: 0.04		

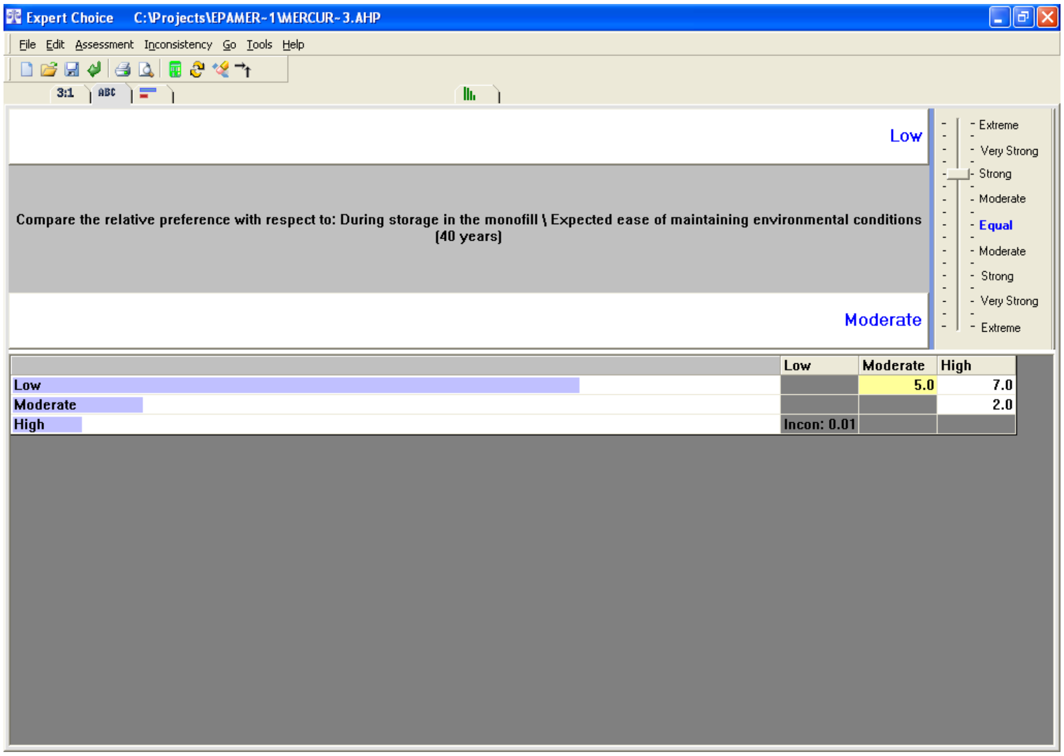
Figure A-23. Assessing Intensities for the Rating Scale for Criterion to Minimize Environmental Impacts During Transportation of Reagents



Goal: Minimize environmental impacts during life cycle\During transportation \Transportation of reagents

Intensity Name	Priority
Low	1.000
Medium	.405
High	.164

Figure A-24. Priorities for Scale of Criterion to Minimize Environmental Impacts During Transportation of Reagents



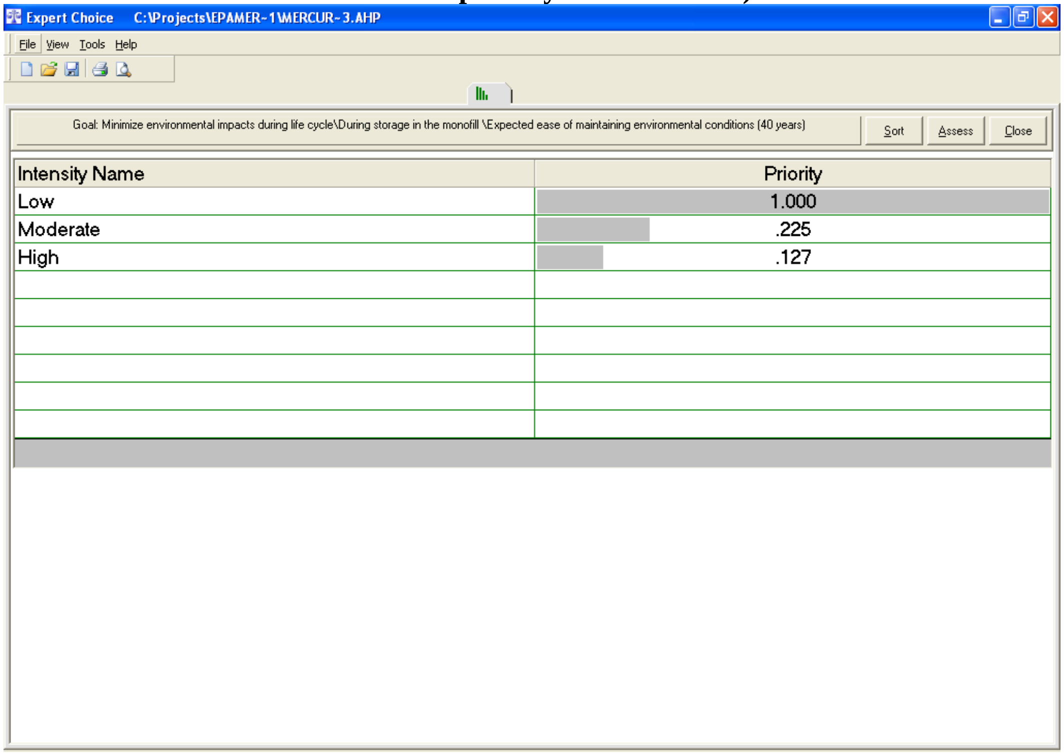
Low

Compare the relative preference with respect to: During storage in the monofill \ Expected ease of maintaining environmental conditions (40 years)

Moderate

	Low	Moderate	High
Low		5.0	7.0
Moderate			2.0
High	Incon: 0.01		

Figure A-25. Assessing Intensities for the Rating Scale for Criterion to Minimize Environmental Impacts During Storage in Monofill (Expected Ease Maintaining for 40 Years and Expected Long-Term Susceptibility after 40 Years)



Goal: Minimize environmental impacts during life cycle\During storage in the monofill \Expected ease of maintaining environmental conditions (40 years)

Intensity Name	Priority
Low	1.000
Moderate	.225
High	.127

Figure A-26. Priorities for Scale of Criterion to Minimize Environmental Impacts During Storage in Monofill (Expected Ease Maintaining for 40 Years and Expected Long-Term Susceptibility after 40 Years)

Although several of the rating scales appear to be the same for different criteria (e.g., 8 of 10 criteria use a low-medium-high scale), factors and phenomena were applied uniquely for each criterion so the specific definitions of low, medium, and high were criterion-specific. For example, a low-medium-high scale was used to evaluate the 12 alternatives with regard to the objective of minimizing environmental impacts from other solid waste streams. To determine the scores (i.e., low, medium, or high), the wastes generated during routine operations were evaluated for the following characteristics:

- Non-mercury hazardous waste (assigned 2 points) versus non-hazardous waste (0 points)
- Volumes of waste (mobile alternatives assigned 2 points and stationary assigned 0 points)
- Non-plastic organic wastes (1 point)
- Mercury contents in waste (determine if any technologies deserve an additional point for generating more mercury-containing waste)
- Powdered (1 point if alternatives include powdered reagents and 0 points if not).

Appendix B describes the “Factors and Phenomena That Need To Be Evaluated When Assigning Intensities to Alternatives.” Following the assessment of intensities and prioritizations of scale units, the 12 technology alternatives were evaluated against the scales. Figure A-27 illustrates the scoring of intensities for the 12 Technology Alternatives with respect to the lowest-level criteria (1 first-level criterion and 9 second-level criteria).

Step 5: Synthesize to Identify the “Best” Alternative.

Once judgments are entered for each part of the model, the information was synthesized to achieve an overall preference. The synthesis ranks the technology alternatives in relation to the goal. Following the pair-wise comparisons and evaluations of intensities, the actual synthesis of results is executed virtually instantaneously by Expert Choice®. Figure A-28 illustrates the synthesized results sorted by priority.

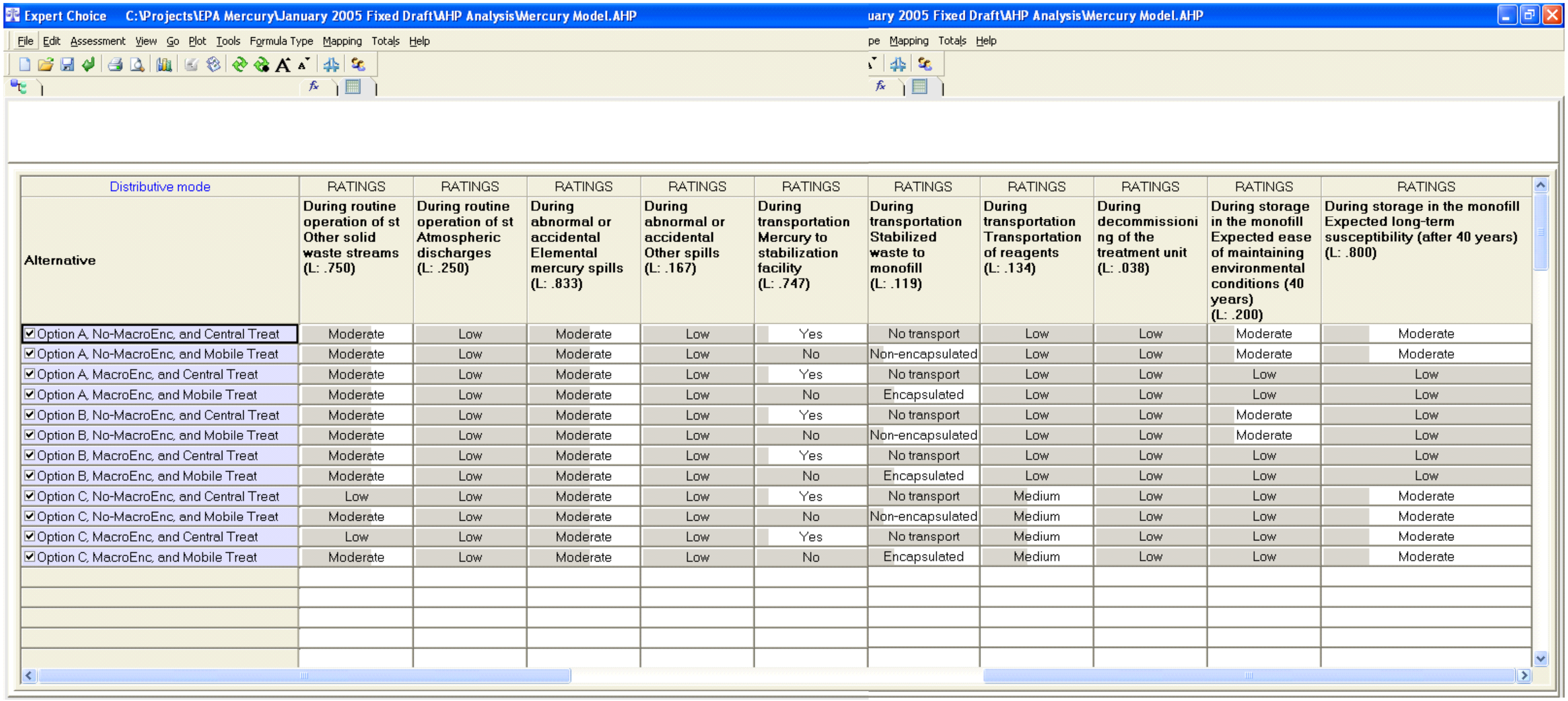
In evaluating the synthesis from the perspective of the AHP fundamental principles, the final inconsistency index shown on Figure A-28 shows that the pair-wise comparisons and confirmations agree. Generally, when inconsistency indices exceed 0.1, decision makers should consider re-examining the pair-wise comparisons and intensity assessments because of possible contradictions. However, since the inconsistency index was well below the recommended value, the pair-wise comparisons and intensity assessments were not re-examined for this AHP analysis.

Step 6: Examine and Verify the Decision, Iterate As Required

Step 6 includes the following two sub-steps:

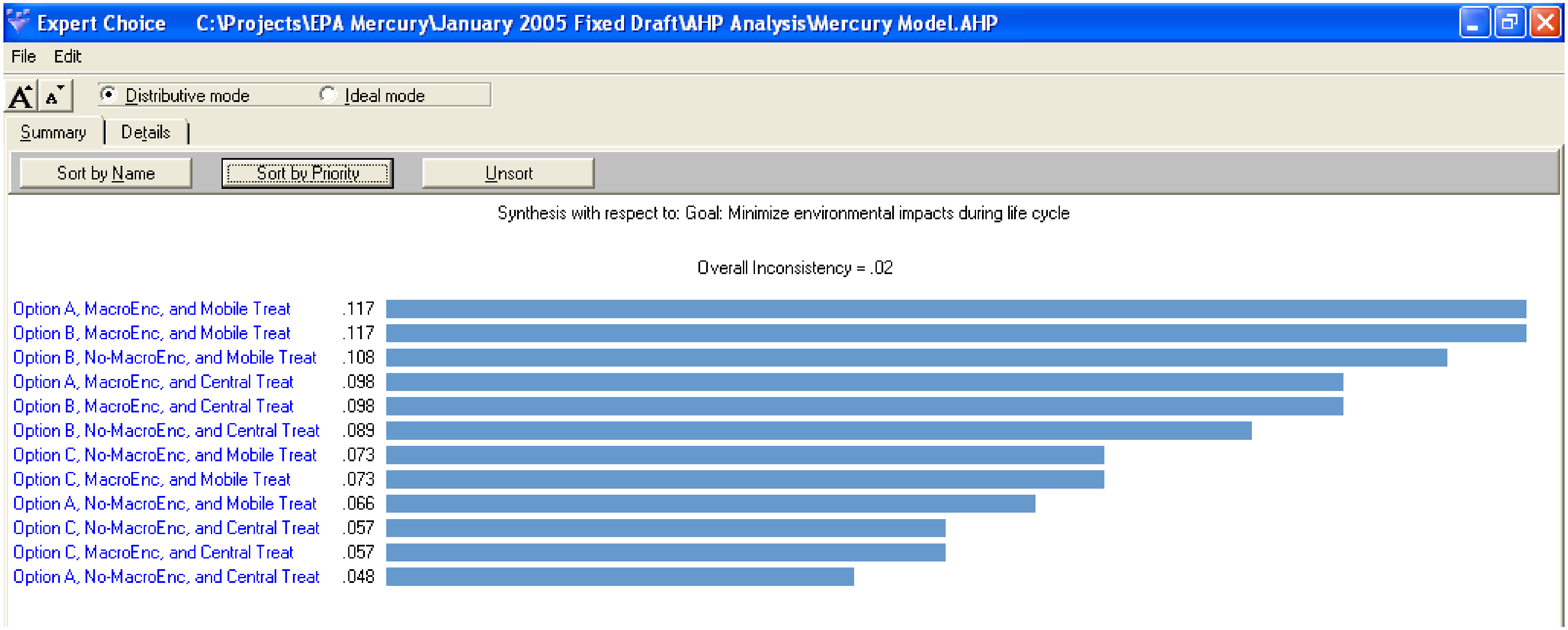
- **Sub-Step 6a:** Examine the solution and perform sensitivity analyses.
- **Sub-Step 6b:** Check the decision against intuition.

Sub-Step 6a: This step is used to determine if the solution recommended from the AHP analysis is sensitive to factors in the model for which accurate data are not available, and, if so, considering spending the resources necessary to collect the necessary data and iterate back to Step 4. Consequently, a “what-if” sensitivity analysis was conducted following the synthesis of the pair-wise comparisons and intensity assessments. This analysis did not alter the overall structure of the model, nor did it change any of the pair-wise comparisons. Instead, several minor changes were made to the assessments of intensities of the final disposal, transportation, and abnormal/accidental operations criteria.



Distributive mode	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS
Alternative	**During routine operation of st Other solid waste streams (L: .750)**	**During routine operation of st Atmospheric discharges (L: .250)**	**During abnormal or accidental Elemental mercury spills (L: .833)**	**During abnormal or accidental Other spills (L: .167)**	**During transportation Mercury to stabilization facility (L: .747)**	**During transportation Stabilized waste to monofill (L: .119)**	**During transportation Transportation of reagents (L: .134)**	**During decommissioning of the treatment unit (L: .038)**	**During storage in the monofill Expected ease of maintaining environmental conditions (40 years) (L: .200)**	**During storage in the monofill Expected long-term susceptibility (after 40 years) (L: .800)**
☑ Option A, No-MacroEnc, and Central Treat	Moderate	Low	Moderate	Low	Yes	No transport	Low	Low	Moderate	Moderate
☑ Option A, No-MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Non-encapsulated	Low	Low	Moderate	Moderate
☑ Option A, MacroEnc, and Central Treat	Moderate	Low	Moderate	Low	Yes	No transport	Low	Low	Low	Low
☑ Option A, MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Encapsulated	Low	Low	Low	Low
☑ Option B, No-MacroEnc, and Central Treat	Moderate	Low	Moderate	Low	Yes	No transport	Low	Low	Moderate	Low
☑ Option B, No-MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Non-encapsulated	Low	Low	Moderate	Low
☑ Option B, MacroEnc, and Central Treat	Moderate	Low	Moderate	Low	Yes	No transport	Low	Low	Low	Low
☑ Option B, MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Encapsulated	Low	Low	Low	Low
☑ Option C, No-MacroEnc, and Central Treat	Low	Low	Moderate	Low	Yes	No transport	Medium	Low	Low	Moderate
☑ Option C, No-MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Non-encapsulated	Medium	Low	Low	Moderate
☑ Option C, MacroEnc, and Central Treat	Low	Low	Moderate	Low	Yes	No transport	Medium	Low	Low	Moderate
☑ Option C, MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Encapsulated	Medium	Low	Low	Moderate

Figure A-27. Intensity Scoring of Technology Alternatives



● Distributive mode ○ Ideal mode

Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat	.117
Option B, MacroEnc, and Mobile Treat	.117
Option B, No-MacroEnc, and Mobile Treat	.108
Option A, MacroEnc, and Central Treat	.098
Option B, MacroEnc, and Central Treat	.098
Option B, No-MacroEnc, and Central Treat	.089
Option C, No-MacroEnc, and Mobile Treat	.073
Option C, MacroEnc, and Mobile Treat	.073
Option A, No-MacroEnc, and Mobile Treat	.066
Option C, No-MacroEnc, and Central Treat	.057
Option C, MacroEnc, and Central Treat	.057
Option A, No-MacroEnc, and Central Treat	.048

Figure A-28. Synthesis of AHP Analysis of Mercury Treatment Technologies Using Expert Choice® 11

Expert Choice® 11 includes the following five powerful set of tools for conducting graphically oriented, interactive sensitivity analyses that enable different views of sensitivity:

- **Performance Sensitivity:** This chart type displays how each alternative performs with respect to the goal and each criterion. Additional charts are required to evaluate sensitivities of each second-level criterion. In Figure A-29, the horizontal colored lines illustrate the relative rankings or performances of each technology relative to each criterion or the goal (overall). The y-axis provides the relative priorities and the criteria are listed across the bottom (x-axis). For example, Figure A-28 shows no difference in performance between technologies when evaluated with respect to the criteria of minimizing environmental impacts during abnormal conditions and during decommissioning, which is depicted by the intersection of colored lines. The vertical line over the work "Overall" indicates the ranking of technology alternatives relative to the goal. Figure A-29 illustrates the Performance Sensitivity graph for the baseline conditions of the goal.

- **Dynamic Sensitivity:** As implied by the name, this tool allows users to change the priorities of the criteria interactively on the chart to determine how the changes affect the priorities of the technology alternatives. This was the preferred tool for conducting the sensitivity analysis in this report. Figure A-30 illustrates the Dynamic Sensitivity chart for the baseline conditions. It shows the relative rankings of the criteria on the left side and the technologies on the right; both rankings are provided as bar-charts and percentages. As changes are made to the criteria weightings by sliding the bars right or left reflecting greater or lesser relative importance, respectively, the impact to the relative ranking of the other criteria on the left side and technology rankings on the right side change accordingly.

- **Gradient Sensitivity:** Gradient sensitivity charts illustrate the composite priority of the technology alternatives with respect to the priority of a single criterion and show "key tradeoffs" when two or more alternatives intersect each other. Figure A-31 illustrates the priorities of the technology alternatives (y-axis) with respect to the priorities of the criterion of minimizing environmental impacts during routine operations of the stabilization facility (x-axis). The vertical red line represents the default priority of this criterion, which equals 0.065 in this case.

- **Head-to-Head Sensitivity:** This chart type displays how any two alternatives compare with respect to the goal and each criterion. Therefore, in addition to the chart for the goal, there could be as many head-to-head sensitivity charts as there are pairs of criteria. Figure A-32 illustrates the head-to-head sensitivity between technology alternative 1 (Option A process+no macroencapsulation+centralized treatment) versus 2 (Option A process+no macroencapsulation+mobile treatment). Alternative 1 is shown on the left half of the figure and alternative 2 is shown on the right half. The criteria are listed down the middle of the chart. The directions of the bars that originate from the middle indicate the technology preferences relative to the particular criterion. For example in Figure A-32, Alternative 2 is preferred over Alternative 1 during transportation (red bar) and overall (grey bar) since the bars are pointing towards Alternative 2. The sizes of the bars represent the relative magnitudes of the preferences.

- **Two-Dimensional Sensitivity:** These charts are also known as Bubble Plots and display how alternatives (represented by circles) perform with respect to any of two different criteria. Figure A-33 illustrates how the criterion of minimizing environmental impacts during storage in the monofill (x-axis) performs relative to the criterion of minimizing environmental impacts during transportation (y-axis). Two-dimensional plots are divided into four quadrants. Favorable alternatives appear higher and to the right (i.e., the upper-right quadrant includes most favorable technology) while less favorable alternatives appear lower and to the left (i.e., the lower-left quadrant includes the least favorable technologies). Although the technology alternative names are truncated on Figure A-33, the most preferred technology (furthest up and to the right) is Technology Alternative 4 (Option A process+macroencapsulation+mobile treatment) and the least preferred technologies are either Technology Alternatives 1 (Option A process+no macroencapsulation+centralized treatment) or 9 (Option C process+no macroencapsulation+centralized treatment). It is important to note that this type of sensitivity chart illustrates performance with respect to two particular criteria of concern, so there could be as many charts as there are head-to-head comparisons.

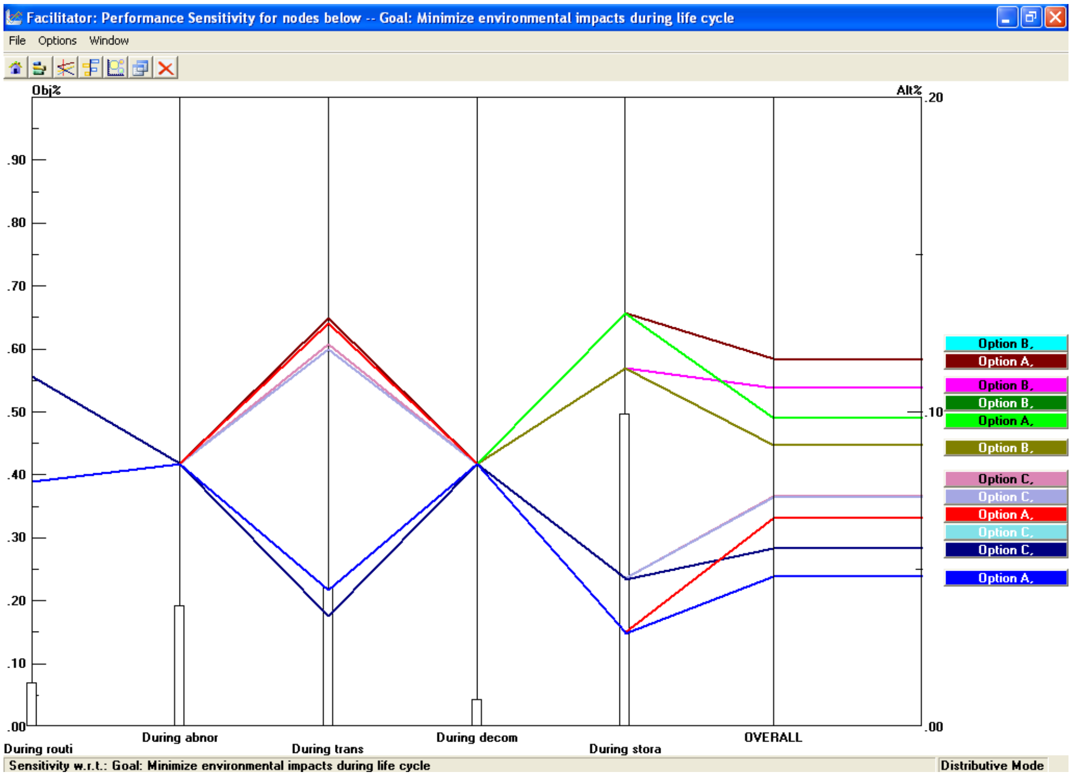


Figure A-29. Performance Sensitivity Chart for Baseline Conditions

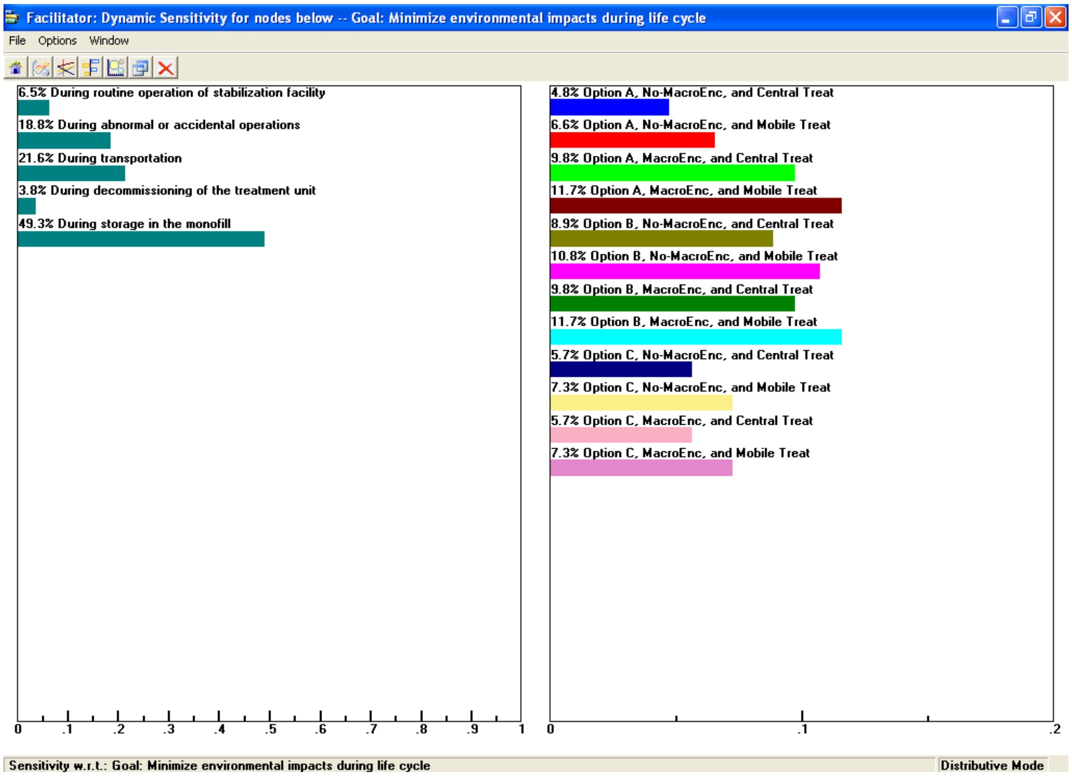


Figure A-30. Dynamic Sensitivity Chart for Baseline Conditions

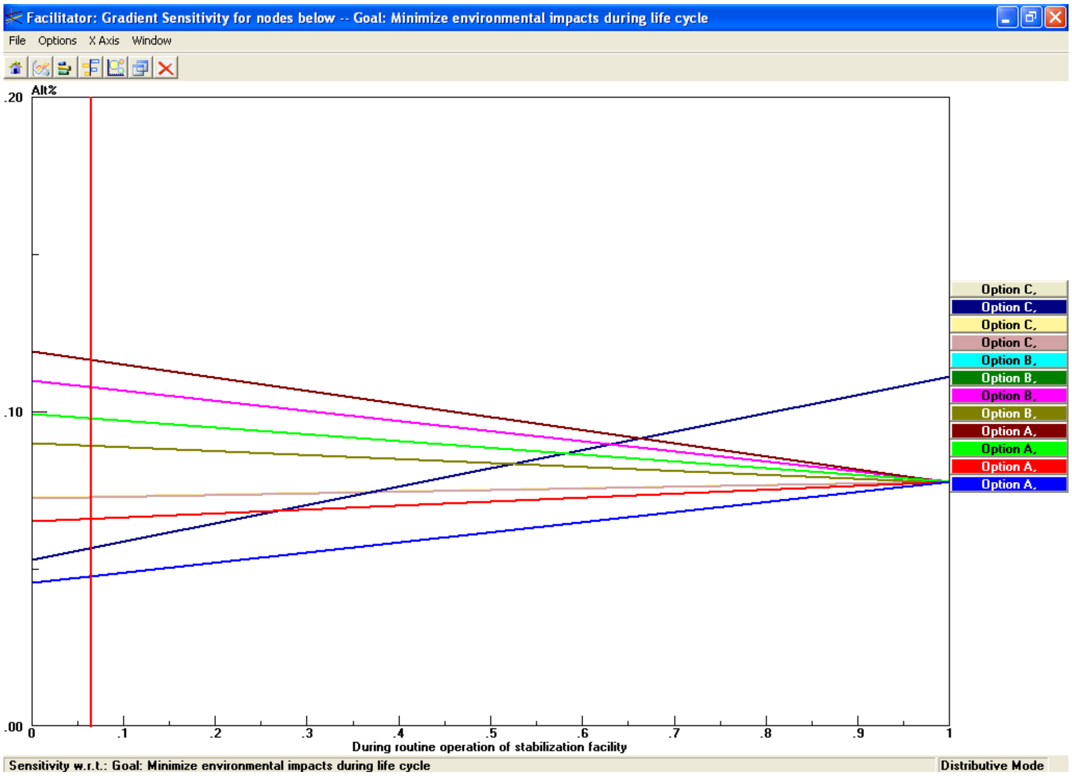


Figure A-31. Gradient Sensitivity Chart for Baseline Conditions

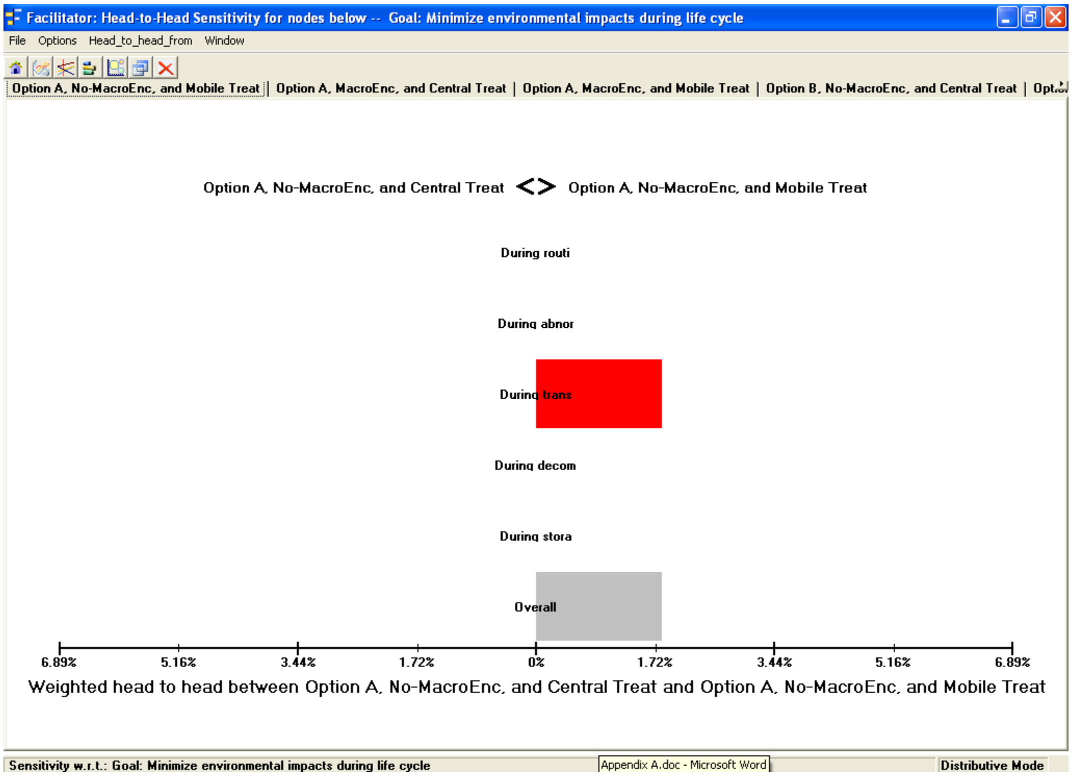


Figure A-32. Head-to-Head Sensitivity Chart for Baseline Conditions

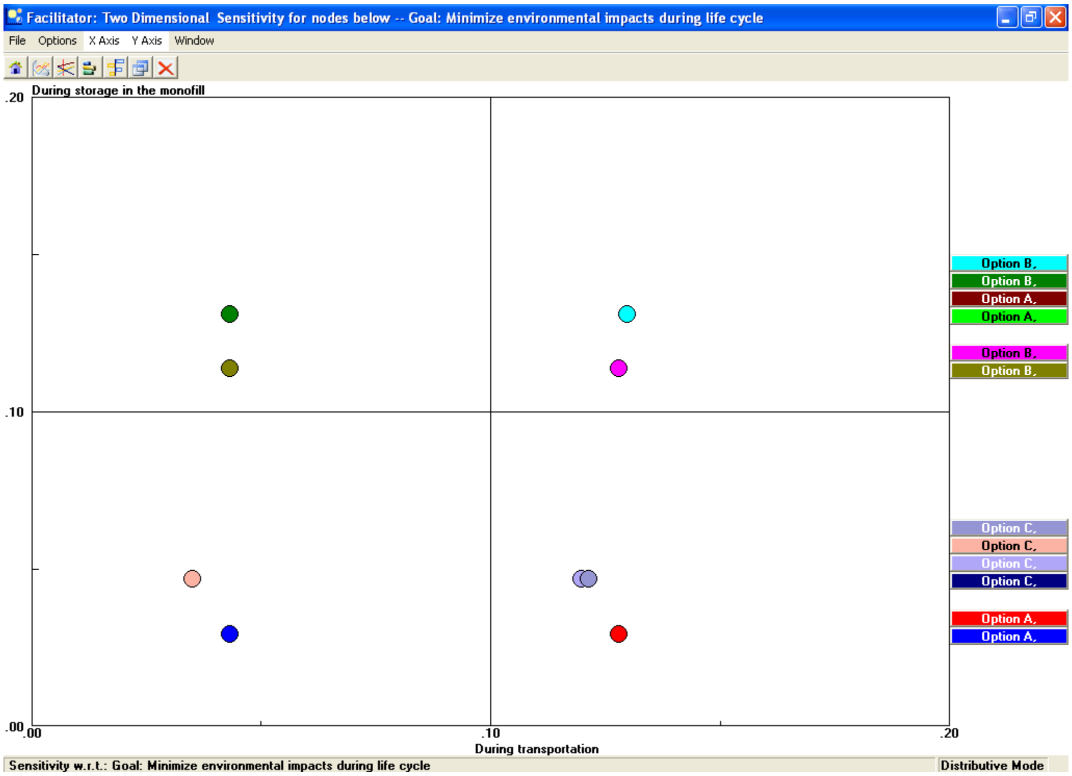
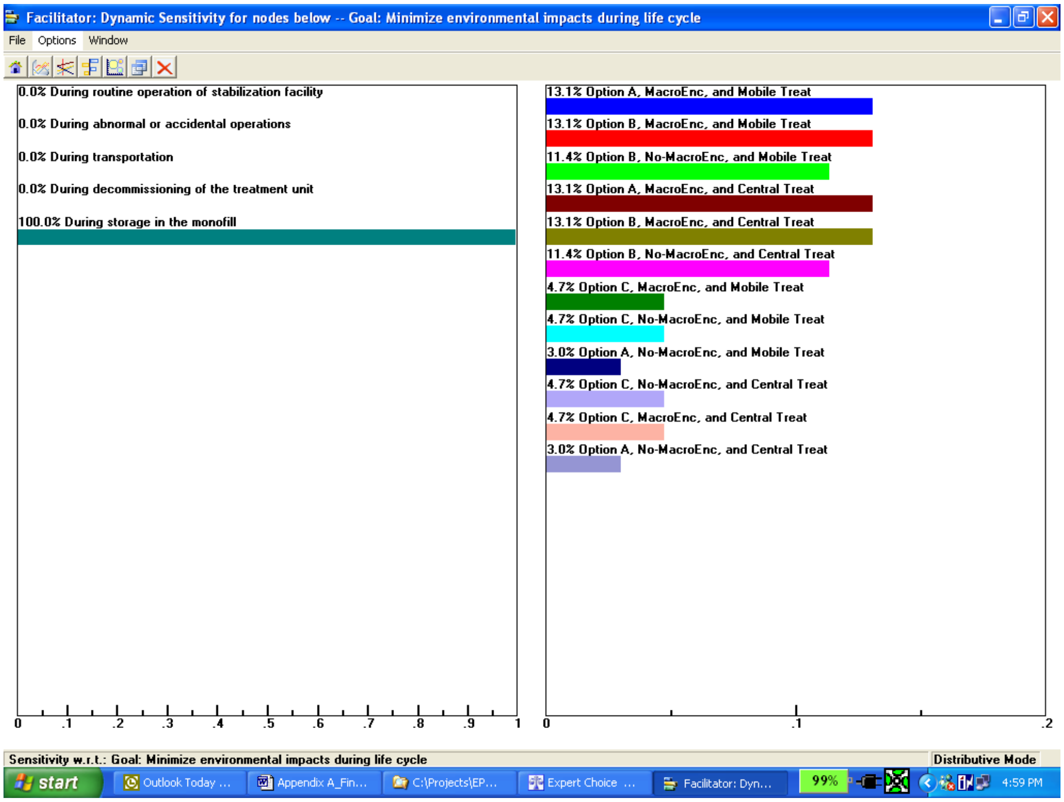


Figure A-33. Two-Dimensional Sensitivity Chart for Baseline Conditions

In conducting the sensitivity analyses, Expert Choice® includes an option to open the Performance, Dynamic, Gradient, and Head-to-Head charts simultaneously. Changes made to the Performance charts are reflected in the other charts. This feature was used when conducting the sensitivity analyses for this project. Figure A-30 above illustrated the Dynamic Sensitivity chart under baseline conditions and can be used as a point of reference in assessing the differences resulting from the following changes made as a function of the sensitivity analyses:

- Changing the weight of the final disposal criterion from baseline (49.3%) to 100% (i.e., more important, Figure A-34)
- Changing the weight of the final disposal criterion from baseline (49.3%)to 0% (i.e., less important, Figure A-35)
- Changing the weight of the transportation criterion from baseline (21.6%) to 40% (i.e., more important, Figure A-36)
- Changing the weight of the transportation criterion from baseline (21.6%)to 10% (i.e., less important, Figure A-37)
- Changing the weight of the abnormal/ accidental operations criterion from baseline (18.8%) to 40% (i.e., more important, Figure A-38)
- Changing the weight of the abnormal/ accidental operations criterion from baseline (18.8%) to 10% (i.e., less important, Figure A-39)
- Changing the weight of the routine operations criterion from 6.5% to 13% (i.e., more important, Figure A-40)
- Changing the weight of the routine operations criterion from 6.5% to 3.2% (i.e., less important, Figure A-41)
- Changing the weight of the decommissioning criterion from 3.8% to 7.6% (i.e., more important, Figure A-42)
- Changing the weight of the decommissioning criterion from 3.8% to 1.8% (i.e., less important, Figure A-43).

In addition to the sensitivity analyses, eleven sets of uncertainty analyses (UAs) were conducted to assess the confidence in the results. UAs identify the extent to which variation in the information and data influences appropriate conclusions. 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. Figure A-44 summarizes the 11 UAs by illustrating the changes that were made to the intensity evaluations. Figures A-45 through A-55 illustrate the synthesized results resulting from the eleven UAs

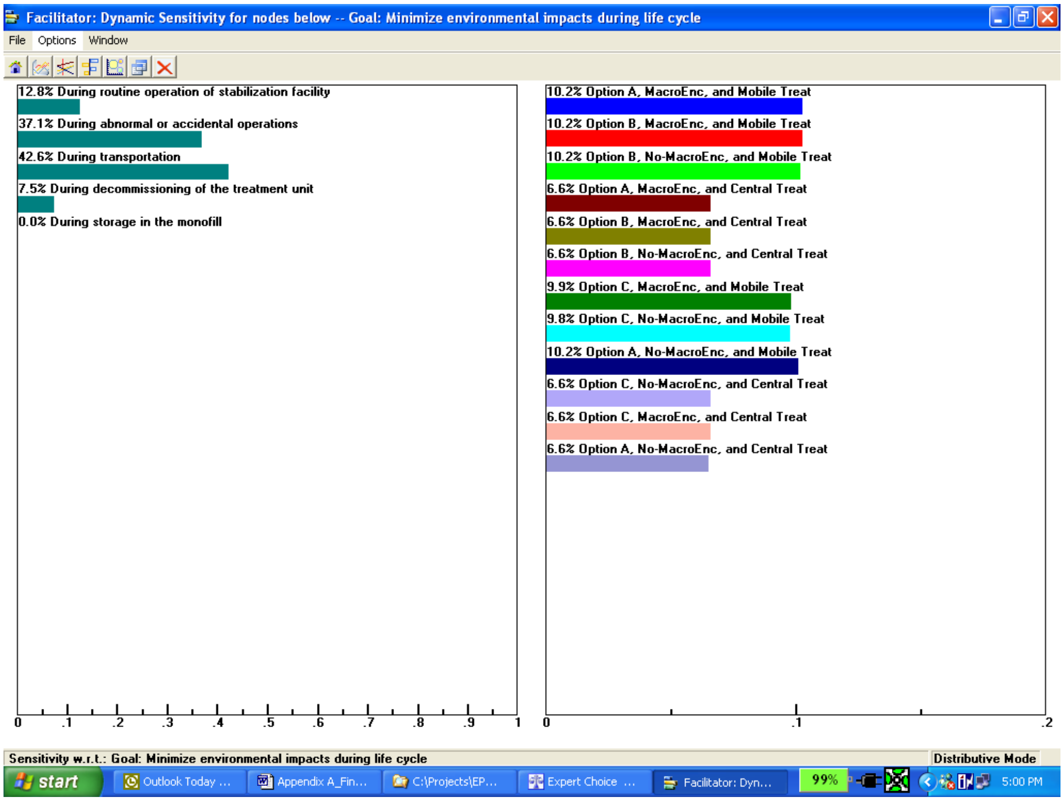

Facilitator: Dynamic Sensitivity for nodes below -- Goal: Minimize environmental impacts during life cycle

0.0% During routine operation of stabilization facility
0.0% During abnormal or accidental operations
0.0% During transportation
0.0% During decommissioning of the treatment unit
100.0% During storage in the monofill

13.1% Option A, MacroEnc, and Mobile Treat
13.1% Option B, MacroEnc, and Mobile Treat
11.4% Option B, No-MacroEnc, and Mobile Treat
13.1% Option A, MacroEnc, and Central Treat
13.1% Option B, MacroEnc, and Central Treat
11.4% Option B, No-MacroEnc, and Central Treat
4.7% Option C, MacroEnc, and Mobile Treat
4.7% Option C, No-MacroEnc, and Mobile Treat
3.0% Option A, No-MacroEnc, and Mobile Treat
4.7% Option C, No-MacroEnc, and Central Treat
4.7% Option C, MacroEnc, and Central Treat
3.0% Option A, No-MacroEnc, and Central Treat

Sensitivity w.r.t.: Goal: Minimize environmental impacts during life cycle
Distributive Mode

Figure A-34. Sensitivity of Changing Final Disposal Criterion from Baseline to 100%


Facilitator: Dynamic Sensitivity for nodes below -- Goal: Minimize environmental impacts during life cycle

12.8% During routine operation of stabilization facility
37.1% During abnormal or accidental operations
42.6% During transportation
7.5% During decommissioning of the treatment unit
0.0% During storage in the monofill

10.2% Option A, MacroEnc, and Mobile Treat
10.2% Option B, MacroEnc, and Mobile Treat
10.2% Option B, No-MacroEnc, and Mobile Treat
6.6% Option A, MacroEnc, and Central Treat
6.6% Option B, MacroEnc, and Central Treat
6.6% Option B, No-MacroEnc, and Central Treat
9.9% Option C, MacroEnc, and Mobile Treat
9.8% Option C, No-MacroEnc, and Mobile Treat
10.2% Option A, No-MacroEnc, and Mobile Treat
6.6% Option C, No-MacroEnc, and Central Treat
6.6% Option C, MacroEnc, and Central Treat
6.6% Option A, No-MacroEnc, and Central Treat

Sensitivity w.r.t.: Goal: Minimize environmental impacts during life cycle
Distributive Mode

Figure A-35. Sensitivity of Changing Final Disposal Criterion from Baseline to 0%

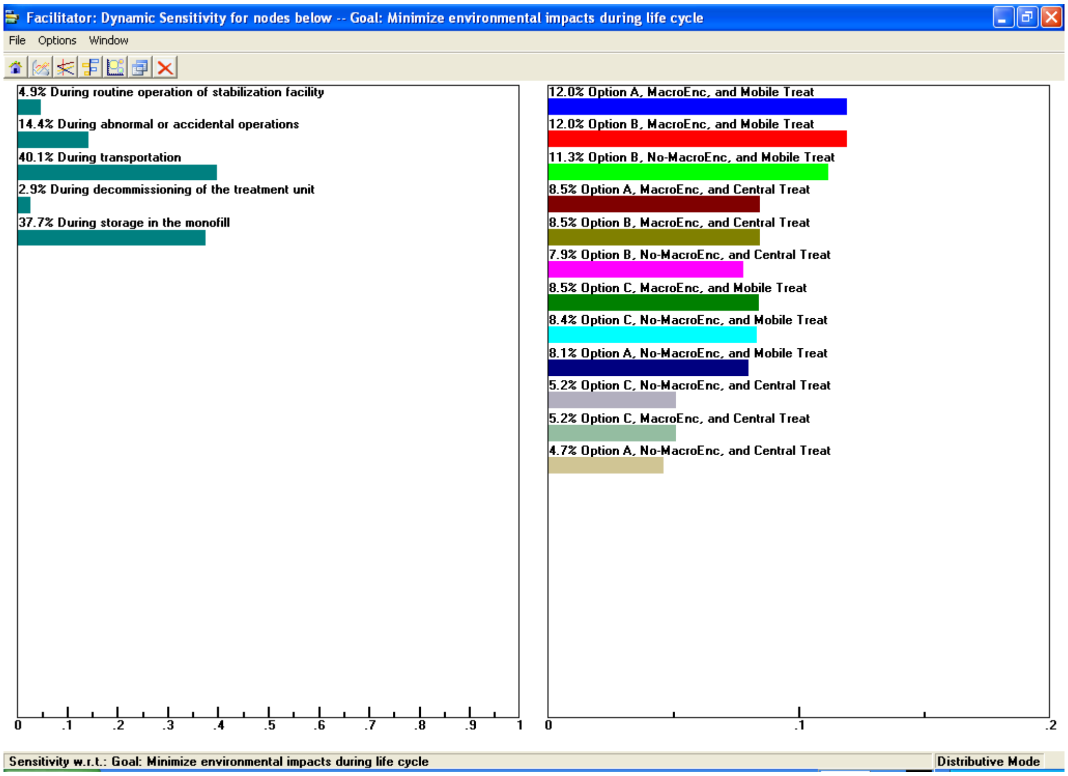


Figure A-36. Sensitivity of Changing Transportation Criterion from Baseline to 40%

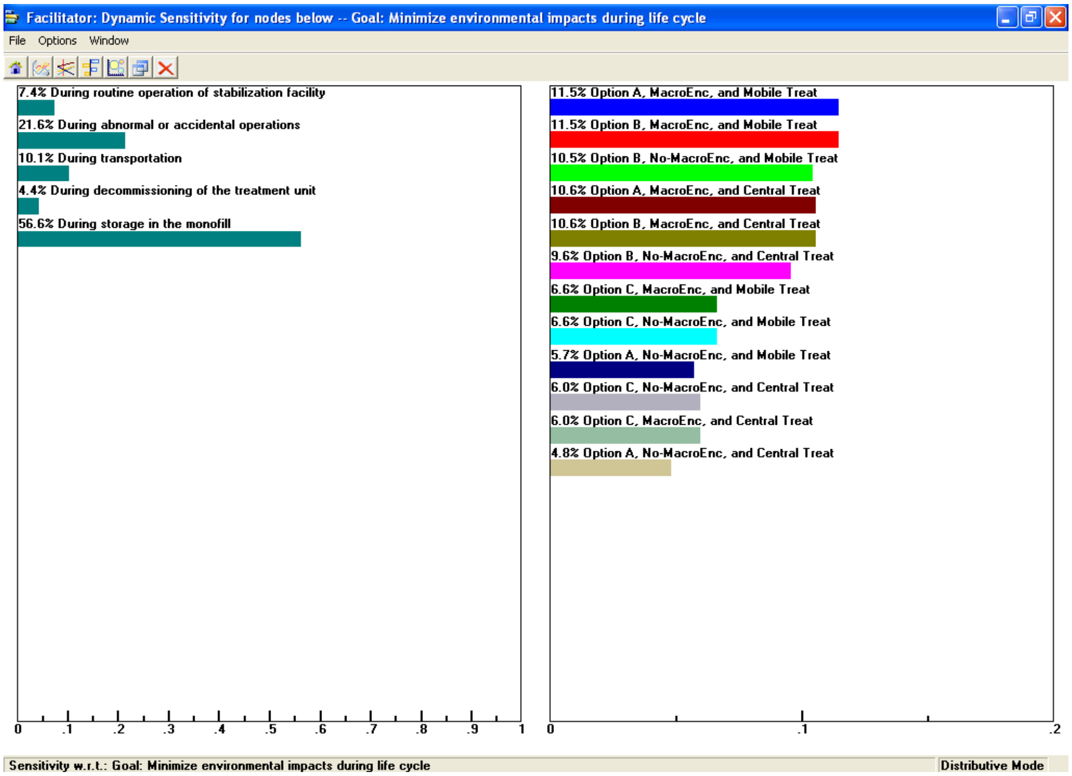
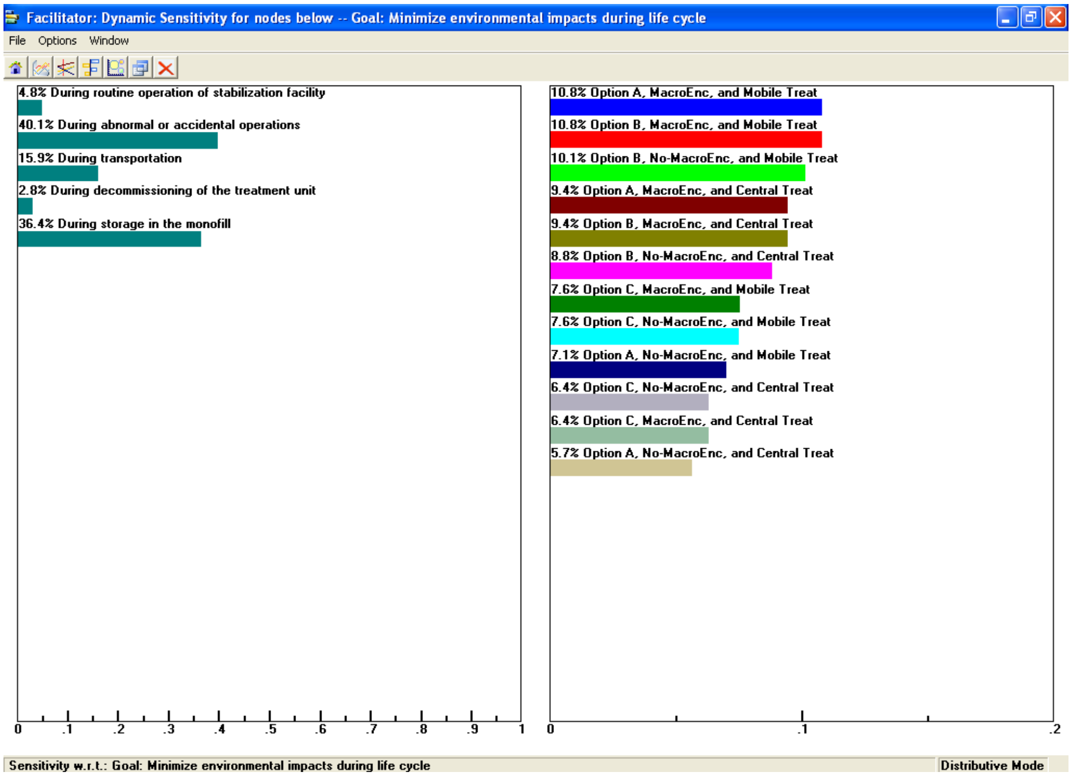


Figure A-37. Sensitivity of Changing Transportation Criterion from Baseline to 10%

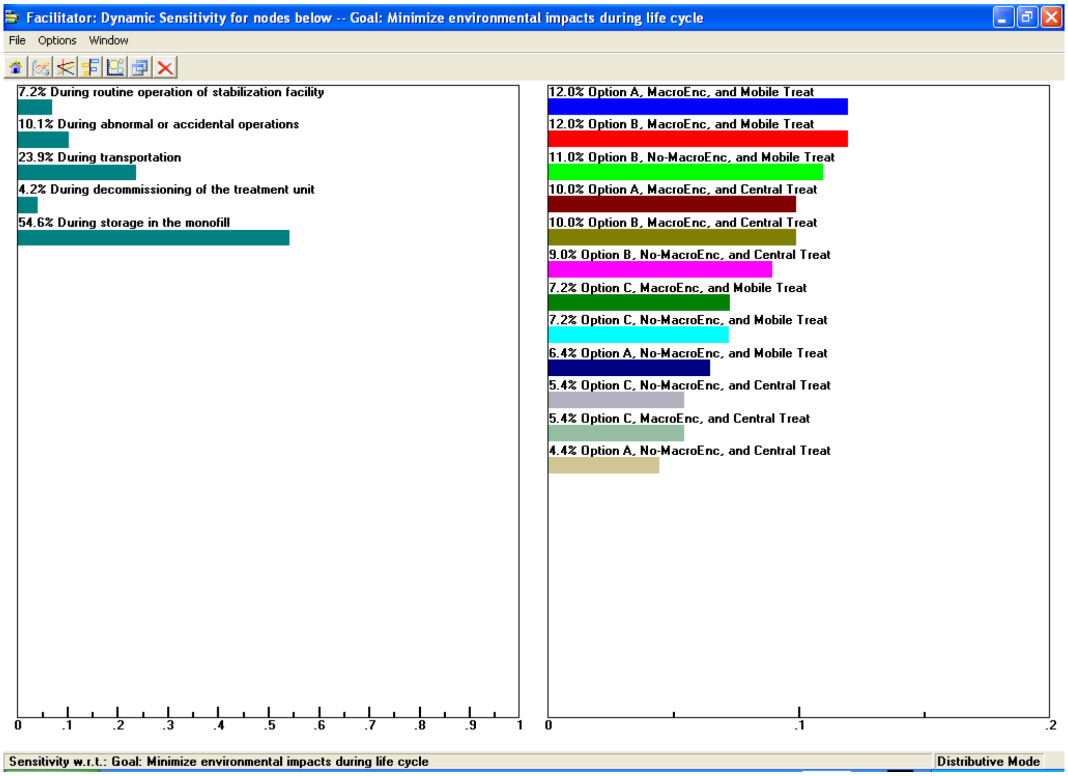


4.8% During routine operation of stabilization facility
40.1% During abnormal or accidental operations
15.9% During transportation
2.8% During decommissioning of the treatment unit
36.4% During storage in the monofill

10.8% Option A, MacroEnc, and Mobile Treat
10.8% Option B, MacroEnc, and Mobile Treat
10.1% Option B, No-MacroEnc, and Mobile Treat
9.4% Option A, MacroEnc, and Central Treat
9.4% Option B, MacroEnc, and Central Treat
8.8% Option B, No-MacroEnc, and Central Treat
7.6% Option C, MacroEnc, and Mobile Treat
7.6% Option C, No-MacroEnc, and Mobile Treat
7.1% Option A, No-MacroEnc, and Mobile Treat
6.4% Option C, No-MacroEnc, and Central Treat
6.4% Option C, MacroEnc, and Central Treat
5.7% Option A, No-MacroEnc, and Central Treat

Sensitivity w.r.t.: Goal: Minimize environmental impacts during life cycle
Distributive Mode

Figure A-38. Sensitivity of Changing Abnormal/Accidental Operations Criterion from Baseline to 40%

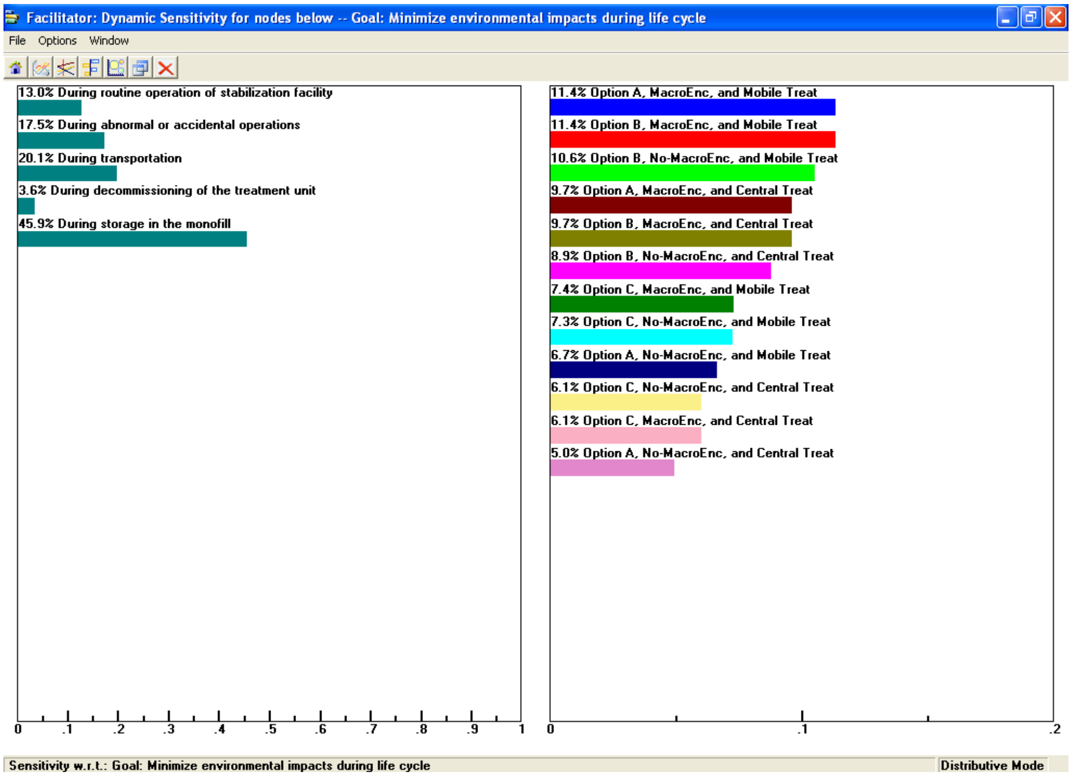


7.2% During routine operation of stabilization facility
10.1% During abnormal or accidental operations
23.9% During transportation
4.2% During decommissioning of the treatment unit
54.6% During storage in the monofill

12.0% Option A, MacroEnc, and Mobile Treat
12.0% Option B, MacroEnc, and Mobile Treat
11.0% Option B, No-MacroEnc, and Mobile Treat
10.0% Option A, MacroEnc, and Central Treat
10.0% Option B, MacroEnc, and Central Treat
9.0% Option B, No-MacroEnc, and Central Treat
7.2% Option C, MacroEnc, and Mobile Treat
7.2% Option C, No-MacroEnc, and Mobile Treat
6.4% Option A, No-MacroEnc, and Mobile Treat
5.4% Option C, No-MacroEnc, and Central Treat
5.4% Option C, MacroEnc, and Central Treat
4.4% Option A, No-MacroEnc, and Central Treat

Sensitivity w.r.t.: Goal: Minimize environmental impacts during life cycle
Distributive Mode

Figure A-39. Sensitivity of Changing Abnormal/Accidental Operations Criterion from Baseline to 10%



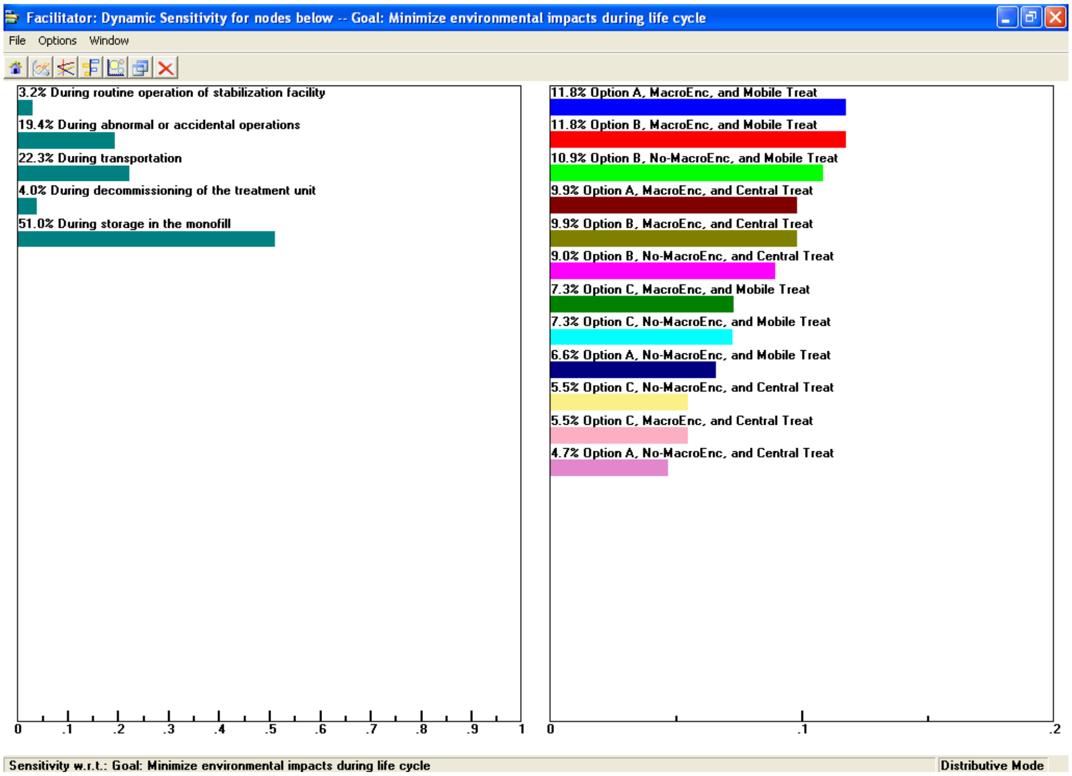
Facilitator: Dynamic Sensitivity for nodes below -- Goal: Minimize environmental impacts during life cycle

13.0% During routine operation of stabilization facility
17.5% During abnormal or accidental operations
20.1% During transportation
3.6% During decommissioning of the treatment unit
45.9% During storage in the monofill

11.4% Option A, MacroEnc, and Mobile Treat
11.4% Option B, MacroEnc, and Mobile Treat
10.6% Option B, No-MacroEnc, and Mobile Treat
9.7% Option A, MacroEnc, and Central Treat
9.7% Option B, MacroEnc, and Central Treat
8.9% Option B, No-MacroEnc, and Central Treat
7.4% Option C, MacroEnc, and Mobile Treat
7.3% Option C, No-MacroEnc, and Mobile Treat
6.7% Option A, No-MacroEnc, and Mobile Treat
6.1% Option C, No-MacroEnc, and Central Treat
6.1% Option C, MacroEnc, and Central Treat
5.0% Option A, No-MacroEnc, and Central Treat

Sensitivity w.r.t.: Goal: Minimize environmental impacts during life cycle

Figure A-40. Sensitivity of Changing Routine Operations Criterion from Baseline to 13%



Facilitator: Dynamic Sensitivity for nodes below -- Goal: Minimize environmental impacts during life cycle

3.2% During routine operation of stabilization facility
19.4% During abnormal or accidental operations
22.3% During transportation
4.0% During decommissioning of the treatment unit
51.0% During storage in the monofill

11.8% Option A, MacroEnc, and Mobile Treat
11.8% Option B, MacroEnc, and Mobile Treat
10.9% Option B, No-MacroEnc, and Mobile Treat
9.9% Option A, MacroEnc, and Central Treat
9.9% Option B, MacroEnc, and Central Treat
9.0% Option B, No-MacroEnc, and Central Treat
7.3% Option C, MacroEnc, and Mobile Treat
7.3% Option C, No-MacroEnc, and Mobile Treat
6.6% Option A, No-MacroEnc, and Mobile Treat
5.5% Option C, No-MacroEnc, and Central Treat
5.5% Option C, MacroEnc, and Central Treat
4.7% Option A, No-MacroEnc, and Central Treat

Sensitivity w.r.t.: Goal: Minimize environmental impacts during life cycle

Figure A-41. Sensitivity of Changing Routine Operations Criterion from Baseline to 3.2%

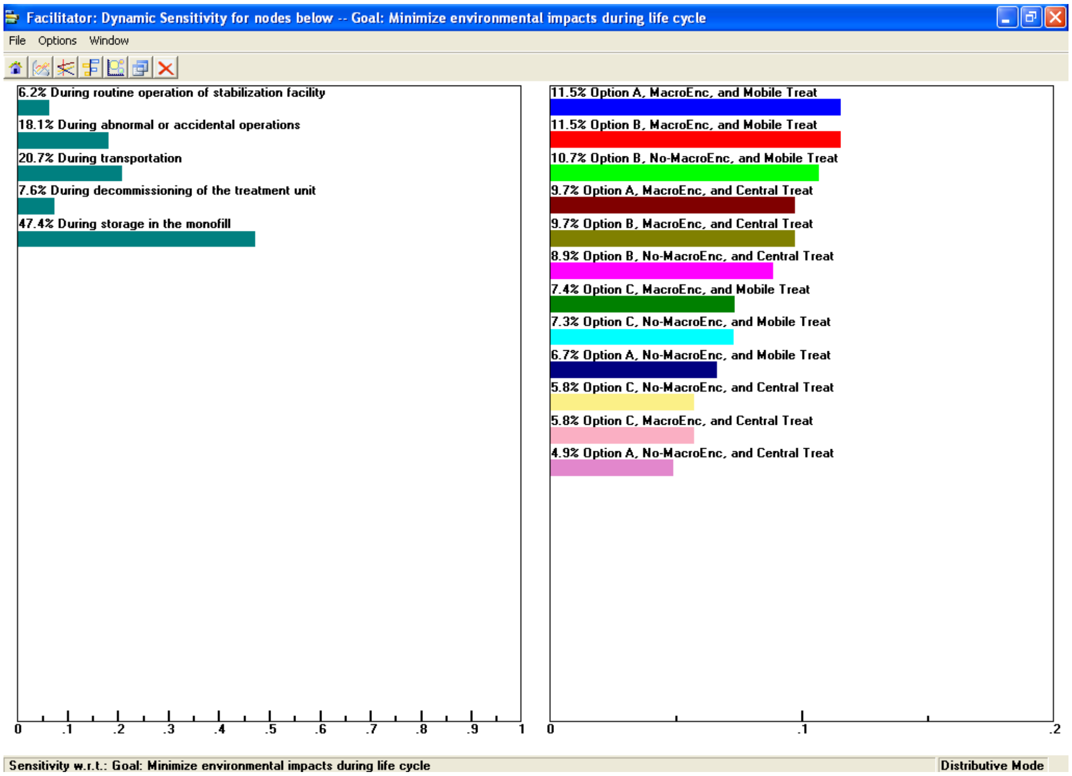


Figure A-42. Sensitivity of Changing Decommissioning Criterion from Baseline to 7.6%

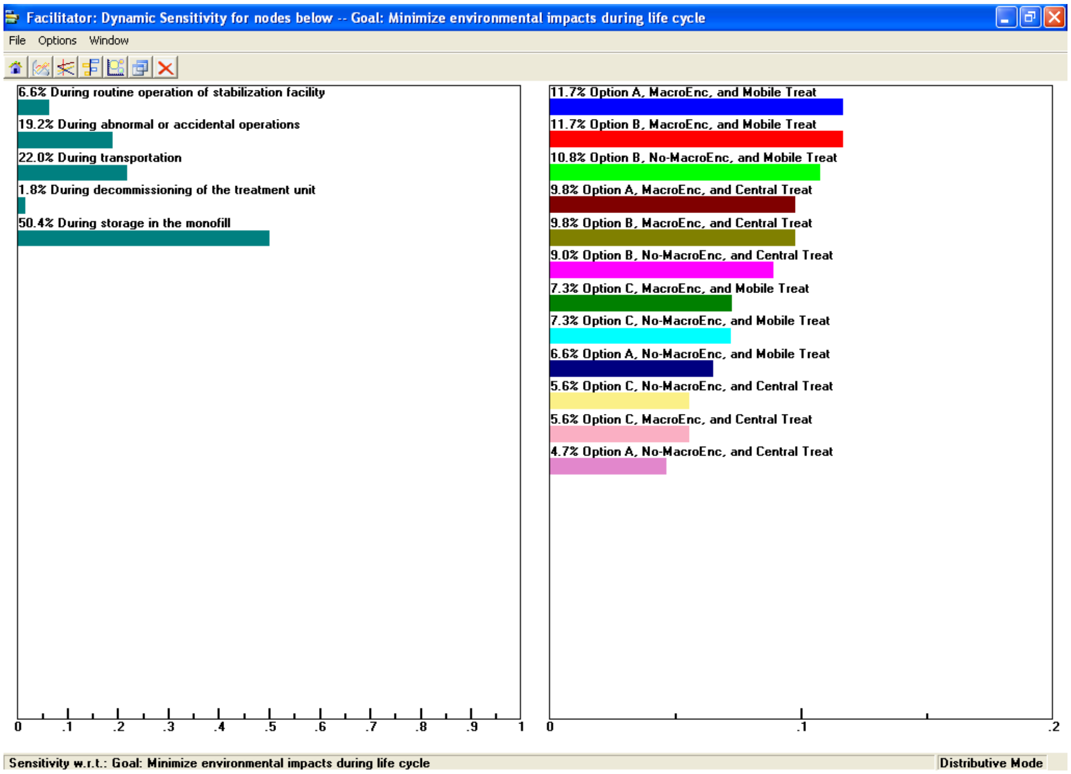
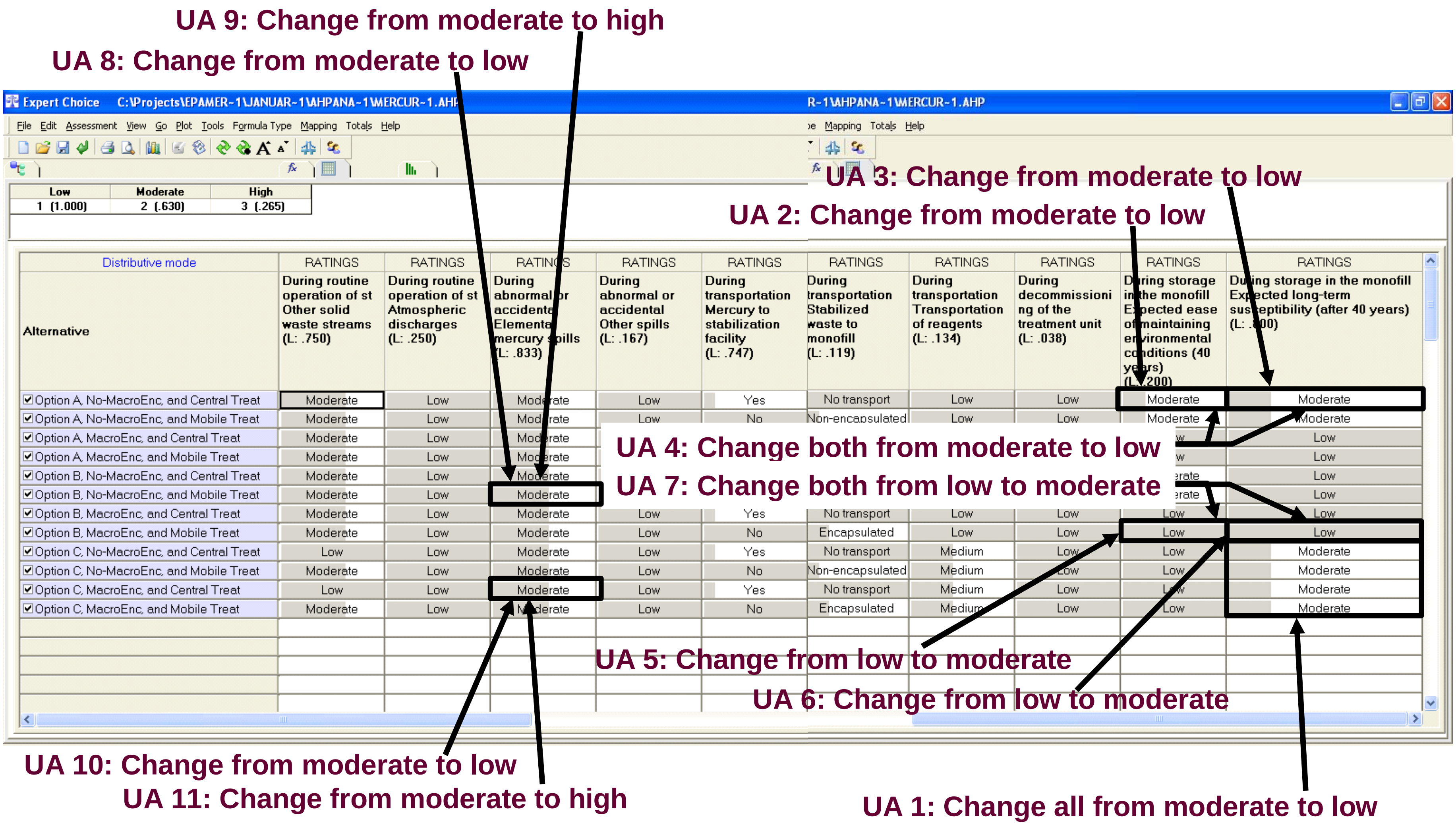


Figure A-43. Sensitivity of Changing Decommissioning Criterion from Baseline to 1.8%



UA 9: Change from moderate to high

UA 8: Change from moderate to low

UA 3: Change from moderate to low

UA 2: Change from moderate to low

Low	Moderate	High
1 (1.000)	2 (.630)	3 (.265)

Distributive mode	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS	RATINGS
Alternative	During routine operation of st Other solid waste streams (L: .750)	During routine operation of st Atmospheric discharges (L: .250)	During abnormal or accidental Elemental mercury spills (L: .833)	During abnormal or accidental Other spills (L: .167)	During transportation Mercury to stabilization facility (L: .747)	During transportation Stabilized waste to monofill (L: .119)	During transportation Transportation of reagents (L: .134)	During decommissioning of the treatment unit (L: .038)	During storage in the monofill Expected ease of maintaining environmental conditions (40 years) (L: .200)	During storage in the monofill Expected long-term susceptibility (after 40 years) (L: .800)
☑ Option A, No-MacroEnc, and Central Treat	Moderate	Low	Moderate	Low	Yes	No transport	Low	Low	Moderate	Moderate
☑ Option A, No-MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Non-encapsulated	Low	Low	Moderate	Moderate
☑ Option A, MacroEnc, and Central Treat	Moderate	Low	Moderate						w	Low
☑ Option A, MacroEnc, and Mobile Treat	Moderate	Low	Moderate						w	Low
☑ Option B, No-MacroEnc, and Central Treat	Moderate	Low	Moderate						erate	Low
☑ Option B, No-MacroEnc, and Mobile Treat	Moderate	Low	Moderate						erate	Low
☑ Option B, MacroEnc, and Central Treat	Moderate	Low	Moderate	Low	Yes	No transport	Low	Low	Low	Low
☑ Option B, MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Encapsulated	Low	Low	Low	Low
☑ Option C, No-MacroEnc, and Central Treat	Low	Low	Moderate	Low	Yes	No transport	Medium	Low	Low	Moderate
☑ Option C, No-MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Non-encapsulated	Medium	Low	Low	Moderate
☑ Option C, MacroEnc, and Central Treat	Low	Low	Moderate	Low	Yes	No transport	Medium	Low	Low	Moderate
☑ Option C, MacroEnc, and Mobile Treat	Moderate	Low	Moderate	Low	No	Encapsulated	Medium	Low	Low	Moderate

UA 4: Change both from moderate to low

UA 7: Change both from low to moderate

UA 5: Change from low to moderate

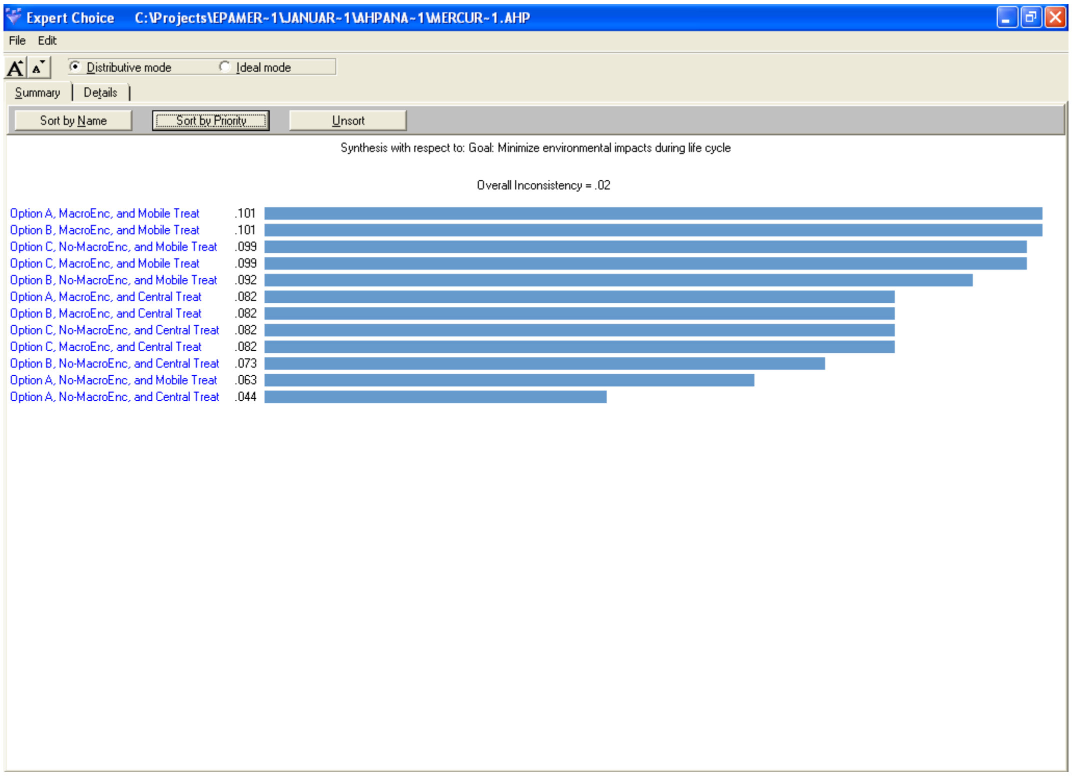
UA 6: Change from low to moderate

UA 10: Change from moderate to low

UA 11: Change from moderate to high

UA 1: Change all from moderate to low

Figure A-44. Uncertainty Analyses



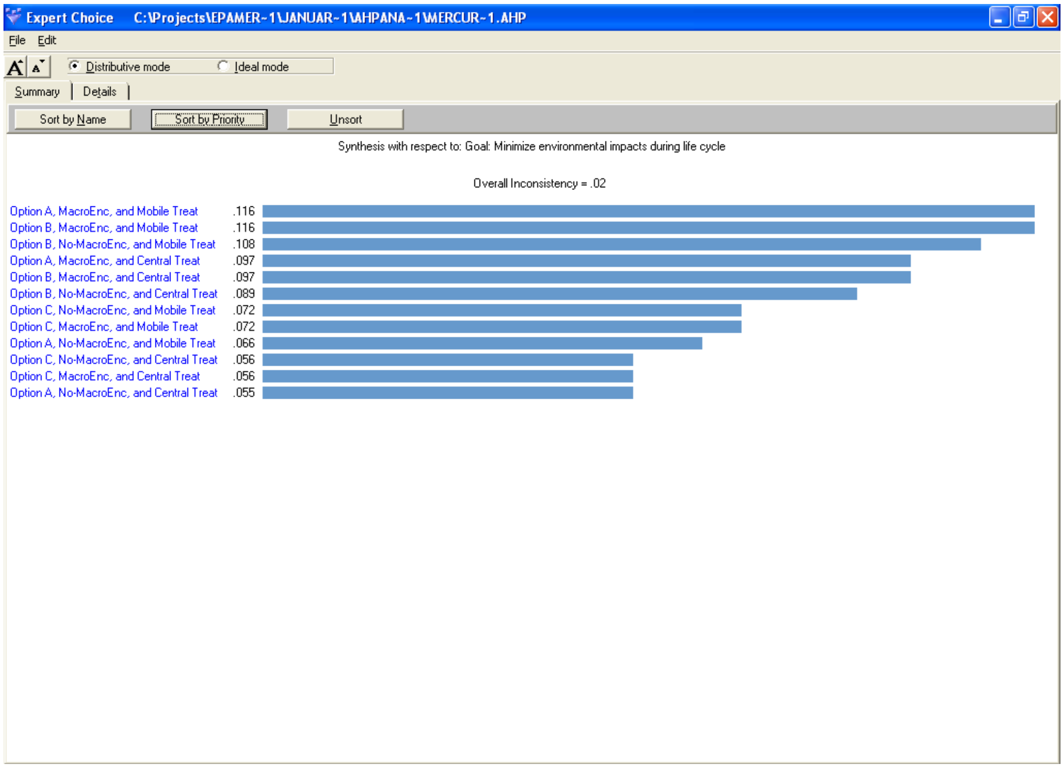
● Distributive mode ○ Ideal mode

Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat	.101
Option B, MacroEnc, and Mobile Treat	.101
Option C, No-MacroEnc, and Mobile Treat	.099
Option C, MacroEnc, and Mobile Treat	.099
Option B, No-MacroEnc, and Mobile Treat	.092
Option A, MacroEnc, and Central Treat	.082
Option B, MacroEnc, and Central Treat	.082
Option C, No-MacroEnc, and Central Treat	.082
Option C, MacroEnc, and Central Treat	.082
Option B, No-MacroEnc, and Central Treat	.073
Option A, No-MacroEnc, and Mobile Treat	.063
Option A, No-MacroEnc, and Central Treat	.044

Figure A-45. Synthesized Results from UA 1



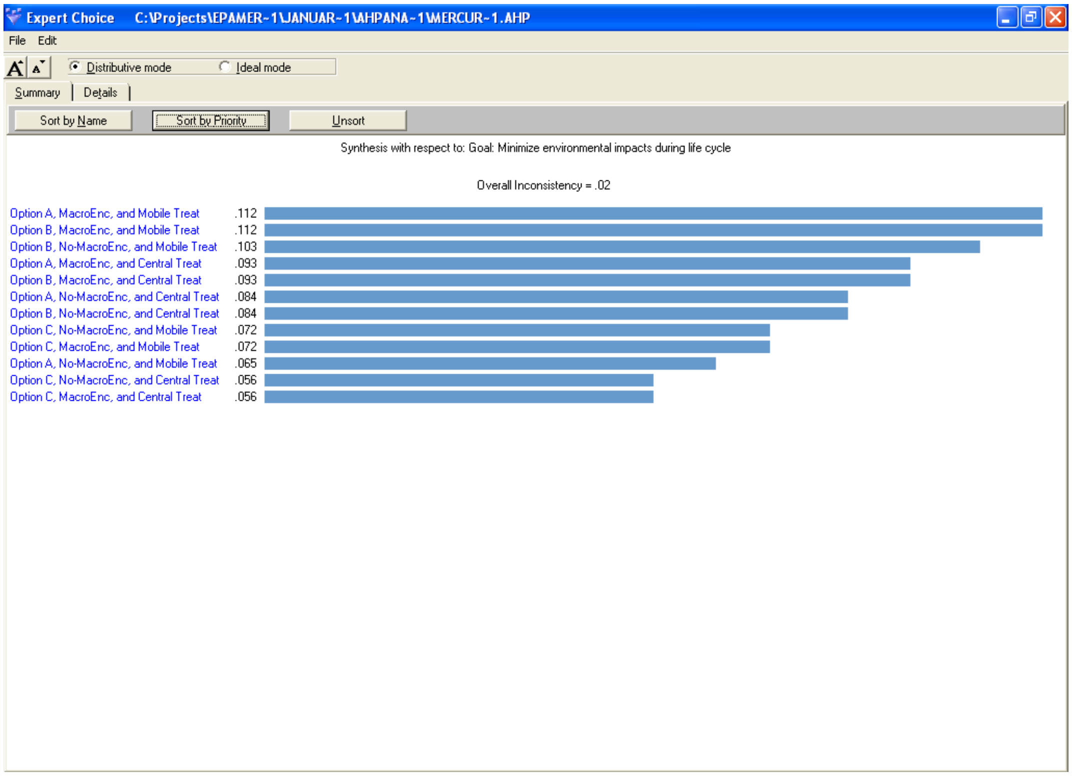
● Distributive mode ○ Ideal mode

Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat	.116
Option B, MacroEnc, and Mobile Treat	.116
Option B, No-MacroEnc, and Mobile Treat	.108
Option A, MacroEnc, and Central Treat	.097
Option B, MacroEnc, and Central Treat	.097
Option B, No-MacroEnc, and Central Treat	.089
Option C, No-MacroEnc, and Mobile Treat	.072
Option C, MacroEnc, and Mobile Treat	.072
Option A, No-MacroEnc, and Mobile Treat	.066
Option C, No-MacroEnc, and Central Treat	.056
Option C, MacroEnc, and Central Treat	.056
Option A, No-MacroEnc, and Central Treat	.055

Figure A-46. Synthesized Results from UA 2



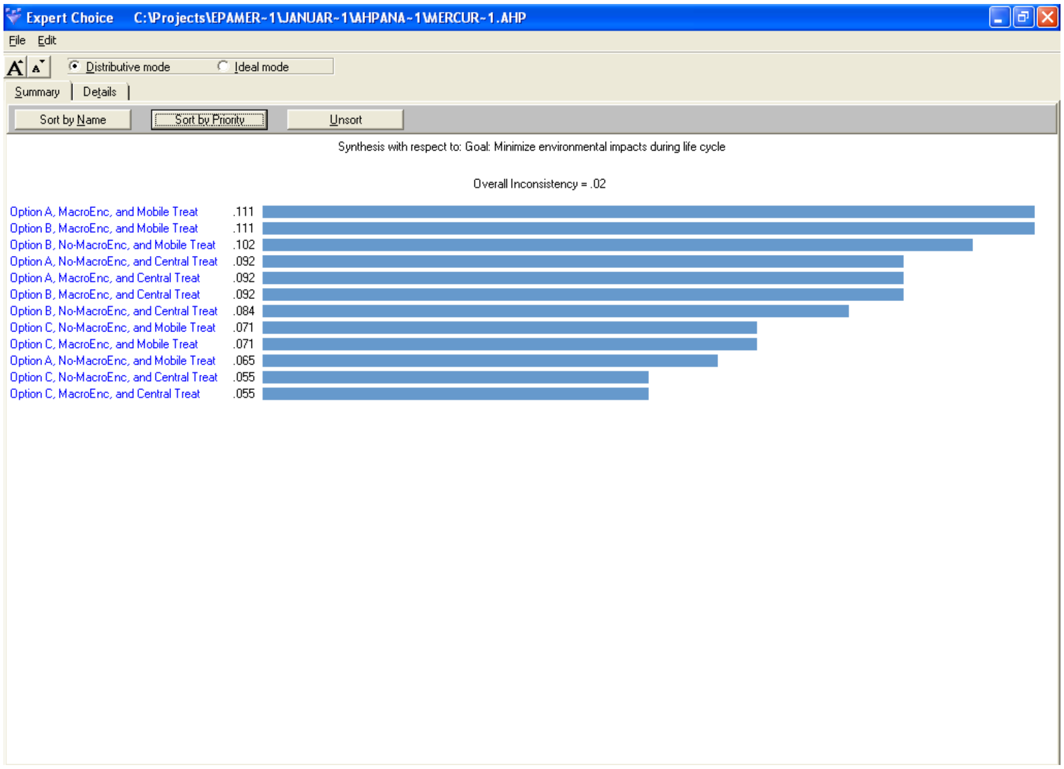
● Distributive mode ○ Ideal mode

```
Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat        .112
Option B, MacroEnc, and Mobile Treat        .112
Option B, No-MacroEnc, and Mobile Treat     .103
Option A, MacroEnc, and Central Treat       .093
Option B, MacroEnc, and Central Treat       .093
Option A, No-MacroEnc, and Central Treat    .084
Option B, No-MacroEnc, and Central Treat    .084
Option C, No-MacroEnc, and Mobile Treat     .072
Option C, MacroEnc, and Mobile Treat        .072
Option A, No-MacroEnc, and Mobile Treat     .065
Option C, No-MacroEnc, and Central Treat    .056
Option C, MacroEnc, and Central Treat       .056
```

Figure A-47. Synthesized Results from UA 3



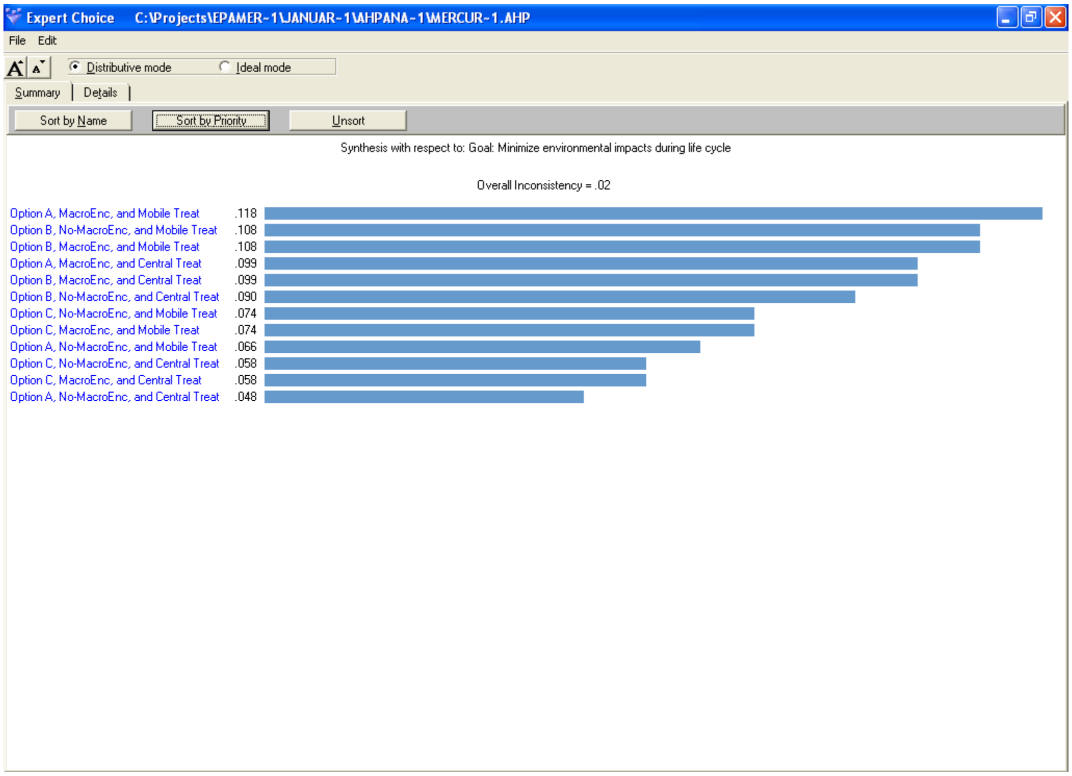
● Distributive mode ○ Ideal mode

```
Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat        .111
Option B, MacroEnc, and Mobile Treat        .111
Option B, No-MacroEnc, and Mobile Treat     .102
Option A, No-MacroEnc, and Central Treat    .092
Option A, MacroEnc, and Central Treat       .092
Option B, MacroEnc, and Central Treat       .092
Option B, No-MacroEnc, and Central Treat    .084
Option C, No-MacroEnc, and Mobile Treat     .071
Option C, MacroEnc, and Mobile Treat        .071
Option A, No-MacroEnc, and Mobile Treat     .065
Option C, No-MacroEnc, and Central Treat    .055
Option C, MacroEnc, and Central Treat       .055
```

Figure A-48. Synthesized Results from UA 4

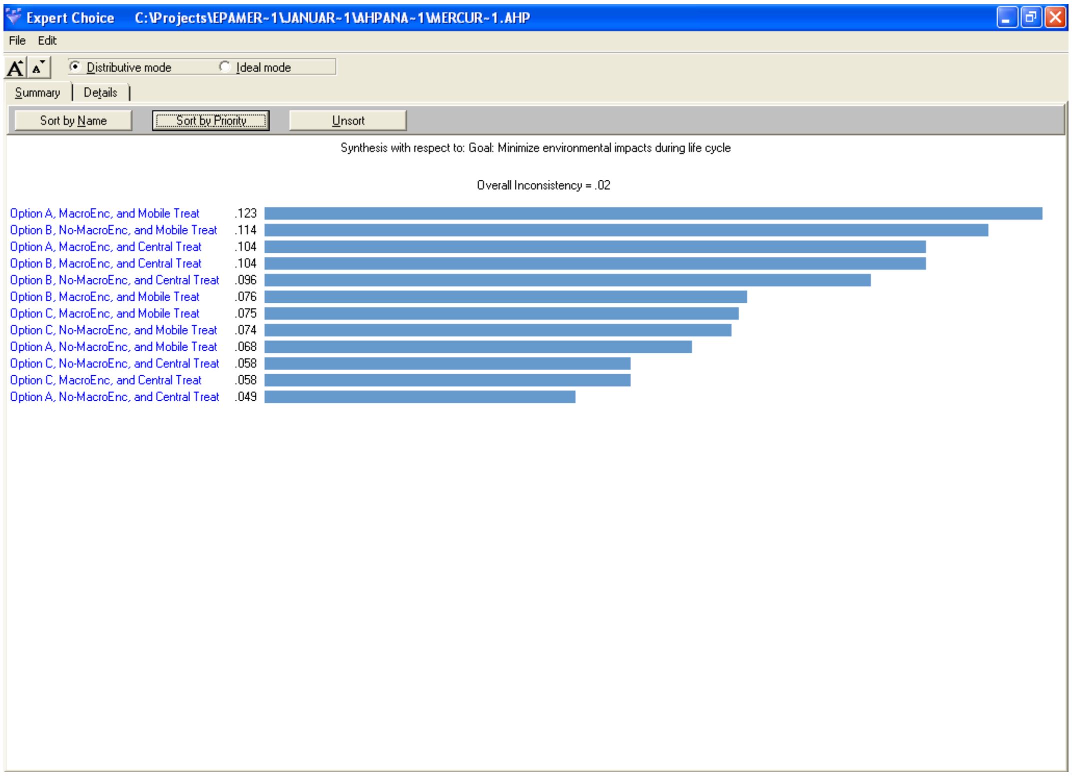


Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat	.118
Option B, No-MacroEnc, and Mobile Treat	.108
Option B, MacroEnc, and Mobile Treat	.108
Option A, MacroEnc, and Central Treat	.099
Option B, MacroEnc, and Central Treat	.099
Option B, No-MacroEnc, and Central Treat	.090
Option C, No-MacroEnc, and Mobile Treat	.074
Option C, MacroEnc, and Mobile Treat	.074
Option A, No-MacroEnc, and Mobile Treat	.066
Option C, No-MacroEnc, and Central Treat	.058
Option C, MacroEnc, and Central Treat	.058
Option A, No-MacroEnc, and Central Treat	.048

Figure A-49. Synthesized Results from UA 5

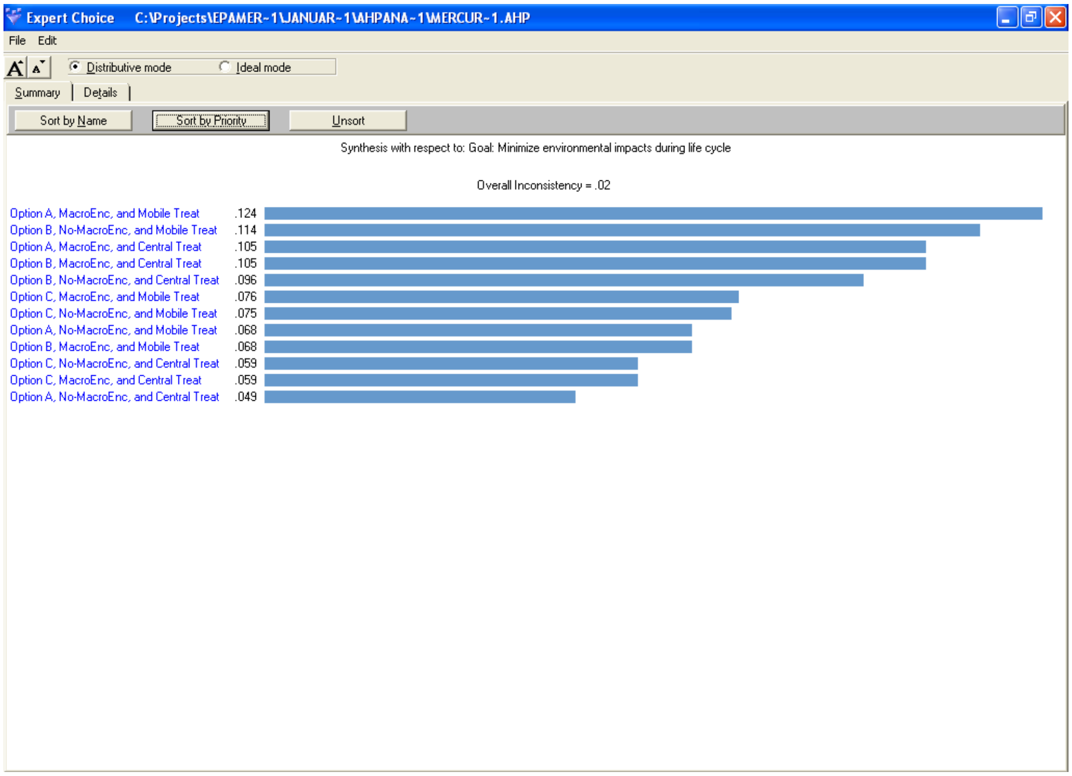


Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat	.123
Option B, No-MacroEnc, and Mobile Treat	.114
Option A, MacroEnc, and Central Treat	.104
Option B, MacroEnc, and Central Treat	.104
Option B, No-MacroEnc, and Central Treat	.096
Option B, MacroEnc, and Mobile Treat	.076
Option C, MacroEnc, and Mobile Treat	.075
Option C, No-MacroEnc, and Mobile Treat	.074
Option A, No-MacroEnc, and Mobile Treat	.068
Option C, No-MacroEnc, and Central Treat	.058
Option C, MacroEnc, and Central Treat	.058
Option A, No-MacroEnc, and Central Treat	.049

Figure A-50. Synthesized Results from UA 6

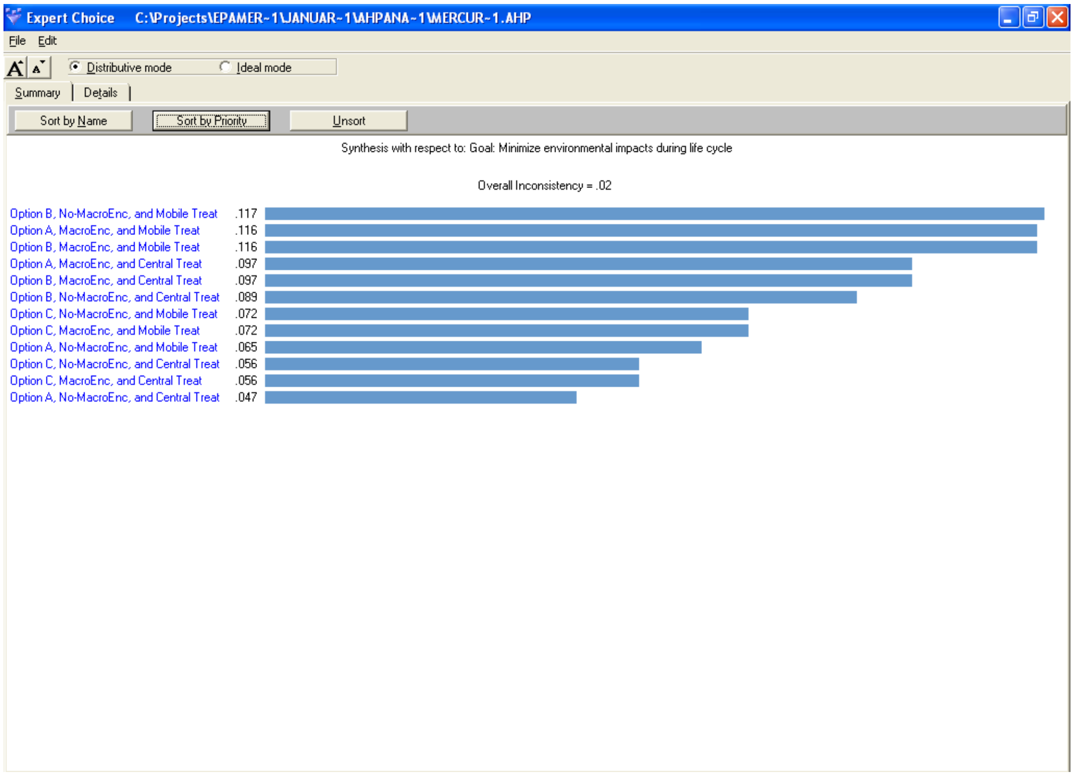


Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat	.124
Option B, No-MacroEnc, and Mobile Treat	.114
Option A, MacroEnc, and Central Treat	.105
Option B, MacroEnc, and Central Treat	.105
Option B, No-MacroEnc, and Central Treat	.096
Option C, MacroEnc, and Mobile Treat	.076
Option C, No-MacroEnc, and Mobile Treat	.075
Option A, No-MacroEnc, and Mobile Treat	.068
Option B, MacroEnc, and Mobile Treat	.068
Option C, No-MacroEnc, and Central Treat	.059
Option C, MacroEnc, and Central Treat	.059
Option A, No-MacroEnc, and Central Treat	.049

Figure A-51. Synthesized Results from UA 7

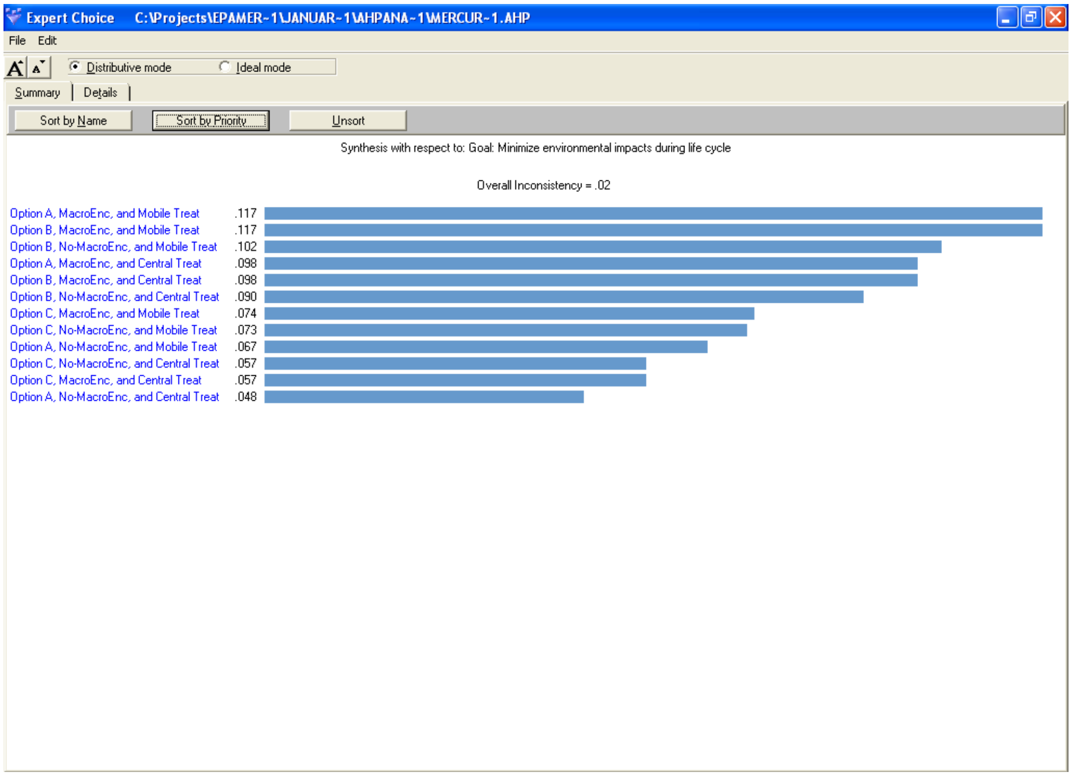


Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option B, No-MacroEnc, and Mobile Treat	.117
Option A, MacroEnc, and Mobile Treat	.116
Option B, MacroEnc, and Mobile Treat	.116
Option A, MacroEnc, and Central Treat	.097
Option B, MacroEnc, and Central Treat	.097
Option B, No-MacroEnc, and Central Treat	.089
Option C, No-MacroEnc, and Mobile Treat	.072
Option C, MacroEnc, and Mobile Treat	.072
Option A, No-MacroEnc, and Mobile Treat	.065
Option C, No-MacroEnc, and Central Treat	.056
Option C, MacroEnc, and Central Treat	.056
Option A, No-MacroEnc, and Central Treat	.047

Figure A-52. Synthesized Results from UA 8



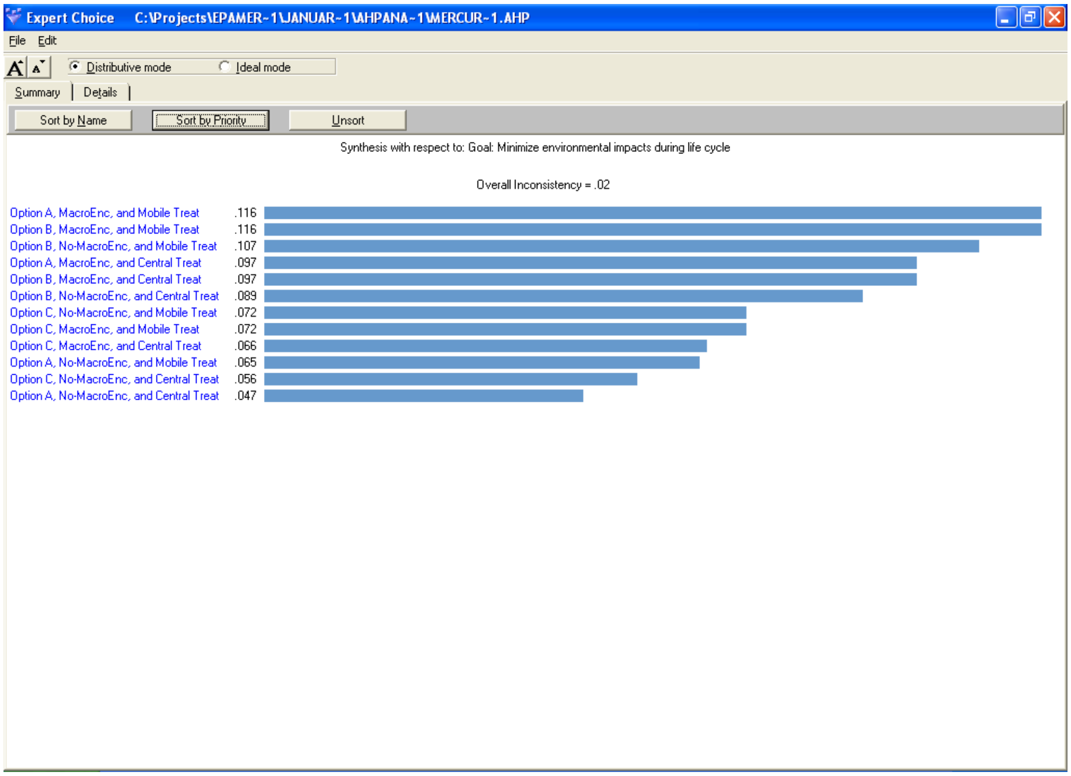
● Distributive mode ○ Ideal mode

```
Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat        .117
Option B, MacroEnc, and Mobile Treat        .117
Option B, No-MacroEnc, and Mobile Treat     .102
Option A, MacroEnc, and Central Treat       .098
Option B, MacroEnc, and Central Treat       .098
Option B, No-MacroEnc, and Central Treat    .090
Option C, MacroEnc, and Mobile Treat        .074
Option C, No-MacroEnc, and Mobile Treat     .073
Option A, No-MacroEnc, and Mobile Treat     .067
Option C, No-MacroEnc, and Central Treat    .057
Option C, MacroEnc, and Central Treat       .057
Option A, No-MacroEnc, and Central Treat    .048
```

Figure A-53. Synthesized Results from UA 9



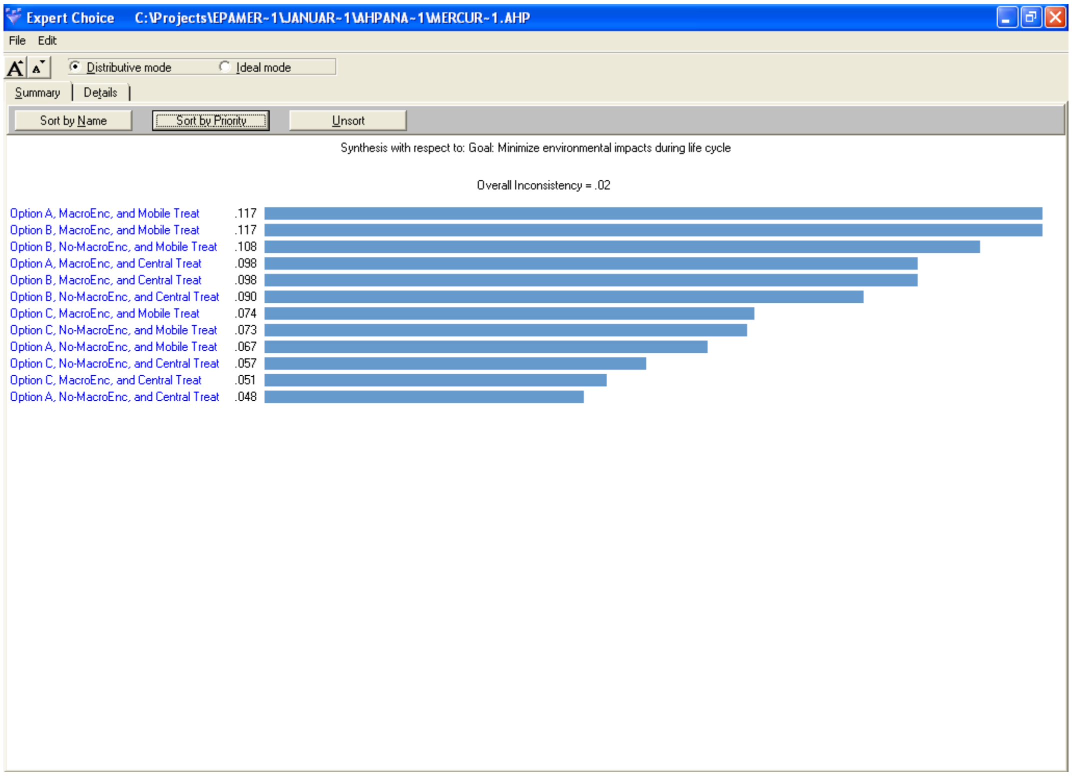
● Distributive mode ○ Ideal mode

```
Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat        .116
Option B, MacroEnc, and Mobile Treat        .116
Option B, No-MacroEnc, and Mobile Treat     .107
Option A, MacroEnc, and Central Treat       .097
Option B, MacroEnc, and Central Treat       .097
Option B, No-MacroEnc, and Central Treat    .089
Option C, No-MacroEnc, and Mobile Treat     .072
Option C, MacroEnc, and Mobile Treat        .072
Option C, MacroEnc, and Central Treat       .066
Option A, No-MacroEnc, and Mobile Treat     .065
Option C, No-MacroEnc, and Central Treat    .056
Option A, No-MacroEnc, and Central Treat    .047
```

Figure A-54. Synthesized Results from UA 10



● Distributive mode ○ Ideal mode

Synthesis with respect to: Goal: Minimize environmental impacts during life cycle

Overall Inconsistency = .02

Option A, MacroEnc, and Mobile Treat	.117
Option B, MacroEnc, and Mobile Treat	.117
Option B, No-MacroEnc, and Mobile Treat	.108
Option A, MacroEnc, and Central Treat	.098
Option B, MacroEnc, and Central Treat	.098
Option B, No-MacroEnc, and Central Treat	.090
Option C, MacroEnc, and Mobile Treat	.074
Option C, No-MacroEnc, and Mobile Treat	.073
Option A, No-MacroEnc, and Mobile Treat	.067
Option C, No-MacroEnc, and Central Treat	.057
Option C, MacroEnc, and Central Treat	.051
Option A, No-MacroEnc, and Central Treat	.048

Figure A-55. Synthesized Results from UA 11

Sub-Step 6b: If the results of the synthesis, sensitivity analysis, or uncertainty analysis had not agreed with intuition, then the AHP process would have been reviewed and, if necessary, modified from any point between structuring the model through the completion of the uncertainty analysis. However, the results of the AHP appear to coincide with intuition.

Step 7: Document the Decision for Justification and Control

The conclusion of the AHP analysis suggests that alternatives 4 (Option A process+macroencapsulation+mobile treatment), 8 (Option B process+macroencapsulation +mobile treatment), and potentially 6 (Option B process+no macroencapsulation+mobile treatment) are the technology alternatives most favored by the AHP analysis. These recommendations are based not only on the AHP analysis, but also interpretation of the information factoring into the AHP analysis. Consequently, any changes to either the interpretation of the information or the AHP analysis could alter the recommendations of technology alternatives resulting from the AHP analysis.

Most importantly, the AHP analysis conducted in this appendix was to support informed management decisions. Consequently, administrative judgment, socio-political factors, or cost not specifically included in the AHP analysis may factor into the final selection of the preferred technology alternative(s) and could cause a difference in the recommendation resulting from the AHP analysis.

APPENDIX B

FACTORS AND PHENOMENA THAT NEED TO BE EVALAUTED WHEN ASSIGNING INTENSITIES TO ALTERNATIVES

Table of Contents

List of Tables

List of Figures

APPENDIX B
FACTORS AND PHENOMENA THAT NEED TO BE EVALUATED WHEN ASSIGNING INTENSITIES TO ALTERNATIVES

B.1 Factors Influencing the Assignment of Intensities to Alternative

The following lists contain factors or phenomena that influenced the assigning of intensities to each elemental mercury treatment and disposal alternative. This list was developed during the EPA/SAIC AHP brainstorming session on June 17/18, 2004. The team developed a rudimentary scoring system. A low point score is desirable and corresponds to a low intensity.

The scoring system outlined here was not formally used in the assignment of intensities. However, the factors discussed for each criterion were an important starting point for research for each alternative.

Goal: Minimize Environmental Impacts During Life cycle

a) During routine operation of stabilization facility (0.065)[1]
   - *Other solid waste streams* (0.750) (everything but atmospheric releases; more concerned with total waste as opposed to daily totals) – assigned intensity scale: low, medium, high (pairwise: +2, +3, +3 – see Table 3-1).
      a. Non-mercury hazardous waste (2 points) vs. non-hazardous waste (0 points)
      b. Volume (Mobile - 2 points; Stationary - 0 points); need to look at each technology independently to see if they deserve a extra points if they generate considerably more waste; need to look at larger volumes during scale-up.
      c. Includes non-plastic organics (add 1 point).
      d. Mercury content in waste (look at each technology comparatively to see if one technology deserves an additional point for generating more mercury-containing waste).
      e. Powdered (Yes - 1 point; No - 0 points).
   - *Atmospheric discharges* (0.250) – assigned intensity scale low, medium, high (pairwise: +2, +3, +2)
      a. Mercury (not scored because it does not discriminate because each technology would emit some mercury, but it would be required to meet a regulatory limit, i.e., each technology would be required to meet the same limit).
      b. Ability to control fugitive emissions (process-by-process evaluation).
      c. Hydrogen sulfide emissions (1 point if a technology emits H_2S; 0 if it does not).
      d. Volatile reagents (1 point if a technology emits VOCs; 0 if it does not).

b) During abnormal or accidental operations (0.188)
   - *Elemental mercury spills* (0.833) – assigned intensity scale low, medium, high (pairwise: +2, +3, +2).
      a. Handling of mercury - refers to probability of spill (process-by-process evaluation; mobile versus fixed; 1 point for a technology if it has additional handling procedures - this may drop out as a discriminator).
      b. Unconventional containers (1 point for mobile treatment because they are more likely to encounter unconventional containers; 0 points for stationary).
      c. Familiarity with procedures (1 point for mobile because they are more likely to have personnel who are less familiar with process; 0 points for stationary).

---

[1] Values in parentheses are the weights assigned to criteria or subcriteria as a result of the EPA/SAIC team's brainstorming efforts. See Table 3-1.

    d. Review DLA's Mercury Management Environmental Impact Statement for possible relevant information.
  - *Other spills* (0.167) – low, medium, high (pairwise: +2, +3, +2).
    a. Final waste form (a spill is not going to be a problem due to the stabilized nature of the final waste form; score = 0 for all technologies).
    b. Toxicity of reagents (1 if on a hazardous material list; 0 if it is not).
    c. Solid, liquid, or gas? (not likely to have gaseous materials; change to question about volatility - 1 if volatile, 0 if not).
    d. Potential volume (related to inventory, need to make a judgment about what constitutes a large/small quantity).

c) <u>During transportation</u> (0.216)
  - *Mercury to stabilization facility* (0.747) – assigned intensity scale no, yes (pairwise: +9). Assignment of intensities by inspection.
  - *Stabilized waste to monofill* (0.119) – assigned intensity scale none, encapsulated, non-encapsulated (pairwise: +5, +7, +2). Assignment of intensities by inspection.
  - *Transportation of reagents* (0.134) – assigned intensity scale low, medium, high (pairwise: +3, +5, +3).
    a. Volume (process-by-process comparison - which one uses more).
    b. Hazards of reagents (1 point for any hazard; 0 for no hazard).
    c. Frequency of shipment (redundant - will not be scored, covered by volume).
    d. Powdered (Yes - 1 point; No - 0 points).

d) <u>During decommissioning of the treatment unit</u> (0.038) – No subcriteria, assigned intensity scale low, medium, high (pairwise: +2, +3, +2).
  a. Complexity (mobile = 0; fixed = 1).
  b. Size (process-by-process comparison).

e) <u>During storage in the monofill</u> (0.493)
  - *Expected ease of maintaining environmental conditions* (40 years) (0.200) – assigned intensity scale low, medium, high (pairwise: +5, +7, +2).
    a. Difficulty in maintaining pH (process-by-process evaluation - need to look at technologies).
    b. Redox potential (process-by-process evaluation - need to look at technologies).
    c. Infiltration (not applicable to selecting technologies, but it is location-specific).
    d. Liner material durability (0 = available, 1 = unavailable; check to see if liner is available for technology-dependent conditions).
    e. Encapsulated/not-encapsulated (0 = encapsulated; 1 = non-encapsulated).
    f. Mercury vapor.
  - *Expected long-term susceptibility to degradation* (after 40 years) (0.800) – assigned intensity scale low, medium, high (pairwise: +5, +7, +2).
    a. Leachate rates (favor technologies that are less sensitive to required pH and redox conditions).
    b. Difficulty in maintaining pH (process-by-process evaluation - need to look at technologies).
    c. Redox potential (process-by-process evaluation - need to look at technologies).
    d. Infiltration (not applicable to selecting technologies, but it is location-specific).
    e. Liner material durability (0 = available, 1 = unavailable; check to see if liner is available for technology-dependent conditions).
    f. Encapsulated/not-encapsulated (0 = encapsulated; 1 = non-encapsulated)
    g. Mercury vapor.

B.2 Assignment of Intensities to Alternatives

This section describes how intensities were assigned to alternatives

B.2.1 Recap of Treatment Technologies

Three technologies (Options A, B, and C) were selected for evaluation. These technologies were selected for evaluation following a review of potentially applicable treatment methods, see Chapter 2. All three technologies have been used for the treatment of elemental mercury. Variations of these processes have also been used for the treatment of mercury-containing wastes such as soils. The references used for the evaluation of Options A, B, and C are listed in Section 5.2 of the main body of the report.

(a) *Option* A

Option A 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°C to 70°C for several hours. This converts mercury to the mercuric sulfide form. Additional sulfur polymer cement is added and heated to 135°C. The molten mixture is poured into a mold to cool and solidify. Pilot scale processing has been conducted using a one cubic foot vertical cone blender/ dryer with internal mixing and external heating. Mercury is removed from off-gas using a cyrogenic trap and solid filters. The process has been demonstrated for both elemental mercury and for mercury-containing soil.

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

(b*) Option B*

The Option B technology converts mercury to mercuric sulfide, and is capable of treating elemental mercury or mercury in waste material. Raw materials for the Option B process include a sulfur-based reagent. The treated material can be a granular material or a monolithic material. The Option B 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. An EPA elemental mercury study included an additional, laboratory scale microencapsulation step beyond the pug mill treatment.

(c) *Option C*

This is a batch mercury amalgamation process conducted at ambient temperature. 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. The Option C vendor has treated elemental mercury batchwise in the following manner:

1. Elemental mercury is placed in a polyethylene bottle that serves as a reaction vessel. The batch size is one to two kilograms mercury.

2. Amalgamation reagents are added and the bottle contents are mixed.
3. Additional chemical stabilization reagents are added, if necessary, if ionic forms of mercury are suspected of being present.
4. After 24 to 48 hours, the reaction is complete and the final form of the amalgam is a solid mass within the polyethylene bottle.

B.2.2 Encapsulation

As described above, each of the technologies includes a combination of chemical reaction and encapsulation to reduce environmental mobility of mercury. For example, the reagents typically provide both a reaction mechanism and an encapsulation mechanism, not unlike cement-based hazardous waste stabilization. In addition, containers such as cans or bottles (with drums likely applicable for larger quantities) are used to hold the treated waste, providing an additional degree of macroencapsulation.

For this evaluation, macroencapsulation consists of a separate step to be conducted following the treatment step, which is independent of the mercury treatment technology. The evaluation considers a technology similar to the ARROW-PAK system (DOE 2002). The encapsulation method selected is not intended to represent the 'best' method, but is expected to display some of the environmental advantages and cost disadvantages inherent with any macroencapsulation system. For example, molten polyethylene is alternatively used for macroencapsulation of wastes (DOE 1998a).

In the ARROW-PAK system, polyethylene (HDPE) sleeves are used in conjunction with HDPE endcaps, which are fused together following insertion of the waste. The ARROW-PAK system is described as super-compacting waste in 55-gallon drums, placing the compacted drums into 85-gallon overpacks, and placing the overpacks into the tube (DOE 2002). In its application to treated mercury waste, the super compaction step may not necessarily be practical given the existing high density of the treated mercury and the encapsulation already provided by the treatment process. In addition, the ARROW-PAK system is expected to be available in a variety of sizes; the cost and environmental analyses will incorporate appropriate assumptions for container size.

B.2.3 Treatment Location

Elemental mercury is first assumed to be stored at a number of existing facilities providing storage or recovery. Hypothetical examples of such facilities include recovery facilities for fluorescent bulbs or other mercury-containing equipment; chlor-alkali facilities where mercury is no longer needed due to process change or closure; and U.S. government storage. Such facilities can be located throughout the U.S.

For alternatives involving centralized treatment, elemental mercury is transported from these locations to a single facility where the elemental mercury is treated and disposed. For alternatives involving mobile treatment, the mercury is treated at these recovery or storage facilities, macro-encapsulated (if applicable) and then transported to a single disposal site.

B.2.4 Disposal

All alternatives include disposal at a single monofill. The monofill is designed and used solely for the management of the treated mercury. While the monofill may be constructed at a facility with several other land disposal units, the intent is that the monofill is located separately from these other units to allow for better control of the disposal conditions.

B.2.5 Assignment of Intensities

This section describes how intensities were assigned to each alternative for each criterion or subcriterion.

B.2.5.1 Routine Operation of Stabilization Facility: Solid Waste Discharges

The mercury treatment operation will typically generate several types of wastes that will require disposal, discharge, or further offsite treatment. Airborne discharges are discussed in Section B.2.5.2; this section addresses all other types. Generated wastes include the following:

- Personal protective equipment
- Clean-out wastes
- Empty raw material containers (both elemental mercury and other inputs)
- Air pollution control wastes such as filters
- Waste encapsulant material (for treatment methods employing encapsulation)

The quantities, toxicity, and hazard of these waste materials will affect the overall environmental impacts. Based on the available information, none of the processes or operations is expected to generate large quantities of wastes. Following are some aspects to waste generation:

- *Non-mercury hazardous waste generation*: while all processes generate mercury-containing hazardous wastes, none of the processes are expected to generate non-mercury hazardous wastes. All processes will generate empty containers for other reagents; these are not expected to be hazardous wastes.
- *Organic content*: none of the processes are expected to generate organic-containing wastes, other than plastic. The encapsulation step is not expected to significantly affect environmental impacts. The encapsulating materials are primarily inert plastics and any waste materials are expected to be easily managed as solids.
- *Waste volume*: many of the processes generate similar quantities of wastes, such as the following:
    - Similar personal protective equipment (e.g., protective clothing and respiratory equipment) will be required for all management alternatives.
    - All processes will generate the same quantities of empty elemental mercury containers (i.e., flasks).
    - Similar air pollution control wastes are expected (e.g., cartridge filters used to remove mercury) for each of the technology options.

  There are some differences between the alternatives, based on the following:
    - Mobile equipment will be expected to generate a greater quantity of clean-out wastes in preparation for movement from site to site.
    - Little to no clean-up wastes were identified for the Option C process. Both the Option A and the Option B processes use mixers/ reactors that will require periodic cleaning.

  No specific estimates can be made regarding waste volume beyond these qualitative judgments.
- *Wastes in powdered form*: each of the technologies use raw material reagents in powdered form that will generate some waste. Powdered waste forms are expected to be slightly more difficult to control than other forms.

Based on the above, the centralized Option C process (i.e., Alternatives 9 and 11 – see Section 3.1) is expected to have **low** environmental impacts with regard to solid waste discharges due to the low quantities of clean-up waste expected to be generated. Based on the Option C process description, very little auxiliary waste is expected to be generated. As with any process, mercury will be present in personal protective equipment and ambient air filtration/ air treatment devices, while small amounts of other raw materials may be present in empty reagent bags or drums.

All other alternatives (i.e., Alternatives 1 through 8, 10, and 12) are expected to have **moderate** environmental impacts with regard to solid waste discharges, due to the increased quantities of clean-up waste expected to be generated. Encapsulation is not expected to significantly affect these environmental impacts.

B.2.5.2 Routine Operation of Stabilization Facility: Atmospheric Discharges

Mercury treatment will generate atmospheric releases of mercury as well as other pollutants. These discharges can include the following:

- *Mercury*: it is assumed that each technology would emit similar (i.e., low) levels of mercury. USEPA identified that as a result of operating procedures and/or regulatory permits, mercury emissions at recycling facilities are low (64 Federal Register 28956; May 28, 1999). These control mechanisms include monitoring and carbon adsorption. For mercury treatment facilities, whether mobile or centralized, similar precautions are expected to be required with respect to mercury.
- *Fugitive emissions of mercury*: there is a potential for fugitive emissions of mercury, such as during reactor vessel loading/ unloading. In these and other operations, mercury may be more difficult to control. Based on review of the technologies, none is expected to be more likely to generate uncontrolled fugitive air emissions than the others.
- *Other hazardous pollutants (e.g., hydrogen sulfide, VOCs)*: none of the processes are expected to generate or release hydrogen sulfide or VOCs.
- *Other pollutants*: none of the processes are expected to generate or release other air pollutants (e.g., sulfur oxides, odor).

Based on the above, all management alternatives (i.e., Alternatives 1 through 12) are expected to have **low** environmental impacts with regard to atmospheric discharges during normal operation.

B.2.5.3 Abnormal or Accidental Operation of Stabilization Facility: Spills of Elemental Mercury

There are potential environmental risks to handling elemental mercury. The following are some accident scenarios that may be applicable for a treatment facility with regard to mercury. If concrete floors and concrete berms are present at all mercury-handling points (as would be expected in most cases), the liquid form of mercury is expected to be contained. Therefore, the primary release pathway is to the air (although other media can be contaminated due to re-settling). These scenarios are adapted from the DLA Mercury Management EIS (DLA 2004):

- Drop and breakage of a single flask of mercury or a pallet containing multiple flasks (e.g., 30 – 45 flasks).
- A fire occurring at a forklift while holding a pallet of flasks. The contents of the flasks would be evaporated.
- Building fires and fires in nearby areas (e.g., industrial park).
- Other natural disasters (e.g., earthquake, tornado).

The above four scenarios are ordered from roughly highest to lowest probability (i.e., a single flask spill is more likely than a tornado). At the same time, the effects from a low probability event such as a tornado are potentially catastrophic, with the potential for large quantities of mercury to impact the environment. For the DLA, the catastrophic events were assumed to have a negligible frequency and were not quantitatively evaluated. Only spills from container breakage were evaluated.

DLA (2004) conservatively estimated that one flask or one pallet would be dropped and broken for each 1,000 handled. Therefore, a greater amount of handling will result in a greater risk of breakage. The following handling is expected to be required for a mercury treatment operation:

- Move elemental mercury from storage location to truck or rail (centralized treatment only)
- Off-load elemental mercury at centralized storage location (centralized treatment only)
- Move elemental mercury from storage area to treatment area within the same facility (both centralized and mobile treatment)
- Transfer mercury from storage flask to treatment reactor equipment (both centralized and mobile treatment)

While there is a greater frequency of handling at a centralized treatment location than at a mobile treatment location, some additional risks of spills may be present at mobile treatment locations:

- *Unconventional containers*: different types of containers may be present at locations encountered by a mobile treatment unit. There may be a slight increase in spill risk associated with the handling of different types of containers.
- *Familiarity with procedures*: personnel associated with a mobile treatment unit may be less familiar with the processes than personnel associated with a centralized location.

In addition to these handling concerns, accidents or upsets with the process itself may result in an accidental discharge of mercury. For example, the air pollution control mechanisms may fail or the reactor vessels may breach, spilling the contents. The Option A process incorporates elevated temperatures, where unreacted mercury is much more volatile. Therefore, any equipment failure associated with the Option A process would result in greater environmental impacts than the other two processes, in which reactions occur at a more ambient temperature.

Overall, due to the non-negligible risk of spills at both centralized and mobile locations, and the negligible differences expected among the different technologies, all alternatives (i.e., Alternatives 1 to 12) are expected to present a **moderate** environmental impact with regard to mercury spills.

B.2.5.4 Abnormal or Accidental Operation of Stabilization Facility: Other Spills

In addition to mercury, there are other materials present at the treatment facility that may be released to the environment. These include:

- *Final waste form*: a spill of treated mercury waste at the operating facility is expected to pose no environmental impacts because the treated materials are solid or monolithic, and spills would be expected to occur in contained areas as occurs with the elemental mercury. Similarly, further handling of the final waste form as a result of encapsulation activity will pose negligible risks.
- *Treatment reagents*: as discussed in Section 2.7, these reagents include the following:
    - Inert gases: at least one process (Option A) uses inert gases in its process. Environmental impacts from these gases are expected to be negligible.
    - Sulfur and sulfides: sulfur, sulfur polymer cement, and sodium sulfide are all non-volatile solids. Their powder form may present a small potential for environmental impact during a spill. Sodium sulfide presents a greater toxicity than sulfur, although the volume used is expected to be lower.
    - Other proprietary reagents: it is assumed that environmental impacts from spills of other proprietary reagents are similar to those above.
- *Encapsulating material*: encapsulating material (e.g., solid plastic) is expected to have negligible environmental impact.

The mechanisms for release of these materials are similar to that for elemental mercury; namely container breakage and catastrophic incidents such as fires. Due to the physical form of the materials, the likely containment mechanisms in place to control solid or liquid releases, and the low volatility of the materials to limit airborne releases, the environmental impacts from spills of other (non-elemental mercury) materials is expected to be **low** in all instances (i.e., for Alternatives 1 through 12).

B.2.5.5 Transportation of Mercury to Stabilization Facility

In this step, elemental mercury is moved from a central storage/ collection location to a central treatment location. In cases where the storage and treatment locations are the same, there would be no risks. This is the case with all mobile treatment alternatives. In all other cases (i.e., centralized treatment), the precise degree of risk is dependent on the number of trips, facility locations, method of transport, etc. The risks are not dependent on treatment technology.

There are potential environmental risks to transporting elemental mercury. Elemental mercury is expected to be transported by truck or rail. The following are several potential risks that may occur during transportation; these are adapted from the DLA Mercury Management EIS (DLA 2004):

- Accidents resulting in a spill of mercury that will evaporate or otherwise impact the environment.
- Accidents resulting in a fire, and as a consequence some of the mercury will evaporate.
- Accidents resulting in injury or death, generally unrelated to the nature of the cargo. These effects are outside the scope of the present report because they are not directly related to the environmental impacts of mercury.
- Risks of the above occurrences are typically assumed to be directly proportional to the number of miles traveled (e.g., there is twice as much risk with 100 miles of transport than there is with 50 miles of transport).

As a result of this evaluation, all alternatives involving mobile treatment are assigned an intensity of ‘**no**’ (i.e., Alternatives 2, 4, 6, 8, 10, 12). The remaining six alternatives would be assigned an intensity of ‘**yes**.’

B.2.5.6 Transportation of Stabilized Waste to Monofill

This step involves the movement of treated mercury waste from a central treatment location to the disposal site. In cases where the treatment and disposal locations are the same, there would be no risks. This is the case with all centralized treatment alternatives. In all other cases (i.e., mobile treatment), risks are expected to result from similar scenarios as discussed above in Section B.2.5.5. However, risks from treated wastes are expected to be much smaller than risks from elemental mercury. Further, risks are expected to be slightly lower for encapsulated waste than for non-encapsulated waste. In the event of an accident, the encapsulation material will help prevent the containerized waste from being released to the environment.

As a result of this evaluation, all alternatives involving central treatment are assigned an intensity of ‘**no transport**’ (i.e., Alternatives 1, 3, 5, 7, 9, 11). The three remaining alternatives involving encapsulation would be assigned an intensity of ‘**encapsulated**’ (i.e., Alternatives 4, 8, 12). The three remaining alternatives not involving encapsulation would be assigned an intensity of ‘**not encapsulated**’ (i.e., Alternatives 2, 6, 10).

B.2.5.7 Transportation of Reagents

Various raw materials are required to treat the mercury, regardless of the treatment location. These materials include treatment reagents such as sulfur. Factors potentially affecting environmental impacts from transportation include the following:

- *Volume of reagents required (e.g., per pound of mercury treated)*: these affect the number of vehicle-miles and the subsequent probability of a release.
- *Hazards of reagents*: toxicity, reactivity, and flammability.
- *Physical state of reagents*: powdered or volatile reagents are expected to be more difficult to clean up (or more likely to impact the environment) than other forms.

In addition to reagents, encapsulation material (e.g., the polypropylene container) will also require transport to the treatment site. The shipment of encapsulation material is unlikely to have environmental impacts similar to the above, because the encapsulation material is a solid mass of low hazard. Shipments will affect the generation of pollutants such as greenhouse gas from truck exhaust; such environmental impacts are outside the scope of this present analysis.

Risks from transportation of reagents are expected to differ based only on the three technology types. For example, risks are assumed to be independent of whether an additional encapsulation step is performed, and whether treatment is conducted at a mobile location or a centralized location.

Table B-1 summarizes the hazards posed by the reagents identified as raw materials in each of the technologies. For comparison, the hazards associated with mercury are also listed. Unfortunately, several reagents are identified as proprietary and in these cases no evaluation can be conducted.

(a) *Option A*

The following reagents are used in Option A for treating elemental mercury:

- Sulfur polymer cement, ground to a fine powder of approximately 60 mesh (0.25 mm). Sulfur polymer cement is a product formed from the reaction of 95 percent sulfur and five percent organic modifier. The organic modifier is an oligomer/ polymer.
- A sulfide additive such as sodium sulfide (Na_2S), also in powder form.
- Argon gas or nitrogen gas is used to maintain an inert atmosphere (e.g., absent of oxygen) during the reaction.

Argon and nitrogen gases are non-reactive and non-flammable; their principal hazards are those associated with any compressed gas (i.e., rapid decompression). The process uses relatively high quantities of sulfur polymer cement and lesser quantities of sulfide additive. There is a 2:1 weight ratio of added reagents to elemental mercury; three percent is sulfide additive. As shown in Table B-1, the hazards of SPC are much lower than the hazards of sodium sulfide. Therefore, although both reagents are present in powdered form (which may increase potential releases or hazard), the overall environmental impacts for reagent transport associated with this technology (i.e., Alternatives 1-4) are expected to be low.

Table B-1. Reagents Used in Mercury Treatment Technologies

Chemical	Technology	Hazards	Notes
Mercury	---	Extreme health hazard (poison) via inhalation, no flammable hazard, slight reactivity hazard	For reference/ comparison
Sulfur polymer cement (powdered)	Options A and B	Slight health, flammability, and reactivity hazards	Based on MSDS for powdered sulfur. Hazards for powdered SPC are expected to be similar or lower.
Calcium polysulfide	Option B	Corrosive and ingestion health hazards	Based on MSDS
Sodium sulfide (powdered)	Option A	Severe health (corrosive) to mucous membranes; slight flammability and reactivity hazards	Based on MSDS
Argon or nitrogen gas	Option A	None with gas; some decompression hazards with pressurized container	
Proprietary (assume powder form)	Option C	Hazards are unknown; powder forms present greater hazards	
Proprietary	Option B, Option C	Unknown	

(b) *Option B*

The following reagents are used for treating elemental mercury in Option B:

- Powdered sulfur.
- Calcium polysulfide.
- Smaller quantities of additional proprietary reagents.

The principal reagent is expected to be the powdered sulfur. The overall quantities of reagents used are approximately 1:1 (weight percent of reagents to mercury). The environmental impacts of reagent transport associated with this technology (i.e., Alternatives 5-8) are expected to be similar to those for Option A, and are therefore **low**.

(c) *Option C*

Available information regarding the reagents used during treatment of elemental mercury is proprietary. Initial treatment is known to be an amalgamation that satisfies the requirements of 40 CFR 268.42 (i.e., "utilizes inorganic reagents such as copper, zinc, nickel, gold, and sulfur"). Based on the fact that the other two technologies employ powdered reagents, it is assumed that the Option C process also employs powdered reagents. Powdered reagents have greater surface area and will react more readily with the mercury.

Due to the proprietary nature of the process reagents, it is difficult to identify hazards. Option C uses larger quantities of reagents than the other processes; the ratio of reagents to mercury is approximately 5.6:1 versus slightly lower ratios for the other processes. Due to the larger quantities of reagents used, and the uncertainties regarding their hazard, the environmental impacts associated with this technology (i.e., Alternatives 9-12) are expected to be **moderate**.

B.2.5.8 Decommissioning of the Stabilization Unit

A one-time, permanent dismantling of the treatment unit will be conducted. If the stabilization unit is mobile, the unit will require periodic cleaning and dismantling as it moves from one location to another. Such operations are considered within the range of normal activities evaluated in Sections B.2.5.1 and B.2.5.2.

Permanent decommissioning is expected to involve the following activities:

- Removal or disposal of excess reagents.
- Decontaminating all process equipment and subsequent disposal or scrapping of equipment
- Decontaminating floors, building surfaces, etc.
- Disposal/ processing of mercury-containing wastes generated from these decommissioning operations.

These activities are not expected to differ significantly by technology or mobility (i.e., centralized versus mobile). Small differences in complexity with regard to these factors are not expected to significantly impact the quantities or composition of the generated wastes. Therefore, the environmental impacts are expected to be **low** in all instances (i.e., for Alternatives 1 through 12).

B.2.5.9 Monofill Disposal: Expected Ease of Maintaining Environmental Conditions (within 40 years and following 40 years)

In evaluating environmental impacts, two criteria were identified with respect to monofill disposal: (1) the expected ease of maintaining environmental conditions within 40 years, and (2) expected long-term susceptibility to degradation following 40 years. A 40-year time frame was selected for consistency with alternatives evaluated for the DLA; it is also a time period in which many short-term fluctuations of a disposal environment have been completed.

Many of the factors influencing environmental impact are similar regardless of whether the period of time reviewed is less than or greater than 40 years.

In minimizing environmental impacts of mercury from disposal, it is important to minimize both the leaching and the volatilization of mercury from the waste. This is accomplished through a combination of using treatment techniques that best immobilize the mercury, and selecting and maintaining an environment in which the waste is best immobilized. These factors are discussed below.

(a) *Volatilization*

Data for mercury vapor releases from treated elemental mercury are available from prior DOE studies. Data are available for each of the three processes evaluated for this report. These data do not represent long-term stability results and therefore insufficient data are available to identify either the significance of this pathway (relative to leaching) or environmental conditions in which volatilization is minimized. Nevertheless, the data are useful in identifying differences in results between the processes and suggesting how vapor releases can be minimized.

There are two concerns with volatilization. First, this represents a release pathway into the environment. Second, it presents a potential problem with macroencapsulation. Macroencapsulation techniques such as the Arrow-pak system result in a sealed container; the generation of gas within such a container may result in increased pressures leading to structural deformation (DOE 2002).

Data are available for elemental mercury, treated elemental mercury, and treated mercury wastes. Data are available specifically for the three vendors evaluated in this report, as well as for similar technologies. For ease of presentation, only data for elemental mercury and elemental mercury treated by the three technologies evaluated in this report are presented.

A recently published study presents data for one of the Vendors evaluated in this report, identifying the mercury vapor concentration over treated elemental mercury as a function of time. The data only identify results for a seven-day period following generation. The results show that the concentration decreases over time following initial treatment, although the timeframe is too short to identify long-term trends. Nevertheless, the results suggest that emissions of mercury can occur immediately following treatment. During this period, the treated mercury can be allowed to set in an area with controlled ventilation prior to macroencapsulation (if applicable) and final disposal. However, no further conclusions regarding mercury volatility, such as in the disposal environment, can be made from the available data.

DOE has evaluated short-term mercury vapor concentrations for elemental mercury treated by two of the vendors evaluated in this report. Results for one of the Vendors showed very little volatilized mercury. However, the samples treated by another Vendor displayed very high mercury vapor levels, comparable to untreated elemental mercury. Correspondence with one of the vendors has suggested uncertainties with the DOE data.

The available volatilization data are presented in Table B-2.

Table B-2. Vapor Pressure Data for Treated Elemental Mercury and Mercury Waste

Waste Type	Technology	Hg (mg/m^3) 1 day	3 day	7 day	Reference
Elemental Hg	Untreated – Calculated	14	14	14	DOE 1994; DOE 1999f
Elemental Hg	Vendor A	11	3.8	1	See Section 5.2
Elemental Hg	Vendor B	Not detected *	Not detected *	Not detected *	See Section 5.2
Elemental Hg	Vendor C	10.04 – 10.21 **	10.22 – 10.40 **	9.95 – 11.78 **	See Section 5.2

Notes: Data are for ambient conditions (~20C)
* Limit of sensitivity is approximately 0.003 mg/m3.
** Results present averages of two separate batch tests after 2 day, 5 day, and 14 day.

Based on the results in Table B-2, the Vendor C process may generate significant quantities of mercury vapor, such that any further macroencapsulation may be compromised, and which result in a potential environmental impact pathway. Uncertainties with these results include whether or not such volatilization would continue for an intermediate to long period of time (e.g., whether volatilization rate would decrease). There is further uncertainty regarding the validity of the DOE results.

(b) *Favorable pH Conditions and Expected Ease of Maintenance*

The pH of the monofill is an important parameter in determining mercury leaching from treated elemental mercury. The monofill pH will be determined by the pH of the materials being disposed (e.g., both the waste and the fill material), precipitation/ run-on, and chemical or biological changes within the disposal cell. The solubilities of the chemical species within the treated waste (which result in the degree of mercury leaching) are a function of pH.

Each of the treatment technologies generate treated wastes with different pH; they each appear to perform best under different pH conditions. Results of USEPA (2002b) testing of treated elemental mercury show the following:

- Treated mercury waste from the Option A process has a pH of approximately 11; leaching solutions with acidic pH generally result in decreased leaching for this treatment process.
- Treated mercury waste from the Option B process has a pH of approximately 7-8; leaching solutions with acidic pH generally result in decreased leaching for this treatment process.

- Treated mercury waste from the Option C process has a pH of approximately 10; leaching solutions with basic pH generally result in decreased leaching for this treatment process.

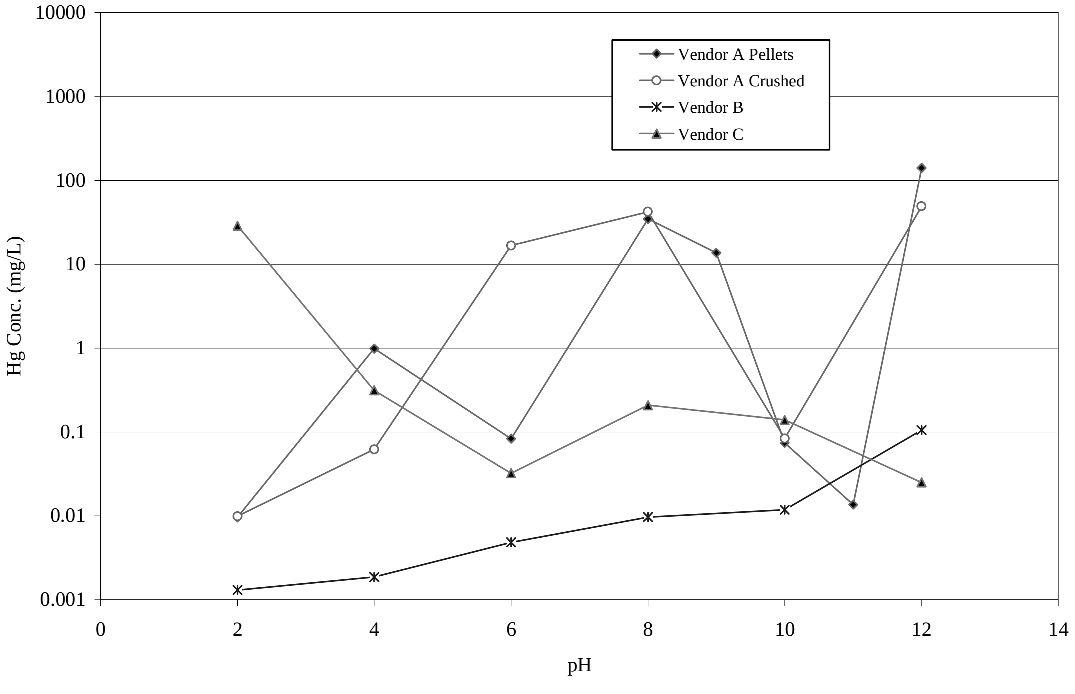
The results from the EPA elemental mercury study are shown in Figure B-1.

Therefore, these results show that it is desirable to maintain pH conditions within the landfill at acidic conditions for the Option A and B processes, while the Option C process favors basic conditions.

The pH of the soil/ fill material will also influence the conditions within the disposal unit. Soil pH varies as a function of geography; low rainfall environments (which are favorable locations because they result in low landfill infiltration) tend to have basic pH. The pH range for most U.S. soils is from 4 to 10 (Utah 2001). The pH of soils can be increased by adding lime, and decreased by adding sulfuric acid. Changing the soil pH can be difficult, for example because in basic soils lime acts as a buffer (Utah 2001).

Many commercial hazardous waste landfills used for the disposal of inorganic wastes have leachate with basic pH. Metal-containing wastes are often stabilized using cement, which favors basic conditions within a landfill. Therefore, it is expected to be somewhat easier to maintain a basic environment because there is sufficient experience in operating disposal units in these conditions. The pH can be adjusted, for example, through the incorporation of lime or cement to the fill material.

From the above information, the combined contributions from the waste and soil tend to result in basic conditions, however basic conditions favor only the Option C process. The Option A and B processes favor acidic conditions that are expected to be more difficult to maintain.



Source: Data from EPA (2002b).

Figure B-1. Leaching of Treated Elemental Mercury

(c) *Long-Term Stability of the Waste Forms*

Testing to identify changes over time is useful in assessing the affect of disposal conditions on the treated mercury. Two studies have been identified that provide some insight with regard to how disposal conditions would influence the treated wastes.

In work conducted by DOE, elemental mercury was treated by the Option B and Option C processes and was exposed to solutions with an initial pH ranging from 3 to 12.5, over a period of time ranging from two weeks to three months. Observations from these experiments show that acidic solutions have a deleterious effect on the Option C waste form, whereas the basic solutions are more aggressive towards the Option B waste form. This is consistent with work carried out by EPA. No conclusions were drawn relating to the trends in mercury leaching over time.

Data available regarding the formation of mercuric sulfide under long-term conditions are available from Svensson et al. (2004); these data are not specific to any particular technology but can potentially be useful for sulfur-based treatment processes in general. These experiments included the mixing of elemental mercury and sulfur and evaluating the effects under various conditions over a two-year period. The highest rate of formation of mercuric sulfide occurred under anaerobic conditions and high pH. These data have limited application because they relate to the formation of mercuric sulfide rather than its degradation. Nevertheless, conditions that favor mercuric sulfide are favorable because unreacted mercury will likely be present in any disposed waste.

(d) *Long-Term Stability of the Encapsulating Material*

In alternatives where the treated mercury is macro-encapsulated prior to disposal, it is desirable for the encapsulating material to last as long as possible. Over time, the material may develop cracks, etc., which result in degraded environmental performance.

ARROW-PAK consists of high-density polyethylene (HDPE) Phillips Marlex® resin, approximately one inch thick (Harrell and Hotard 1995; DOE 2002). The resin is formed into hollow tubes (where drums of waste are placed) and endcaps for the tubes; the caps are subsequently fused to the tubes to provide a seal. The developers conservatively estimate a life expectancy of 100 years minimum (Harrell and Hotard 1995) and DOE estimates an outdoor storage life in the range of 100 to 300 years (DOE 1998b). The material is identified as inert with respect to most temperatures, chemicals, biological organisms, and ultraviolet light conditions likely to be encountered in a disposal environment (Harrell and Hotard 1995).

The properties of polyethylene (such as HDPE) have been shown to be unaffected when exposed to solutions with low or high pH (pH 3 and 12). HDPE is affected by some organic chemicals including halogenated hydrocarbons: however such organic chemicals are not expected in the monofill environment (Reddy and Butul 1999).

(e) *Other Conditions Affecting Disposal*

Redox potential (e.g., the presence or absence of aerobic conditions) is a potentially important property affecting stability or leaching. For example, mercuric sulfide formation is favored (or proceeds faster) in alkaline anaerobic conditions. Virtually all leaching data are available for aerobic conditions. Therefore, it is difficult to incorporate data regarding redox potential into the analysis.

(f) *Conclusions Regarding Criterion: Expected Ease of Maintaining Environmental Conditions for up to 40 Year*s

For this criterion, the following aspects discussed above are expected to be relevant:

- Maintaining landfill pH at favorable conditions
- Stability of the encapsulating material

As discussed above, encapsulation material is expected to provide protection of the waste from the landfill environment for at least 100 years. In addition, wastes from the Option C process favor basic environments that are expected to be easier to maintain. Therefore, for this criterion, processes relating to macroencapsulation alternatives or the Option C process (i.e., Alternatives 3, 4, 7 through 12) are assigned a value of **low** impacts, while the remaining alternatives (i.e., Alternatives 1, 2, 5, 6) are assigned a value of **moderate** impact.

(g) Conclusions *Regarding Criterion: Expected Long-Term Susceptibility to Degradation after 40 Years*

This criterion incorporates the two aspects discussed in (f) immediately above plus several others, as follows:

- Maintaining landfill pH at favorable conditions
- Stability of the encapsulating material
- Volatility and/ or leaching rates

As discussed above, the volatility rate of the Option C-treated waste appears to be significantly greater than for the remaining two processes. This also affects the integrity of any encapsulation technology, as gas build-up is expected to shorten the life of an encapsulating material.

Based on the EPA data, leaching rates for wastes from the Option B process have less variation with respect to pH than the other technologies. While leaching rate is favored at low pH (as with the Option A process), there is significantly less variation in results as the pH moves away from this ‘optimum’ value. Therefore, the importance of maintaining critical pH monofill conditions is less for the Option B process than for the other processes.

Each of the alternatives has various advantages and disadvantages which makes it difficult to assign intensities. Macroencapsulation will typically always have an environmental advantage over no encapsulation, but after a period of time it is appropriate to assume degradation of the containers, at which point the advantages of macroencapsulation are lower (similar to assumptions that can be made concerning the long-term behavior of landfill liners). Wastes from the Option C process will likely exhibit low leaching at elevated pH, but the high rate of volatility (based on available data) will result in increased environmental impacts from this pathway as well as potential shortened life of the macroencapsulation material. Wastes from the Option B process, while less sensitive to pH variation than other processes, favor low pH environments that may require monitoring and adjustment.

Other uncertainties are associated with long-term stability of the disposal site. Over time, the landfill cap, liner materials, and leachate collection systems may erode or cease functioning, resulting in increased infiltration and leachate generation. Such an effect would be negative for any evaluated alternative, but would not be expected to adversely affect one alternative more so than another. Another potential negative effect could result in the landfill environment deviating from ‘favorable’ conditions. For example, as shown in Figure B-1, pH has a significant effect on leachate mercury concentration. However, in a hypothetical long-term scenario, a favorable environment may not be assured and pH may raise or lower over time to ‘less favorable’ conditions. For this reason, as discussed above, the low variation in Option B (relative to Options A and C) would be expected to mitigate such potential failure

With significant uncertainty and variability, processes relating to Option A macroencapsulation alternatives or the Option B process (i.e., Alternatives 3 through 8) are assigned a value of **low** impacts, while the remaining alternatives (i.e., Alternatives 1, 2, 9 through 12) are assigned a value of **moderate** impact.

(h) *Summary of Assignment of Intensities*

Table B-3 contains a summary of the intensities that were assigned in the foregoing.

Table B-3. Assignment of Intensities to Treatment and Disposal Alternatives

	Routine Operations		**Accidental Releases**		**Transportation**				**Monofill Storage**	
Treatment and Disposal Alternative	**Solid Waste Discharges**	**Atmospheric Discharges**	**Mercury Spills**	**Other Spills**	**Mercury**	**Waste**	**Reagents**	**Decom-missioning**	**< 40 years**	**> 40 years**
Option A+ NME[a] + CTA[c]	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Moderate	Moderate
Option A+ NME[b] +MTA[d]	Moderate	Low	Moderate	Low	No	NME	Low	Low	Moderate	Moderate
Option A+ ME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Low	Low
Option A+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Low	Low	Low	Low
Option B+ NME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Moderate	Low
Option B+ NME + MTA	Moderate	Low	Moderate	Low	No	NME	Low	Low	Moderate	Low
Option B+ ME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Low	Low
Option B+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Low	Low	Low	Low
Option C+ NME + CTA	Low	Low	Moderate	Low	Yes	No	Moderate	Low	Low	Moderate
Option C+ NME + MTA	Moderate	Low	Moderate	Low	No	NME	Moderate	Low	Low	Moderate
Option C+ ME + CTA	Low	Low	Moderate	Low	Yes	No	Moderate	Low	Low	Moderate
Option C+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Moderate	Low	Low	Moderate

a. NME = Not Macroencapsulated. b. ME = Macroencapsulated

b. CTA = Centralized Treatment Alternative. d. MTA = Mobile Treatment Alternative

Appendix C
Option A Process
Input Information for Cost Estimates

This appendix provides input that was used to estimate the capital and O&M costs for the Option A treatment process, together with the macroencapsulation process. Any costs quoted in this appendix are point estimates.
They were subsequently assigned uncertainty distributions as described in Section 4.5
and run through a Crystal Ball Monte Carlo analysis.

Treatment Proc Dia

PROCESS CAPACITY

Mercury processed per batch	525	kg
Batches per mixer-shift	1	
Number of mixers	5	
Work week	5	days
Shifts per day	2	
Work year	520	shifts/year
Utilization	80%	
Equipment work year	416	shifts/year
Annual mercury processing capacity	1,092	tons/year
Required mercury processing throughput:	1,000	tons/year

MERCURY, REAGENT, AND WASTE RATIOS

In each batch mixture, % (by mass) of:

Mercury:	33%	
Sodium sulfide:	2%	
Sulfur Polymer Cement:	65%	
Mercury processed per batch:	525	kg
Sodium sulfide per batch:	31.8	kg
Sulfur Polymer Cement per batch:	1034	kg
Total batch mass:	1591	kg

REAGENT CONSUMPTION

Mass of mecury processed in one batch:	525	kg
Mass of mercury processed per year:	1,000	tons/year
	1,000,000	kg/year
Mass of sodium sulfide consumed per year:	60,606	kg
Mass of sulfur polymer cement consumed per year:	1,969,697	kg

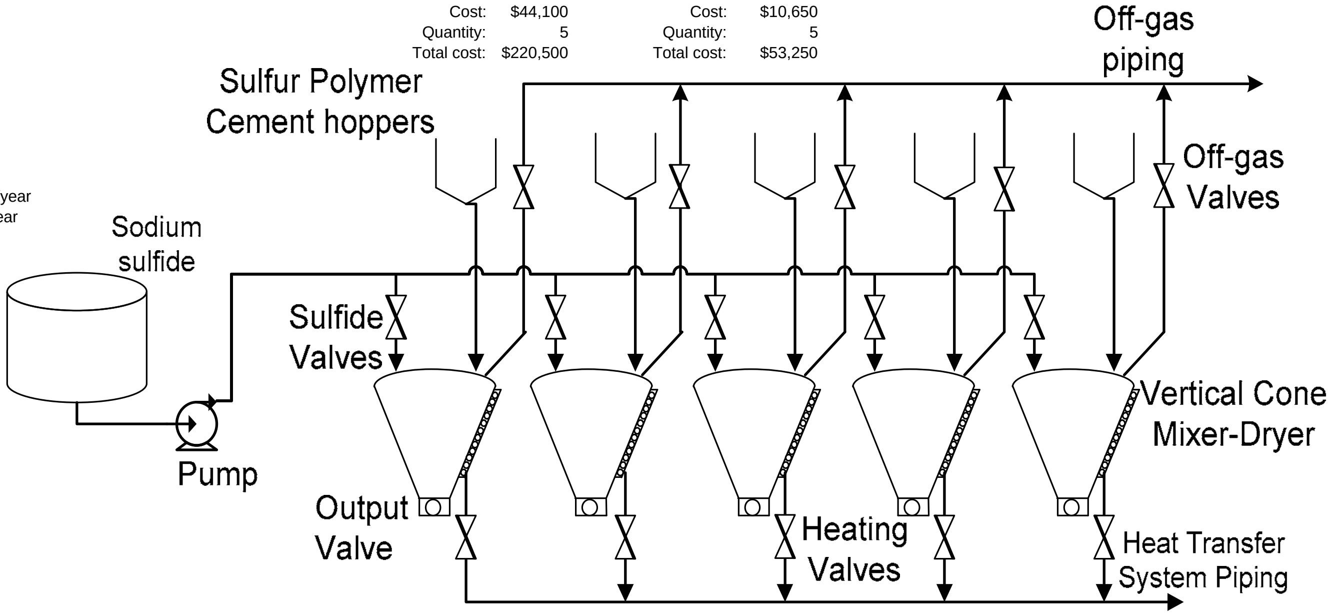
Name: Sodium sulfide
Cost category: Bulk material cost (O&M)
Unit cost: 10.53 $/kg delivered
Quantity consumed per year: 60,606 kg
Total cost: $638,182

Name: Sulfur polymer cement
Cost category: Bulk material cost (O&M)
Unit cost: $0.260 per kg
Quantity consumed per year: 1,969,697 kg
Total cost: $512,121

Name: Crane
Cost category: Capital cost
Cost: $78,000
Quantity: 1
Total cost: $78,000

Name: SPC feeder
Cost category: Capital cost
Cost: $44,100
Quantity: 5
Total cost: $220,500

Name: SPC hopper
Cost category: Capital cost
Cost: $10,650
Quantity: 5
Total cost: $53,250



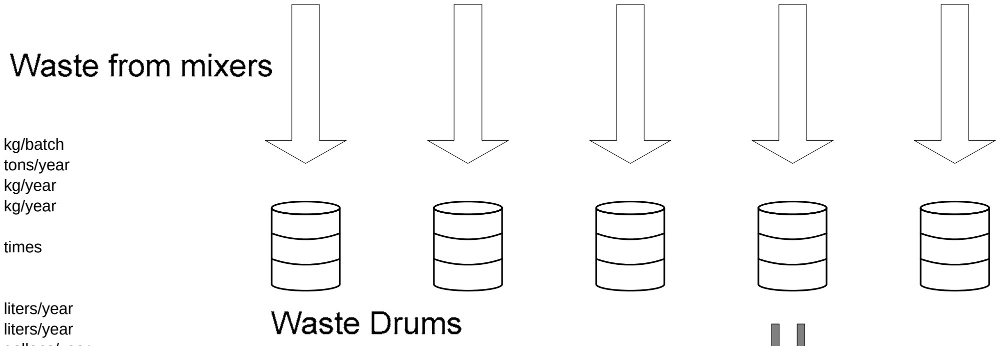
Name: Sodium sulfide tank
Cost category: Capital cost
Cost: $557
Quantity: 1
Total cost: $557

Name: Sodium sulfide pump
Cost category: Capital cost
Cost: $15,000
Quantity: 1
Total cost: $15,000

Name: Sodium sulfide feed valves
Cost category: Capital cost
Cost: $330
Quantity: 5
Total cost: $1,650

Name: Mixer
Cost category: Capital cost
Cost: $180,000
Quantity: 5
Total cost: $900,000

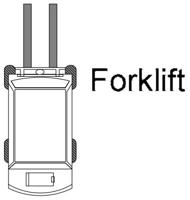
Treatment Proc Dia



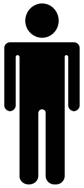
WASTE VOLUME

Mass of mecury processed in one batch:	525	kg/batch
Mass of mercury processed per year:	1,000	tons/year
	1,000,000	kg/year
Mass of waste produced per year:	3,030,303	kg/year
Volume increase from mercury to waste product:	16.5	times
Volume of mercury processed	73,643	liters/year
Volume of waste produced:	1,215,112	liters/year
	320,999	gallons/year
Density of waste:	2.5	kg/L
Weight of waste in one barrel if completely filled:	1145	lb
Limit barrels to 1000 lb of waste:	453.6	kg waste per barrel
Weight of loaded barrel (include empty barrel weight of 34 kg)	487.6	kg
	1075	lb
Required number of 55 gallon barrels	6,681	barrels/year

Name:	55 gallon barrels
Cost category:	O&M
Cost per barrel:	$33
Barrels per year:	6,681
Annual cost:	$220,462



Name:	Forklift
Cost category:	Capital cost
Cost:	$25,000
Quantity:	1
Total cost:	$25,000



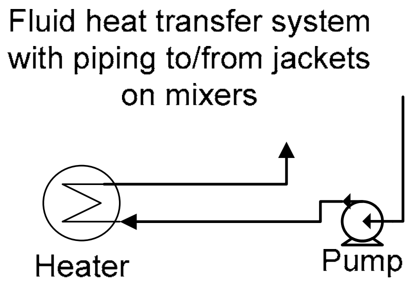
Staff	Qty	Burdened Salary	Total
Operators	8	$45,227	$361,816
Maintenance Tech	1	$66,162	$66,162
Logistics/Shipping	2	$37,306	$74,612
Operations Supervisor	2	$73,664	$147,328
Process Engineer	1	$89,127	$89,127
Administrative Assistant	1	$45,727	$45,727
I&C Tech	1	$66,581	$66,581
Plant Manager	1	$133,022	$133,022
Lab Tech	2	$67,012	$134,024
QA / Health & Safety Coordinator	2	$67,012	$134,024
Total	21		$1,252,423

ENERGY COSTS

Name	Load (kW)	Qty	Total Load (kW)
Mixer motor	150	5	750
Heater	72	5	360
Ventilation vacuum pump	4	1	4
Forklift	75	1	75
Miscellaneous	--	--	178
		Total	1,367

Energy used	4,550,541	kW-hours
Price of energy	0.10	$/kw-hr
Cost of energy (per year):	$455,054	

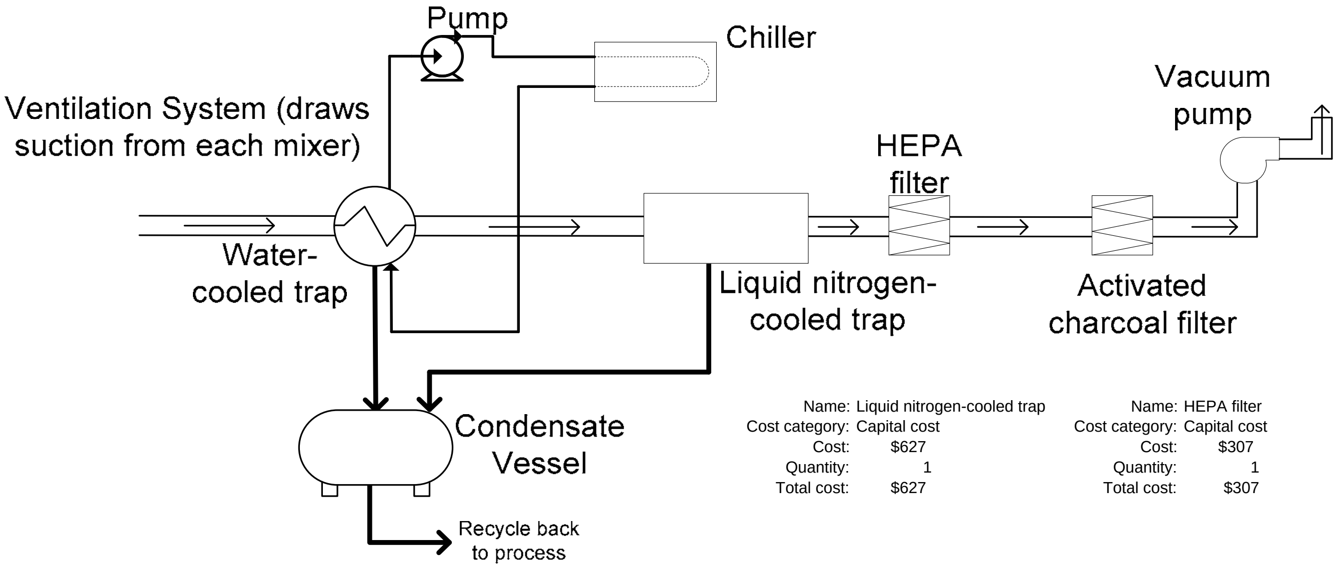
Treatment Proc Dia



Name: Heater
Cost category: Capital cost
Cost: $30,000
Quantity: 5
Total cost: $150,000

Name: Chiller
Cost category: Capital cost
Cost: $5,366
Quantity: 1
Total cost: $5,366

Name: Vacuum pump
Cost category: Capital cost
Cost: $5,987
Quantity: 1
Total cost: $5,987



Name: Off-gas piping/ducts
Cost category: Capital cost
Cost: $5,065
Quantity: 1
Total cost: $5,065

Name: Liquid nitrogen-cooled trap
Cost category: Capital cost
Cost: $627
Quantity: 1
Total cost: $627

Name: HEPA filter
Cost category: Capital cost
Cost: $307
Quantity: 1
Total cost: $307

Name: Carbon filter
Cost category: Capital cost
Cost: $47
Quantity: 1
Total cost: $47

Name: Condenser
Cost category: Capital cost
Cost: $4,186
Quantity: 1
Total cost: $4,186

Treatment Cap Costs (fixed)

Cost Element	Estimate		
	Min	Best	Max
Major Equipment			
Sodium sulfide tank		$557	
Sodium sulfide pump		$15,000	
Sodium sulfide feed valves		$1,650	
Mixers		$900,000	
SPC Feeder		$220,500	
SPC Hopper		$53,250	
Condenser		$4,186	
Liquid nitrogen-cooled trap		$627	
Chiller		$5,366	
HEPA filter		$307	
Carbon filter		$47	
Vacuum pump		$5,987	
Off-gas piping/ducts		$5,065	
Heater		$150,000	
Forklift		$25,000	
Crane		$78,000	
Subtotal: Major Equipment	$1,465,542	$1,465,542	$1,465,542
Allowance for equipment not yet identified	$146,554	$219,831	$293,108
Subtotal: Major Equipment + Allowance	$1,612,096	$1,685,373	$1,758,650
Building site preparation	$128,968	$252,806	$386,903
Building construction, services installation	$419,145	$514,039	$615,528
Subtotal: Building	$548,113	$766,845	$1,002,431
Cost to install major equipment	$628,717	$691,003	$756,220
Piping	$483,629	$581,454	$685,874
Structural foundations (steel, concrete)	$451,387	$471,904	$492,422
Electrical	$128,968	$210,672	$298,971
Instruments	$209,572	$219,098	$228,625
Auxiliaries	$773,806	$867,967	$967,258
Subtotal: Physical Plant	$4,836,288	$5,494,316	$6,190,448
Other field expenses	$564,234	$657,295	$756,220
Engineering	$564,234	$657,295	$756,220
Subtotal: Direct Plant Cost	$5,964,755	$6,808,907	$7,702,887
Initial Start-Up Costs	$119,295	$885,158	$1,848,693
Fees, overhead, and profit	$145,089	$219,098	$298,971
Contingency	$628,717	$657,295	$685,874
Total	$6,857,856	$8,570,459	$10,536,424

Treatment Cap Costs (mob)

Cost element	Estimate		
	Min	Best	Max
Major Equipment			
Sodium sulfide tank		$557	
Sodium sulfide pump		$15,000	
Sodium sulfide feed valves		$1,650	
Mixers		$900,000	
SPC Feeder		$220,500	
SPC Hopper		$53,250	
Condenser		$4,186	
Liquid nitrogen-cooled trap		$627	
Chiller		$5,366	
HEPA filter		$307	
Carbon filter		$47	
Vacuum pump		$5,987	
Off-gas piping/ducts		$5,065	
Heater		$150,000	
Forklift		$25,000	
Crane		$78,000	
Subtotal: Major Equipment	$1,465,542	$1,465,542	$1,465,542
Allowance for equipment not yet identified	$146,554	$219,831	$293,108
Subtotal: Major Equipment + Allowance	$1,612,096	$1,685,373	$1,758,650
Steel for skids	$451,387	$471,904	$492,422
Cost to assemble major equipment skids	$419,145	$460,669	$504,146
Subtotal: Skids	$870,532	$932,573	$996,568
Piping	$483,629	$581,454	$685,874
Electrical	$128,968	$210,672	$298,971
Instruments	$209,572	$219,098	$228,625
Auxiliaries	$773,806	$867,967	$967,258
Subtotal: Physical Plant	$4,078,603	$4,497,137	$4,935,945
Engineering	$1,128,467	$1,314,591	$1,512,439
Subtotal: Direct Plant Cost	$5,207,070	$5,811,728	$6,448,384
Initial Start-Up Costs	$104,141	$755,525	$1,547,612
Fees, overhead, and profit	$145,089	$219,098	$298,971
Contingency	$628,717	$657,295	$685,874
Total	$6,085,017	$7,443,647	$8,980,840

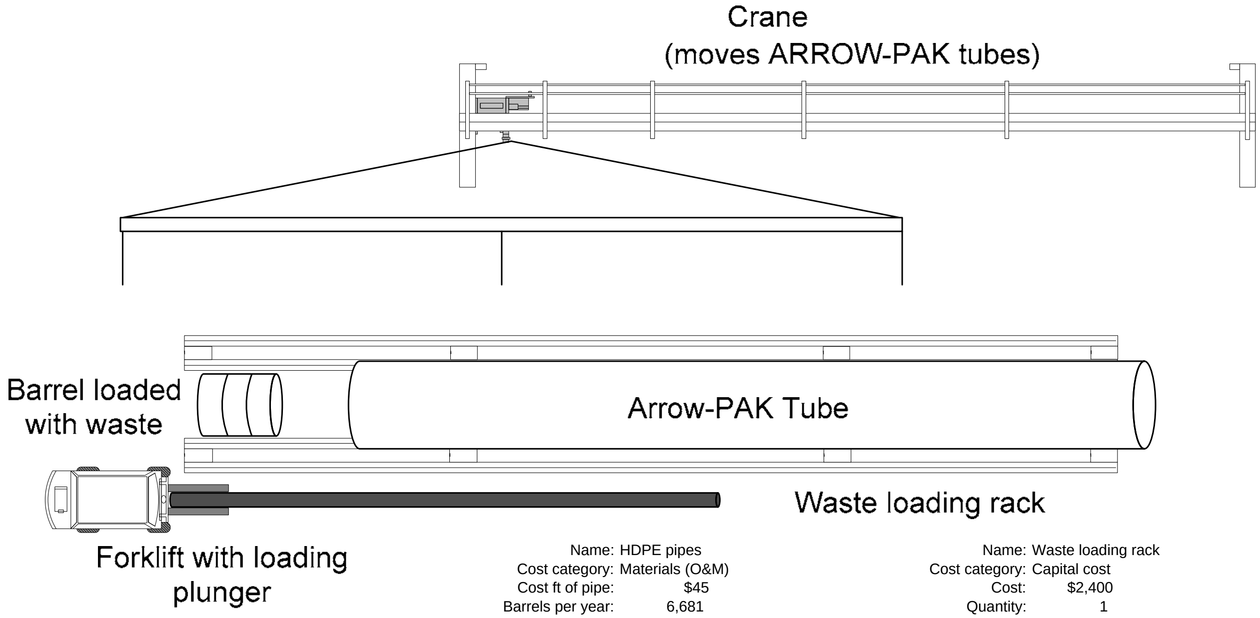
Treatment O&M

Cost Element	Estimated Cost (per year)		
	Min	Best	Max
Sodium sulfide	$638,182	$638,182	$638,182
Sulfur Polymer Cement	$512,121	$512,121	$512,121
Barrels	$220,462	$220,462	$220,462
Staff	$1,252,423	$1,252,423	$1,252,423
Energy	$455,054	$455,054	$455,054
Subtotal: direct costs	$3,078,242	$3,078,242	$3,078,242
Flask disposal	$440,000	$440,000	$440,000
Maintenance & Repairs	$32,242	$101,122	$175,865
Insurance	$16,121	$16,854	$17,587
Property tax	$32,242	$33,707	$35,173
Subtotal: indirect costs	$520,605	$591,684	$668,625
Other overhead	$197,937	$201,846	$206,078
Fee	$719,769	$733,985	$749,373
Contingency	$1,403,550	$1,431,271	$1,461,278
Total	$5,920,103	$6,037,028	$6,163,596

Facility Relocation Costs

Cost Element	Estimated Cost (per move)		
	Min	Best	Max
Transportation of equipment			
Assembling treatment process lines	$209,572	$230,334	$252,073
Start-up	$10,414	$75,552	$154,761
Contingency	$85,795	$119,296	$158,665
Total	$305,781	$425,183	$565,500

Macroencap Proc Dia



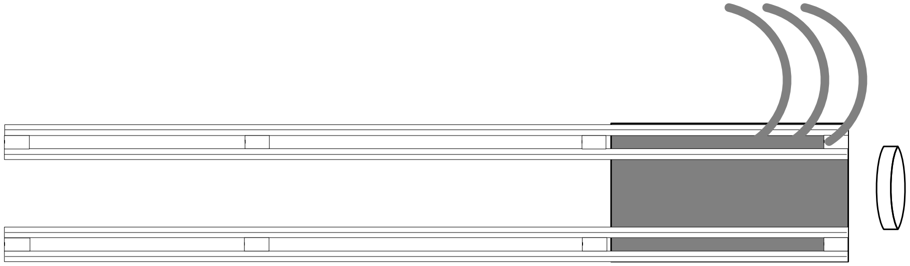
Name: Crane
Cost category: Capital cost
Cost: $78,000
Quantity: 1
Total cost: $78,000

Name: Forklift
Cost category: Capital cost
Cost: $25,000
Quantity: 1
Total cost: $25,000

Name: HDPE pipes
Cost category: Materials (O&M)
Cost ft of pipe: $45
Barrels per year: 6,681
Height of barrel: 2.92 ft
Feet of pipe per year: 19,485
Annual cost: $876,838

Name: Waste loading rack
Cost category: Capital cost
Cost: $2,400
Quantity: 1
Total cost: $2,400

Macroencap Proc Dia



ARROW-PAK Tube Capacity

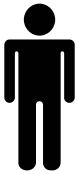
Arrow-Pak tube weight limit	9500	lb
Weight of empty tube	950	lb
Weight of loaded 55-gallon barrel	1075	lb
Number of barrels allowed by weight limit	7	
Arrow-Pak tube length limit (without endcaps)	22	ft
Length of barrel	34	in
Number of barrels allowed by length limit	7	

Fusion Equipment

Name:	Fusion equipment
Cost category:	Capital cost
Cost:	$3,500
Quantity:	1
Total cost:	$3,500

Endcaps

Name:	HDPE endcaps
Cost category:	Materials (O&M)
HDPE endcaps per year:	1,909
Cost per endcap:	$250
Annual cost:	$477,190



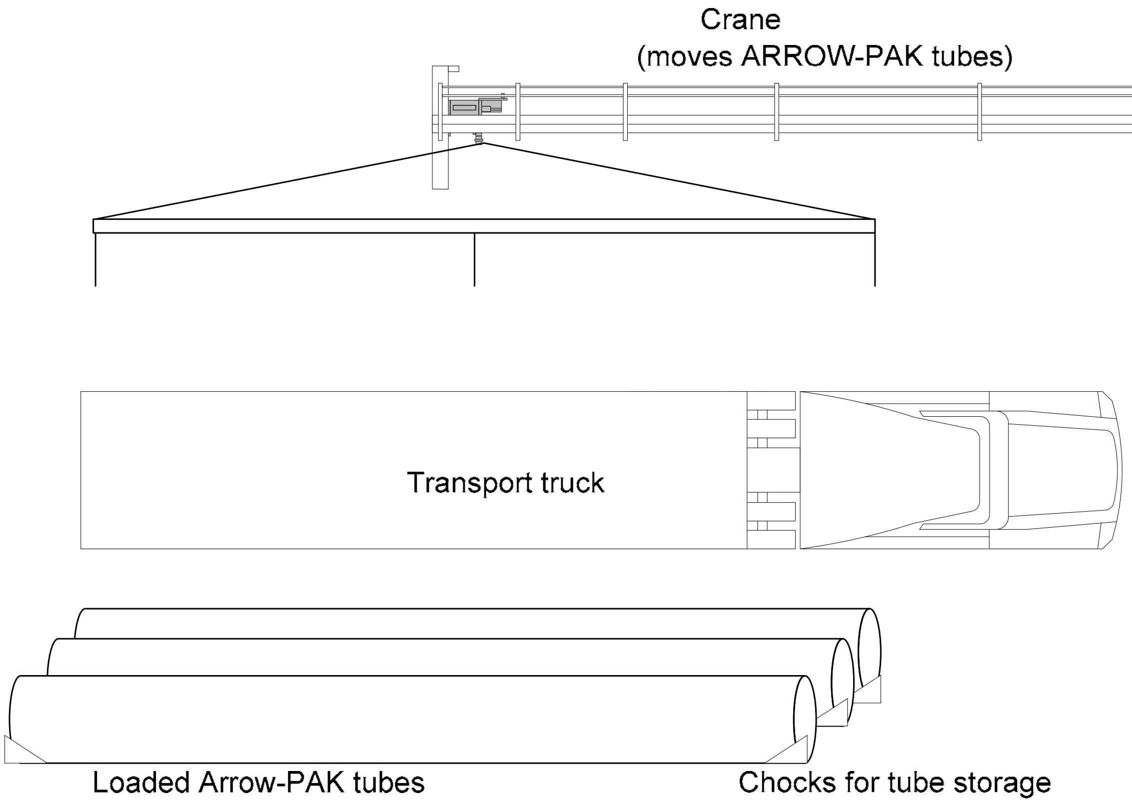
Staff	**Qty**	**Burdened Salary**	**Total**
Operators	6	$45,227	$271,362
Fusion Specialist	2	$66,162	$132,324
Supervisor	2	$73,664	$147,328
Loading Forman	2	$73,664	$147,328
Total	12		$698,342

ENERGY COSTS

Name	**Load (kW)**	**Qty**	**Total Load (kW)**
Fusion equipment	150	1	150
Forklift	75	1	75
Miscellaneous	--	--	34
		Total	259

Energy used	861,120	kW-hours
Price of energy	0.10	$/kw-hr
Cost of energy (per year):	$86,112	

Macroencap Proc Dia



Name: Crane
Cost category: Capital cost
Cost: $78,000
Quantity: 1
Total cost: $78,000

Name: Chocks
Cost category: Capital cost
Cost: $43
Quantity: 20
Total cost: $851

Macroencap Cap Costs (fixed)

	Estimate		
Cost Element	**Min**	**Best**	**Max**
Major Equipment			
Waste loading rack		$2,400	
Forklift with loading plunger		$25,000	
ARROW-PAK handling crane		$78,000	
Fusion equipment		$3,500	
Loading crane		$78,000	
Chocks		$851	
Subtotal: Major Equipment	$187,751	$187,751	$187,751
Allowance for equipment not yet identified	$18,775	$28,163	$37,550
Subtotal: Major Equipment + Allowance	$206,526	$215,914	$225,301
Building site preparation	$16,522	$32,387	$49,566
Building construction, services installation	$53,697	$65,854	$78,855
Subtotal: Building	$70,219	$98,241	$128,422
Cost to install major equipment	$39,240	$45,342	$51,819
Subtotal: Physical Plant	$315,985	$359,496	$405,542
Other field expenses	$20,653	$23,751	$27,036
Engineering	$72,284	$84,206	$96,880
Subtotal: Direct Plant Cost	$408,922	$467,453	$529,458
Initial Start-Up Costs	$8,178	$60,769	$127,070
Fees, overhead, and profit	$61,958	$68,013	$74,349
Contingency	$53,697	$56,138	$58,578
Total	$532,755	$652,372	$789,455

Macroencap Cap Costs (mob)

Cost Element	Estimate		
	Min	**Best**	**Max**
Major Equipment			
Waste loading rack		$2,400	
Forklift with loading plunger		$25,000	
ARROW-PAK handling crane		$78,000	
Fusion equipment		$3,500	
Loading crane		$78,000	
Chocks		$851	
Subtotal: Major Equipment	$187,751	$187,751	$187,751
Allowance for equipment not yet identified	$18,775	$28,163	$37,550
Subtotal: Major Equipment + Allowance	$206,526	$215,914	$225,301
Cost to assemble major equipment skids	$26,229	$30,228	$34,471
Subtotal: Physical Plant	$232,755	$246,142	$259,772
Other field expenses	$20,653	$23,751	$27,036
Engineering	$72,284	$84,206	$96,880
Subtotal: Direct Plant Cost	$325,692	$354,098	$383,688
Initial Start-Up Costs	$6,514	$46,033	$92,085
Fees, overhead, and profit	$61,958	$68,013	$74,349
Contingency	$53,697	$56,138	$58,578
Total	$447,860	$524,282	$608,701

Macroencap O&M

Cost Element	Estimated Cost (per year)		
	Min	Best	Max
HDPE pipes (ARROW-PAKs)	$876,838	$876,838	$876,838
End caps	$477,190	$477,190	$477,190
Staff	$698,342	$698,342	$698,342
Energy	$86,112	$86,112	$86,112
Subtotal: direct costs	$2,138,482	$2,138,482	$2,138,482
Maintenance & Repairs	$4,131	$12,955	$22,530
Insurance	$2,065	$2,159	$2,253
Property tax	$4,131	$4,318	$4,506
Subtotal: indirect costs	$10,326	$19,432	$29,289
Other overhead	$118,184	$118,685	$119,227
Fee	$429,762	$431,583	$433,554
Contingency	$838,035	$841,587	$845,431
Total	$3,534,790	$3,549,769	$3,565,984

Appendix D
Option B Process
Input Information for Cost Estimates

This appendix provides input that was used to estimate the capital and O&M costs for the the Option B process, together with the macroencapsulation process.
Any costs quoted in this appendix are point estimates.
They were subsequently assigned uncertainty distributions as described in Section 4.5
and run through a Crystal Ball Monte Carlo analysis.

Treatment Proc Dia

PROCESS CAPACITY

Mercury processed per batch	375	kg
Batches per mixer-shift	3	
Number of mixers	5	
Work week	5	days
Shifts per day	1	
Work year	260	shifts/year
Utilization	80%	
Equipment work year	208	shifts/year
Annual mercury processing capacity	1,170	tons/year
Required mercury processing throughput:	1,000	tons/year

MERCURY, REAGENT, AND WASTE RATIOS

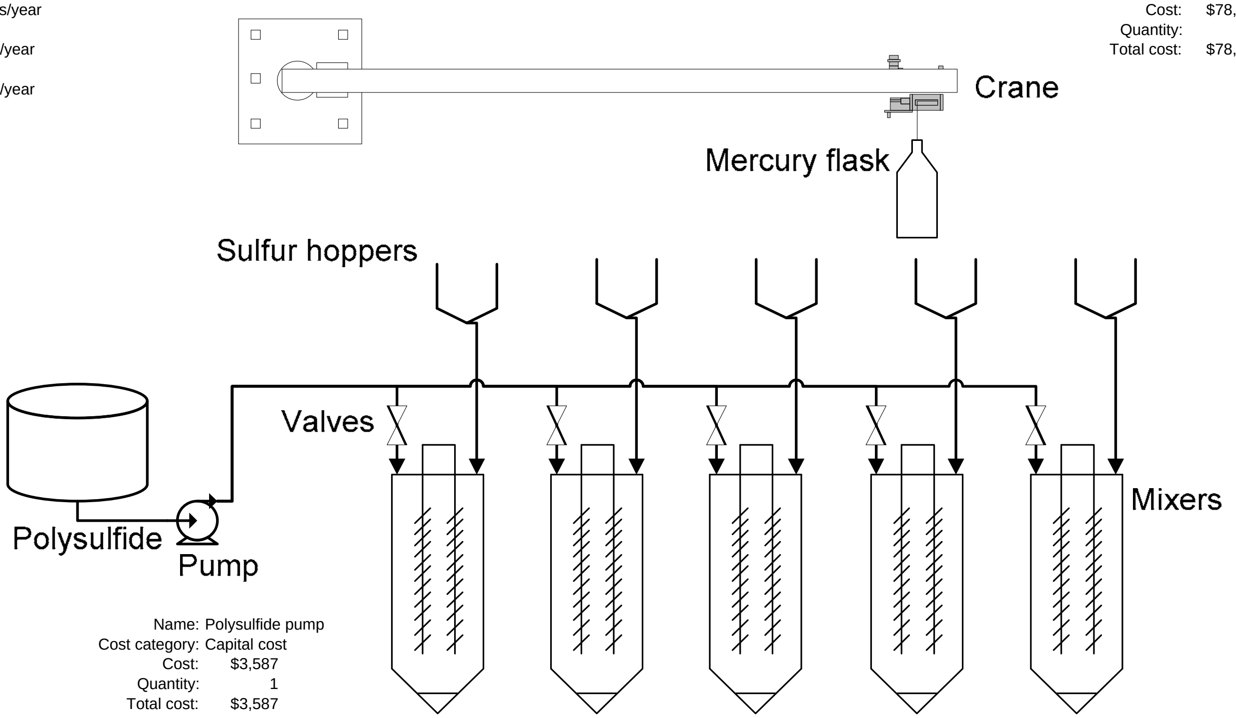
In each batch mixture, % (by mass) of:

Mercury:	67%	
Polysulfide:	3%	
Sulfur:	30%	
Mercury processed per batch:	375	kg
Polysulfide per batch:	16.8	kg
Sulfur per batch:	168	kg
Total batch mass:	560	kg

REAGENT CONSUMPTION

Mass of mecury processed in one batch:	375	kg
Mass of mercury processed per year:	1,000	tons/year
	1,000,000	kg/year
Mass of polysulfide consumed per year:	44,776	kg
Mass of sulfur consumed per year:	447,761	kg

Name: Crane
Cost category: Capital cost
Cost: $78,000
Quantity: 1
Total cost: $78,000



Name: Polysulfide
Cost category: Bulk material cost (O&M)
Unit cost: 0.14 $/kg delivered
Quantity consumed per year: 44,776 kg
Total cost: $6,269

Name: Polysulfide pump
Cost category: Capital cost
Cost: $3,587
Quantity: 1
Total cost: $3,587

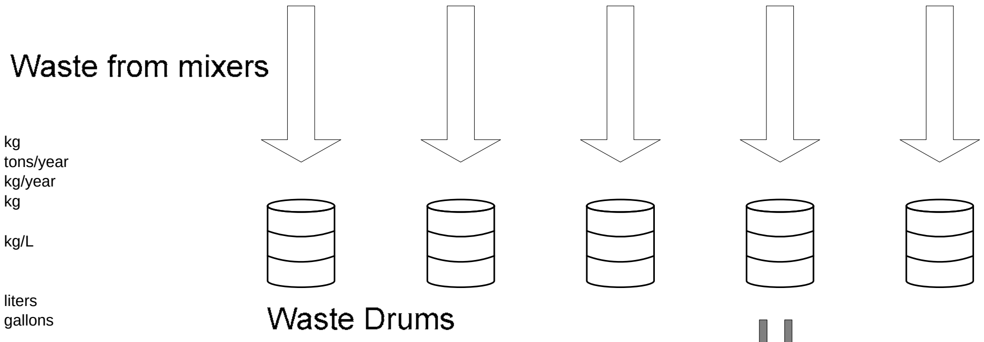
Name: Sulfur
Cost category: Bulk material cost (O&M)
Unit cost: 0.37 $/kg delivered
Quantity consumed per year: 447,761 kg
Total cost: $165,672

Name: Sulfur hoppers
Cost category: Capital cost
Cost: $26,400
Quantity: 5
Total cost: $132,000

Name: Polysulfide feed valves
Cost category: Capital cost
Cost: $760
Quantity: 5
Total cost: $3,800

Name: Mixer
Cost category: Capital cost
Cost: $65,000
Quantity: 5
Total cost: $325,000

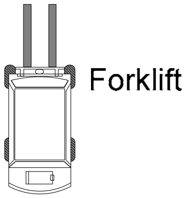
Treatment Proc Dia



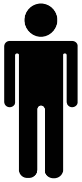
WASTE VOLUME

Mass of mecury processed in one batch:	375	kg
Mass of mercury processed per year:	1,000	tons/year
	1,000,000	kg/year
Mass of waste produced per year:	1,492,537	kg
Density of waste:	1.78	kg/L
Volume of waste produced:	838,504	liters
	221,508	gallons
Required number of 55 gallon barrels	4,027	
Weight of each barrel (includes empty barrel weight of 34 kg)	405	kg
	892	lb

Name:	55 gallon barrels
Cost category:	O&M
Cost per barrel:	$33
Barrels per year:	4,027
Annual cost:	$132,905



Name:	Forklift
Cost category:	Capital cost
Cost:	$25,000
Quantity:	1
Total cost:	$25,000



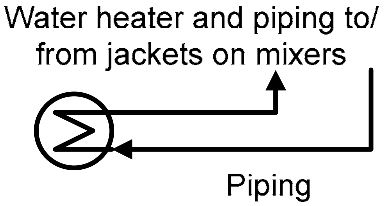
Staff	Qty	Burdened Salary	Total (per year)
Operators	4	$45,227	$180,908
Maintenance Tech	1	$66,162	$66,162
Logistics/Shipping	1	$37,306	$37,306
Operations Supervisor	1	$73,664	$73,664
Process Engineer	1	$89,127	$89,127
Administrative Assistant	1	$45,727	$45,727
I&C Tech	1	$66,581	$66,581
Plant Manager	1	$133,022	$133,022
Lab Tech	1	$67,012	$67,012
QA / Health & Safety Coordinator	1	$67,012	$67,012
Total	13		$826,521

ENERGY COSTS

Name	Load (kW)	Qty	Total Load (kW)
Mixer motor	150	5	750
Heater	72	5	360
Ventilation blower	4	1	4
Forklift	75	1	75
Miscellaneous	--	--	178
		Total	1,367

Energy used	2,275,270	kW-hours
Price of energy	0.10	$/kw-hr
Cost of energy (per year):	$227,527	

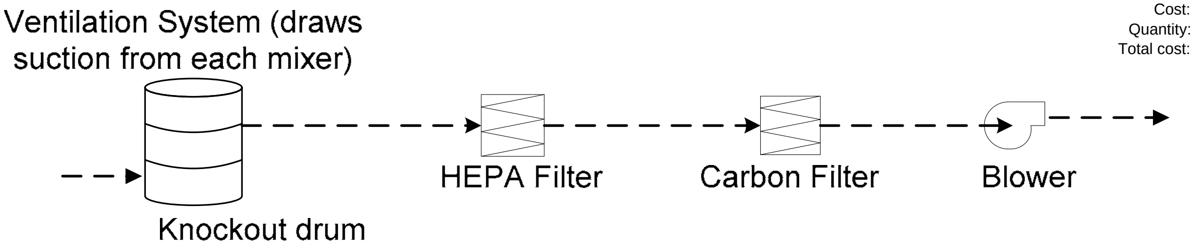
Treatment Proc Dia



Name: Water heater
Cost category: Capital cost
Cost: $2,769
Quantity: 1
Total cost: $2,769

Name: Piping for water
Cost category: Capital cost
Cost: $4,270
Quantity: 1
Total cost: $4,270

Name: Ventilation System Ducts
Cost category: Capital cost
Cost: $5,065
Quantity: 1
Total cost: $5,065



Name: Knockout drum
Cost category: Capital cost
Cost: $6,300
Quantity: 1
Total cost: $6,300

Name: HEPA filter
Cost category: Capital cost
Cost: $307
Quantity: 1
Total cost: $307

Name: Carbon filter
Cost category: Capital cost
Cost: $47
Quantity: 1
Total cost: $47

Name: Blower
Cost category: Capital cost
Cost: $5,987
Quantity: 1
Total cost: $5,987

Treatment Cap Costs (fixed)

Cost Element	Estimate		
	Min	Best	Max
Major Equipment			
Polysulfide pump		$3,587	
Polysulfide feed valves		$3,800	
Sulfur hoppers		$132,000	
Mixers		$325,000	
Knockout drum		$6,300	
HEPA filter		$307	
Carbon filter		$47	
Blower		$5,987	
Ventilation System duct		$5,065	
Water heater		$2,769	
Forklift		$25,000	
Crane		$78,000	
Subtotal: Major Equipment	$587,862	$587,862	$587,862
Allowance for equipment not yet identified	$58,786	$88,179	$117,572
Subtotal: Major Equipment + Allowance	$646,648	$676,041	$705,434
Building site preparation	$51,732	$101,406	$155,196
Building construction, services installation	$168,128	$206,193	$246,902
Subtotal: Building	$219,860	$307,599	$402,097
Cost to install major equipment	$252,193	$277,177	$303,337
Piping	$193,994	$233,234	$275,119
Structural foundations (steel, concrete)	$181,061	$189,291	$197,522
Electrical	$51,732	$84,505	$119,924
Instruments	$84,064	$87,885	$91,706
Auxiliaries	$310,391	$348,161	$387,989
Subtotal: Physical Plant	$1,939,944	$2,203,894	$2,483,128
Other field expenses	$226,327	$263,656	$303,337
Engineering	$226,327	$263,656	$303,337
Subtotal: Direct Plant Cost	$2,392,597	$2,731,206	$3,089,801
Initial Start-Up Costs	$47,852	$355,057	$741,552
Fees, overhead, and profit	$58,198	$87,885	$119,924
Contingency	$252,193	$263,656	$275,119
Total	$2,750,840	$3,437,804	$4,226,397

Treatment Cap Costs (mob)

Cost element	Estimate		
	Min	Best	Max
Major Equipment			
Polysulfide pump		$3,587	
Polysulfide feed valves		$3,800	
Sulfur hoppers		$132,000	
Mixers		$325,000	
Knockout drum		$6,300	
HEPA filter		$307	
Carbon filter		$47	
Blower		$5,987	
Ventilation System duct		$5,065	
Water heater		$2,769	
Forklift		$25,000	
Crane		$78,000	
Subtotal: Major Equipment	$587,862	$587,862	$587,862
Allowance for equipment not yet identified	$58,786	$88,179	$117,572
Subtotal: Major Equipment + Allowance	$646,648	$676,041	$705,434
Steel for skids	$181,061	$189,291	$197,522
Cost to assemble major equipment skids	$168,128	$184,785	$202,224
Subtotal: Skids	$349,190	$374,076	$399,746
Piping	$193,994	$233,234	$275,119
Electrical	$51,732	$84,505	$119,924
Instruments	$84,064	$87,885	$91,706
Auxiliaries	$310,391	$348,161	$387,989
Subtotal: Physical Plant	$1,636,019	$1,803,903	$1,979,918
Engineering	$452,654	$527,312	$606,673
Subtotal: Direct Plant Cost	$2,088,673	$2,331,215	$2,586,592
Initial Start-Up Costs	$41,773	$303,058	$620,782
Fees, overhead, and profit	$58,198	$87,885	$119,924
Contingency	$252,193	$263,656	$275,119
Total	$2,440,837	$2,985,814	$3,602,417

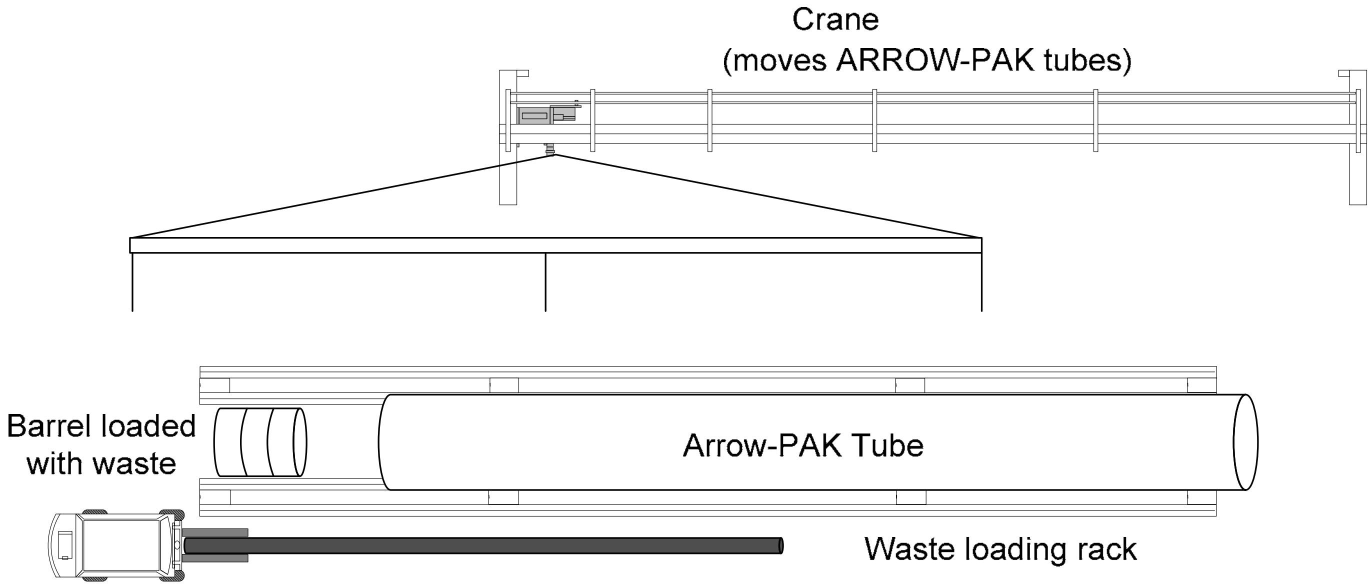
Treatment O&M

Cost Element	Estimated Cost (per year)		
	Min	Best	Max
Polysulfide	$6,269	$6,269	$6,269
Sulfur	$165,672	$165,672	$165,672
Barrels	$132,905	$132,905	$132,905
Staff	$826,521	$826,521	$826,521
Energy	$227,527	$227,527	$227,527
Subtotal: direct costs	$1,358,893	$1,358,893	$1,358,893
Flask disposal	$440,000	$440,000	$440,000
Maintenance & Repairs	$12,933	$40,562	$70,543
Insurance	$6,466	$6,760	$7,054
Property tax	$12,933	$13,521	$14,109
Subtotal: indirect costs	$472,332	$500,844	$531,706
Other overhead	$100,717	$102,286	$103,983
Fee	$366,245	$371,947	$378,120
Contingency	$714,178	$725,297	$737,334
Total	$4,129,413	$4,193,706	$4,263,302

Fclty Reloc Costs

	Estimated Cost (per move)		
Cost Element	**Min**	**Best**	**Max**
Transportation of equipment			
Assembling treatment process lines	$84,064	$92,392	$101,112
Start-up	$4,177	$30,306	$62,078
Contingency	$34,414	$47,852	$63,644
Total	$122,656	$170,550	$226,835

Macroencap Proc Dia



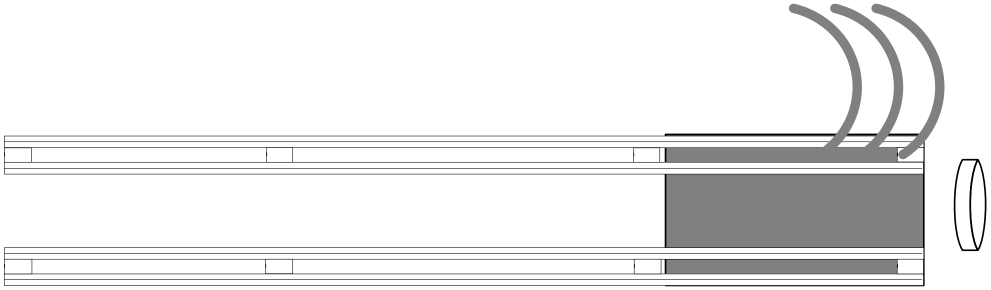
Name: Crane
Cost category: Capital cost
Cost: $78,000
Quantity: 1
Total cost: $78,000

Name: Forklift
Cost category: Capital cost
Cost: $25,000
Quantity: 1
Total cost: $25,000

Name: HDPE pipes
Cost category: Materials (O&M)
Cost ft of pipe: $45
Barrels per year: 4,027
Height of barrel: 2.92 ft
Feet of pipe per year: 11,747
Annual cost: $528,598

Name: Waste loading rack
Cost category: Capital cost
Cost: $2,400
Quantity: 1
Total cost: $2,400

Macroencap Proc Dia



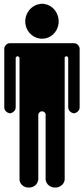
ARROW-PAK Tube Capacity		
Arrow-Pak tube weight limit	9500	lb
Weight of empty tube	950	lb
Weight of loaded 55-gallon barrel	892	lb
Number of barrels allowed by weight limit	9	
Arrow-Pak tube length limit (without endcaps)	22	ft
Length of barrel	34	in
Number of barrels allowed by length limit	7	

Fusion Equipment

Name: Fusion equipment
Cost category: Capital cost
Cost: $3,500
Quantity: 1
Total cost: $3,500

Endcaps

Name: HDPE endcaps
Cost category: Materials (O&M)
HDPE endcaps per year: 1,007
Cost per endcap: $250
Annual cost: $251,713



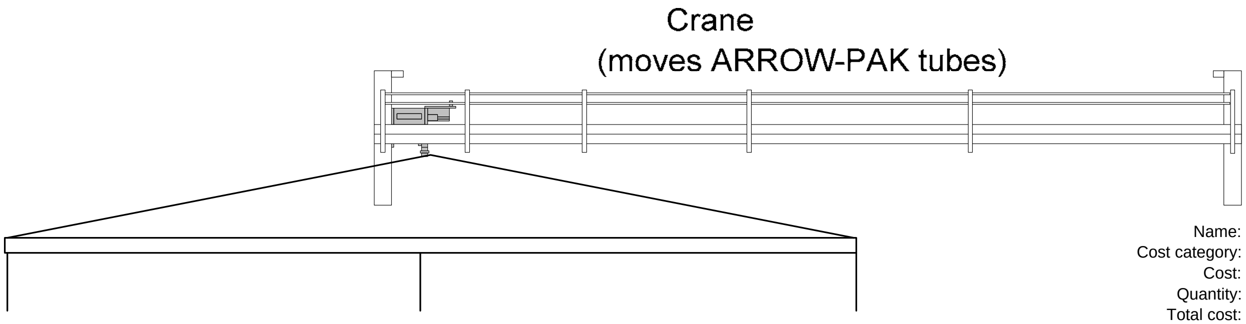
Staff	Qty	Burdened Salary	Total
Operators	3	$45,227	$135,681
Fusion Specialist	1	$66,162	$66,162
Supervisor	1	$73,664	$73,664
Loading Forman	1	$73,664	$73,664
Total	6		$349,171

ENERGY COSTS

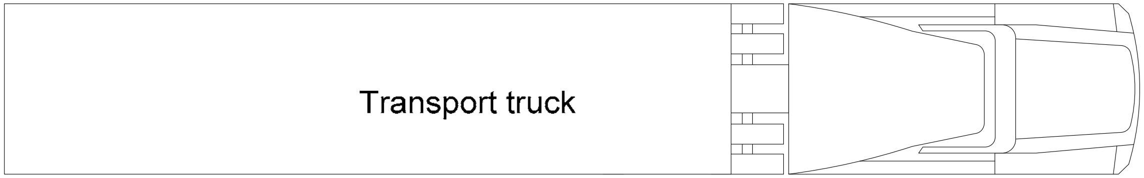
Name	Load (kW)	Qty	Total Load (kW)
Fusion equipment	150	1	150
Forklift	75	1	75
Miscellaneous	--	--	34
		Total	259

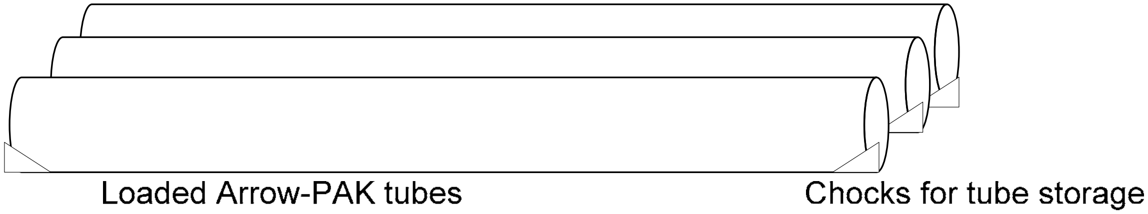
Energy used	430,560	kW-hours
Price of energy	0.10	$/kw-hr
Cost of energy (per year):	$43,056	

Macroencap Proc Dia



Name: Crane
Cost category: Capital cost
Cost: $78,000
Quantity: 1
Total cost: $78,000





Name: Chocks
Cost category: Capital cost
Cost: $43
Quantity: 20
Total cost: $851

Macroencap Cap Costs (fixed)

	Estimate		
Cost Element	**Min**	**Best**	**Max**
Major Equipment			
Waste loading rack		$2,400	
Forklift with loading plunger		$25,000	
ARROW-PAK handling crane		$78,000	
Fusion equipment		$3,500	
Loading crane		$78,000	
Chocks		$851	
Subtotal: Major Equipment	$187,751	$187,751	$187,751
Allowance for equipment not yet identified	$18,775	$28,163	$37,550
Subtotal: Major Equipment + Allowance	$206,526	$215,914	$225,301
Building site preparation	$16,522	$32,387	$49,566
Building construction, services installation	$53,697	$65,854	$78,855
Subtotal: Building	$70,219	$98,241	$128,422
Cost to install major equipment	$39,240	$45,342	$51,819
Subtotal: Physical Plant	$315,985	$359,496	$405,542
Other field expenses	$20,653	$23,751	$27,036
Engineering	$72,284	$84,206	$96,880
Subtotal: Direct Plant Cost	$408,922	$467,453	$529,458
Initial Start-Up Costs	$8,178	$60,769	$127,070
Fees, overhead, and profit	$61,958	$68,013	$74,349
Contingency	$53,697	$56,138	$58,578
Total	$532,755	$652,372	$789,455

Macroencap Cap Costs (mob)

Cost Element	Estimate		
	Min	Best	Max
Major Equipment			
Waste loading rack		$2,400	
Forklift with loading plunger		$25,000	
ARROW-PAK handling crane		$78,000	
Fusion equipment		$3,500	
Loading crane		$78,000	
Chocks		$851	
Subtotal: Major Equipment	$187,751	$187,751	$187,751
Allowance for equipment not yet identified	$18,775	$28,163	$37,550
Subtotal: Major Equipment + Allowance	$206,526	$215,914	$225,301
Cost to assemble major equipment skids	$26,229	$30,228	$34,471
Subtotal: Physical Plant	$232,755	$246,142	$259,772
Other field expenses	$20,653	$23,751	$27,036
Engineering	$72,284	$84,206	$96,880
Subtotal: Direct Plant Cost	$325,692	$354,098	$383,688
Initial Start-Up Costs	$6,514	$46,033	$92,085
Fees, overhead, and profit	$61,958	$68,013	$74,349
Contingency	$53,697	$56,138	$58,578
Total	$447,860	$524,282	$608,701

Macroencap O&M

Cost Element	Estimated Cost (per year)		
	Min	Best	Max
HDPE pipes (ARROW-PAKs)	$528,598	$528,598	$528,598
End caps	$251,713	$251,713	$251,713
Staff	$349,171	$349,171	$349,171
Energy	$43,056	$43,056	$43,056
Subtotal: direct costs	$1,172,538	$1,172,538	$1,172,538
Maintenance & Repairs	$4,131	$12,955	$22,530
Insurance	$2,065	$2,159	$2,253
Property tax	$4,131	$4,318	$4,506
Subtotal: indirect costs	$10,326	$19,432	$29,289
Other overhead	$65,058	$65,558	$66,100
Fee	$236,573	$238,394	$240,365
Contingency	$461,317	$464,868	$468,713
Total	$1,945,812	$1,960,791	$1,977,006

Appendix E
Input to Monofill Costs - Option A Process

This appendix provides input that was used to estimate the capital and O&M costs for the monofill associated with the Option A treatment process.
Any costs quoted in this appendix are point estimates.
They were subsequently assigned uncertainty distributions as described in Section 4.5 and run through a Crystal Ball Monte Carlo analysis.

Dimensions

Dimensions required for a five year cell:	Without macroencapsulation	With macroencapsulation
Length of disposal area	207 ft	227 ft
Width of disposal area	207 ft	218 ft
Area required for storage	42,849 ft^2	49,345 ft^2
	0.98 acres	1.13 acres
Storage volume depth	15 ft	15 ft
Depth below grade	7.5 ft	7.5 ft
Bottom liner thickness	7 ft	7 ft
Run-off ditch depth	6 ft	6 ft
Width at bottom of run-off ditch	1 ft	1 ft
Run-off ditch length	852 ft	912.8 ft
Run-off ditch volume	35,784 ft^3	38,336 ft^3
	1,325 yd^3	1,420 yd^3

Size of a cell without macroencapsulation		
Height of one 55-gallon drum	34	in
Diameter of one 55-gallon drum	23	in
Fill above and below each layer	5.5	in
Height of a layer	45	in
Stack drums	4	high
Thickness of waste layer	15.0	ft
Thickness alloted for waste layer	15	ft
Barrels per year	6,681	
Barrels in five years	33,405	
Barrels per layer required in the cell	8,351.25	
One layer is:	92	by
	92	barrels
Distance between barels in the square	4	in
Distance one barrel occupies	27	in
Length of the side of a cell	207	ft

Size of a cell with macroencapsulation		
Barrels per Arrow-Pak tube	7	
Length of one Arrow-Pak tube	20.3	ft
Diameter of one Arrow-Pak tube	26	in
Fill above and below each layer	5	in
Height of a layer	36	in
Stack tubes	5	high
Thickness of waste layer	15.0	ft
Thickness alloted for waste layer	15	ft
Barrels per year	6,681	
Barrels in five years	33,405	
Tubes in five years	4,772	
Required tubes per layer	954	
Distance between tubes	4	in
Area one tube occupies	20.6	ft by
	30	in
One layer is:	11	tubes long by
	87	tubes wide
Lengths of the sides of the cell	227	ft by
	218	ft

Labor & Materials

Summary of construction costs	Without macroencapsulation	With macroencapsulation
Disposal volume excavation	$110,713	$126,434
Run-on, run-off controls	$11,186	$11,983
Bottom Liner	$681,580	$775,689
Waste and Fill Layer	$13,759	$15,845
Top Liner	$221,595	$252,192
Groundwater Monitoring Wells	$96,670	$96,670
TOTAL	**$1,135,503**	**$1,278,813**

Disposal Volume Excavation						
Excavation required for disposal voume		708,354	ft^3		808,937	ft^3
		26,235	yd^3		29,961	yd^3
Unit cost for excavation		4.22	$/yd^3		4.22	$/yd^3
Cost	$	110,713.11		$	126,433.84	

Run-on, run-off controls						
Run-off ditch						
Excavation required for run-off ditch		35,784	ft^3		38,336	ft^3
		1,325	yd^3		1,420	ft^3
Unit cost for excavation		4.22	$/yd^3		4.22	$/yd^3
Cost	$	5,592.91		$	5,991.70	
Cost of building berm						
Assume excavated soil for run-off ditch is used for berm						
Berm volume		1,325	yd^3		1,420	yd^3
Unit cost for building		4.22	$/yd^3		4.22	$/yd^3
Berm cost	$	5,592.91		$	5,991.70	

Labor & Materials

Bottom Liner						
Area required for storage + liner slope		51,716	ft^2		58,857	ft^2
Cost of compacted clay						
Clay thickness		3	ft		3	ft
Clay volume		155,148	ft^3		176,570	ft^3
		5,746	yd^3		6,540	yd^3
Unit cost		27.63	$/yd^3		27.63	$/yd^3
Cost of compacted clay	$	158,768.49		$	180,690.32	
Geotextile support fabric						
Layers required		3			3	
Area required		51,716	ft^2		58,857	ft^2
Unit cost		0.26	$/ft^2		0.26	$/ft^2
Cost for geotextile support fabric	$	40,338.57		$	45,908.29	
Geotextile filter fabric						
Layers required		1			1	
Area required		51,716	ft^2		58,857	ft^2
Unit cost		0.13	$/ft^2		0.13	$/ft^2
Cost for geotextile filter fabric	$	6,723.10		$	7,651.38	
HDPE liners						
Layers required		2			2	
Area required		51,716	ft^2		58,857	ft^2
Unit cost		0.53	$/ft^2		0.53	$/ft^2
Cost for HDPE liner	$	54,819.09		$	62,388.19	
Gravel drainage layers						
Layers required		2			2	
Thickness of each layer		1	ft		1	ft
Area required		51,716	ft^2		58,857	ft^2
Volume required		103,432	ft^3		117,714	ft^3
		3,831	yd^3		4,360	yd^3
Unit cost		12.57	$/yd^3		12.57	$/yd^3
Cost for compacted gravel	$	48,153.45		$	54,802.20	
Compacted fill soil						
Layers required		1			1	
Thickness of each layer		2	ft		2	ft
Area required		51,716	ft^2		58,857	ft^2
Volume required		103,432	ft^3		117,714	ft^3
		3,831	yd^3		4,360	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost for compacted soil	$	22,142.16		$	25,199.42	
Leachate collection and removal system						
Area required		51,716	ft^2		58,857	ft^2
Installed unit cost		3.39	$/ft^2		3.39	$/ft^2
Cost	$	175,317.64		$	199,524.49	
Leak detection system						
Area required		51,716	ft^2		58,857	ft^2
Installed unit cost		3.39	$/ft^2		3.39	$/ft^2
Cost	$	175,317.64		$	199,524.49	

Waste and Fill Layer						
Volume of fill required		64,274	ft^3		74,018	ft^3
		2,381	yd^3		2,741	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost of flowable fill	$	13,759.29		$	15,845.33	

Labor & Materials

Top Liner

		Without macroencapsulation			With macroencapsulation	
Area required for storage + liner slope		51,716	ft^2		58,857	ft^2
Cost of compacted clay						
Clay thickness		1.5	ft		1.5	ft
Clay volume		77,574	ft^3		88,285	ft^3
		2,873	yd^3		3,270	yd^3
Unit cost		27.63	$/yd^3		27.63	$/yd^3
Cost of compacted clay	$	79,384.24		$	90,345.16	
Geotextile support fabric						
Layers required		2			2	
Area required		51,716	ft^2		58,857	ft^2
Unit cost		0.26	$/ft^2		0.26	$/ft^2
Cost for geotextile support fabric	$	26,892.38		$	30,605.53	
Geotextile filter fabric						
Layers required		1			1	
Area required		51,716	ft^2		58,857	ft^2
Unit cost		0.13	$/ft^2		0.13	$/ft^2
Cost for geotextile filter fabric	$	6,723.10		$	7,651.38	
HDPE liners						
Layers required		1			1	
Area required		51,716	ft^2		58,857	ft^2
Unit cost		0.53	$/ft^2		0.53	$/ft^2
Cost for HDPE liner	$	27,409.54		$	31,194.09	
Gravel drainage layers						
Layers required		1			1	
Thickness of each layer		0.5	ft		0.5	ft
Area required		51,716	ft^2		58,857	ft^2
Volume required		25,858	ft^3		29,428	ft^3
		958	yd^3		1,090	yd^3
Unit cost		12.57	$/yd^3		12.57	$/yd^3
Cost for compacted gravel	$	12,038.36		$	13,700.55	
Compacted fill soil						
Layers required		1			1	
Thickness of each layer		3	ft		3	ft
Area required		51,716	ft^2		58,857	ft^2
Volume required		155,148	ft^3		176,570	ft^3
		5,746	yd^3		6,540	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost for compacted soil	$	33,213.24		$	37,799.13	
Compacted top soil						
Layers required		1			1	
Thickness of each layer		1	ft		1	ft
Area required		51,716	ft^2		58,857	ft^2
Volume required		51,716	ft^3		58,857	ft^3
		1,915	yd^3		2,180	yd^3
Unit cost		17.68	$/yd^3		17.68	$/yd^3
Cost for compacted soil	$	33,864.48		$	38,540.29	
Vegetation to stabilize topsoil						
Area required		51,716	ft^2		58,857	ft^2
		1.19	acres		1.35	acres
Unit cost		1743.40	$/acre		1743.40	$/acre
Cost	$	2,069.83		$	2,355.62	

Groundwater Monitoring Wells

Clusters (three wells) required		4		4	
Cost per cluster	$	24,167.48	$	24,167.48	
Cost	$	96,669.92	$	96,669.92	

Direct O&M (filling)

Summary of Annual Direct O&M Costs (filling)	**Without macroencapsulation**		**With macroencapsulation**
Staff	$352,991		$443,097
Groundwater Monitoring	$4,752		$4,752
Utilities	$10,000		$10,000
Fee	$55,162		$68,677
TOTAL	$422,905		$526,526

Staff	**Burdened Annual Salary**	**Qty**	**Without macroencapsulation**		**With macroencapsulation**	
			Annual utilization	**Total**	**Annual utilization**	**Total**
Operators	$45,227	4	0.58	$105,761.60	0.73	$132,759
Maintenance Tech	$66,162	1	0.58	$38,679.32	0.73	$48,553
Logistics/Shipping	$37,306	1	0.58	$21,809.66	0.73	$27,377
Operations Supervisor	$73,664	1	0.58	$43,065.11	0.73	$54,058
Administrative Assistant	$45,727	1	0.58	$26,732.71	0.73	$33,557
Plant Manager	$133,022	1	0.58	$77,766.71	0.73	$97,618
QA / Health & Safety Coordinator	$67,012	1	0.58	$39,176.25	0.73	$49,176
			Totals:	$352,991.35		$443,097

Groundwater Monitoring		
Number of groundwater monitoring wells	4	4
Samples per year from each well	12	12
Cost for sample analysis	$99	$99
Annual Cost	$4,752	$4,752

Shipments per year without macroencapsulation		
Truck weight limit	40,000	lb
Weight of one barrel loaded with treated mercury	892	lb
Barrels per truck delivery	44	barrels
Flat bed trailer width	8	ft
Flat bed trailer length	40	ft
Area available on flat bed trailer	320	ft^2
Area required by one barrel	5.4	ft^2
Area required by barrels in one shipment	239	ft^2
Barrels per year	6681	
Shipments per year	152	

Shipments per year with macroencapsulation		
Truck weight limit	40,000	lb
Barrels per Arrow-Pak	7	
Weight, one tube w/barrels of treated Hg (empty tube is 950 lb)	7194	lb
Arrow-Pak tubes per truck delivery	5	tubes
Area required by one Arrow-Pak tube	44.0	ft^2
Area required by tubes in one shipment	220	ft^2
Area available on flat bed trailer	320	ft^2
Tubes per year	954	
Shipments per year	190.8	

O&M (post-closure)

Summary of Post-Closure Costs	Without macroencapsulation	With macroencapsulation
Leachate collection and removal system	$10,437	$10,437
Leak detection system	$19,135	$19,135
Ground water	$5,940	$5,940
Utilities	$30,000	$30,000
License and bonding fees	$300,000	$300,000
Fee	$54,827	$54,827
Contingency	$42,034	$42,034
Total 30-year Cost	$462,372	$462,372

Cost for one day of operator time for each inspection	$174

Leachate collection and removal system		
First five years		
Monitoring per year	12	12
Cost per sample	$174	$174
Total cost	$10,437	$10,437

Leak detection system		
First five years		
Monitoring per year	12	12
Cost per sample	$174	$174
Cost (first five years)	$10,437	$10,437
Following twenty-five years		
Monitoring per year	2	2
Cost per sample	$174	$174
Cost (following twenty-five years)	$8,698	$8,698
Total	$19,135	$19,135

Ground water monitoring		
Samples per year	2	2
Cost per sample	$99	$99
Total cost	$5,940	$5,940

Appendix F
Input to Monofill Costs - Option B Process

This appendix provides input that was used to estimate the capital and O&M costs for the monofill associated with the Option B treatment process.
Any costs quoted in this appendix are point estimates.
They were subsequently assigned uncertainty distributions as described in Section 4.5 and run through a Crystal Ball Monte Carlo analysis.

Dimensions

Dimensions required for a five year cell:	Without macroencapsulation	With macroencapsulation
Length of disposal area	160 ft	165 ft
Width of disposal area	160 ft	180 ft
Area required for storage	25,520 ft^2 0.59 acres	29,700 ft^2 0.68 acres
Storage volume depth	15 ft	15 ft
Depth below grade	7.5 ft	7.5 ft
Bottom liner thickness	7 ft	7 ft
Run-off ditch depth	6 ft	6 ft
Width at bottom of run-off ditch	1 ft	1 ft
Run-off ditch length	663 ft	714.0 ft
Run-off ditch volume	27,846 ft^3 1,031 yd^3	29,988 ft^3 1,111 yd^3

Size of a cell without macroencapsulation		
Height of one 55-gallon drum	34	in
Diameter of one 55-gallon drum	23	in
Fill above and below each layer	5.5	in
Height of a layer	45	in
Stack drums	4	high
Thickness of waste layer	15.0	ft
Thickness alloted for waste layer	15	ft
Barrels per year	4,027	
Barrels in five years	20,135	
Barrels per layer required in the cell	5,033.75	
One layer is:	71 71	by barrels
Distance between barels in the square	4	in
Distance one barrel occupies	27	in
Length of the side of a cell	160	ft

Size of a cell with macroencapsulation		
Barrels per Arrow-Pak tube	7	
Length of one Arrow-Pak tube	20.3	ft
Diameter of one Arrow-Pak tube	26	in
Fill above and below each layer	5	in
Height of a layer	36	in
Stack tubes	5	high
Thickness of waste layer	15.0	ft
Thickness alloted for waste layer	15	ft
Barrels per year	4,027	
Barrels in five years	20,135	
Tubes in five years	2,876	
Required tubes per layer	575	
Distance between tubes	4	in
Area one tube occupies	20.6 30	ft by in
One layer is:	8 72	tubes long by tubes wide
Lengths of the sides of the cell	165 180	ft by ft

Labor & Materials

Summary of construction costs	Without macroencapsulation	With macroencapsulation
Disposal volume excavation	$68,335	$78,646
Run-on, run-off controls	$8,704	$9,374
Bottom Liner	$426,778	$488,995
Waste and Fill Layer	$8,195	$9,537
Top Liner	$138,754	$158,982
Groundwater Monitoring Wells	$96,670	$96,670
TOTAL	**$747,436**	**$842,205**

Disposal Volume Excavation						
Excavation required for disposal voume		437,216	ft^3		503,186	ft^3
		16,193	yd^3		18,637	yd^3
Unit cost for excavation		4.22	$/yd^3		4.22	$/yd^3
Cost	$	68,335.21		$	78,646.15	

Run-on, run-off controls						
Run-off ditch						
Excavation required for run-off ditch		27,846	ft^3		29,988	ft^3
		1,031	yd^3		1,111	ft^3
Unit cost for excavation		4.22	$/yd^3		4.22	$/yd^3
Cost	$	4,352.23		$	4,687.01	
Cost of building berm						
Assume excavated soil for run-off ditch is used for berm						
Berm volume		1,031	yd^3		1,111	yd^3
Unit cost for building		4.22	$/yd^3		4.22	$/yd^3
Berm cost	$	4,352.23		$	4,687.01	

Labor & Materials

Bottom Liner						
Area required for storage + liner slope		32,383	ft^2		37,103	ft^2
Cost of compacted clay						
Clay thickness		3	ft		3	ft
Clay volume		97,148	ft^3		111,310	ft^3
		3,598	yd^3		4,123	yd^3
Unit cost		27.63	$/yd^3		27.63	$/yd^3
Cost of compacted clay	$	99,414.38		$	113,907.46	
Geotextile support fabric						
Layers required		3			3	
Area required		32,383	ft^2		37,103	ft^2
Unit cost		0.26	$/ft^2		0.26	$/ft^2
Cost for geotextile support fabric	$	25,258.38		$	28,940.66	
Geotextile filter fabric						
Layers required		1			1	
Area required		32,383	ft^2		37,103	ft^2
Unit cost		0.13	$/ft^2		0.13	$/ft^2
Cost for geotextile filter fabric	$	4,209.73		$	4,823.44	
HDPE liners						
Layers required		2			2	
Area required		32,383	ft^2		37,103	ft^2
Unit cost		0.53	$/ft^2		0.53	$/ft^2
Cost for HDPE liner	$	34,325.49		$	39,329.61	
Gravel drainage layers						
Layers required		2			2	
Thickness of each layer		1	ft		1	ft
Area required		32,383	ft^2		37,103	ft^2
Volume required		64,765	ft^3		74,207	ft^3
		2,399	yd^3		2,748	yd^3
Unit cost		12.57	$/yd^3		12.57	$/yd^3
Cost for compacted gravel	$	30,151.74		$	34,547.40	
Compacted fill soil						
Layers required		1			1	
Thickness of each layer		2	ft		2	ft
Area required		32,383	ft^2		37,103	ft^2
Volume required		64,765	ft^3		74,207	ft^3
		2,399	yd^3		2,748	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost for compacted soil	$	13,864.52		$	15,885.76	
Leachate collection and removal system						
Area required		32,383	ft^2		37,103	ft^2
Installed unit cost		3.39	$/ft^2		3.39	$/ft^2
Cost	$	109,776.79		$	125,780.55	
Leak detection system						
Area required		32,383	ft^2		37,103	ft^2
Installed unit cost		3.39	$/ft^2		3.39	$/ft^2
Cost	$	109,776.79		$	125,780.55	

Waste and Fill Layer						
Volume of fill required		38,280	ft^3		44,550	ft^3
		1,418	yd^3		1,650	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost of flowable fill	$	8,194.78		$	9,537.00	

Labor & Materials

Top Liner		Without macroencapsulation			With macroencapsulation	
Area required for storage + liner slope		32,383	ft^2		37,103	ft^2
Cost of compacted clay						
Clay thickness		1.5	ft		1.5	ft
Clay volume		48,574	ft^3		55,655	ft^3
		1,799	yd^3		2,061	yd^3
Unit cost		27.63	$/yd^3		27.63	$/yd^3
Cost of compacted clay	$	49,707.19		$	56,953.73	
Geotextile support fabric						
Layers required		2			2	
Area required		32,383	ft^2		37,103	ft^2
Unit cost		0.26	$/ft^2		0.26	$/ft^2
Cost for geotextile support fabric	$	16,838.92		$	19,293.77	
Geotextile filter fabric						
Layers required		1			1	
Area required		32,383	ft^2		37,103	ft^2
Unit cost		0.13	$/ft^2		0.13	$/ft^2
Cost for geotextile filter fabric	$	4,209.73		$	4,823.44	
HDPE liners						
Layers required		1			1	
Area required		32,383	ft^2		37,103	ft^2
Unit cost		0.53	$/ft^2		0.53	$/ft^2
Cost for HDPE liner	$	17,162.74		$	19,664.81	
Gravel drainage layers						
Layers required		1			1	
Thickness of each layer		0.5	ft		0.5	ft
Area required		32,383	ft^2		37,103	ft^2
Volume required		16,191	ft^3		18,552	ft^3
		600	yd^3		687	yd^3
Unit cost		12.57	$/yd^3		12.57	$/yd^3
Cost for compacted gravel	$	7,537.93		$	8,636.85	
Compacted fill soil						
Layers required		1			1	
Thickness of each layer		3	ft		3	ft
Area required		32,383	ft^2		37,103	ft^2
Volume required		97,148	ft^3		111,310	ft^3
		3,598	yd^3		4,123	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost for compacted soil	$	20,796.78		$	23,828.63	
Compacted top soil						
Layers required		1			1	
Thickness of each layer		1	ft		1	ft
Area required		32,383	ft^2		37,103	ft^2
Volume required		32,383	ft^3		37,103	ft^3
		1,199	yd^3		1,374	yd^3
Unit cost		17.68	$/yd^3		17.68	$/yd^3
Cost for compacted soil	$	21,204.56		$	24,295.86	
Vegetation to stabilize topsoil						
Area required		32,383	ft^2		37,103	ft^2
		0.74	acres		0.85	acres
Unit cost		1743.40	$/acre		1743.40	$/acre
Cost	$	1,296.04		$	1,484.99	

Groundwater Monitoring Wells				
Clusters (three wells) required		4		4
Cost per cluster	$	24,167.48	$	24,167.48
Cost	$	96,669.92	$	96,669.92

Direct O&M (filling)

Summary of Annual Direct O&M Costs (filling)	Without macroencapsulation		With macroencapsulation
Staff	$213,653		$267,066
Groundwater Monitoring	$4,752		$4,752
Utilities	$10,000		$10,000
Fee	$34,261		$42,273
TOTAL	$262,665		$324,091

Staff	Burdened Annual Salary	Qty	Without macroencapsulation		With macroencapsulation	
			Annual utilization	Total	Annual utilization	Total
Operators	$45,227	4	0.35	$64,013.60	0.44	$80,017
Maintenance Tech	$66,162	1	0.35	$23,411.17	0.44	$29,264
Logistics/Shipping	$37,306	1	0.35	$13,200.58	0.44	$16,501
Operations Supervisor	$73,664	1	0.35	$26,065.72	0.44	$32,582
Administrative Assistant	$45,727	1	0.35	$16,180.32	0.44	$20,225
Plant Manager	$133,022	1	0.35	$47,069.32	0.44	$58,837
QA / Health & Safety Coordinator	$67,012	1	0.35	$23,711.94	0.44	$29,640
			Totals:	$213,652.66		$267,066

Groundwater Monitoring		
Number of groundwater monitoring wells	4	4
Samples per year from each well	12	12
Cost for sample analysis	$99	$99
Annual Cost	$4,752	$4,752

Shipments per year without macroencapsulation		
Truck weight limit	40,000	lb
Weight of one barrel loaded with treated mercury	892	lb
Barrels per truck delivery	44	barrels
Flat bed trailer width	8	ft
Flat bed trailer length	40	ft
Area available on flat bed trailer	320	ft^2
Area required by one barrel	5.4	ft^2
Area required by barrels in one shipment	239	ft^2
Barrels per year	4027	
Shipments per year	92	

Shipments per year with macroencapsulation		
Truck weight limit	40,000	lb
Barrels per Arrow-Pak	7	
Weight, one tube w/barrels of treated Hg (empty tube is 950 lb)	7194	lb
Arrow-Pak tubes per truck delivery	5	tubes
Area required by one Arrow-Pak tube	44.0	ft^2
Area required by tubes in one shipment	220	ft^2
Area available on flat bed trailer	320	ft^2
Tubes per year	575	
Shipments per year	115	

O&M (post-closure)

Summary of Post-Closure Costs	Without macroencapsulation	With macroencapsulation
Leachate collection and removal system	$10,437	$10,437
Leak detection system	$19,135	$19,135
Ground water	$5,940	$5,940
Utilities	$30,000	$30,000
License and bonding fees	$300,000	$300,000
Fee	$54,827	$54,827
Contingency	$42,034	$42,034
Total 30-year Cost	$462,372	$462,372

Cost for one day of operator time for each inspection	$174

Leachate collection and removal system		
First five years		
Monitoring per year	12	12
Cost per sample	$174	$174
Total cost	$10,437	$10,437

Leak detection system		
First five years		
Monitoring per year	12	12
Cost per sample	$174	$174
Cost (first five years)	$10,437	$10,437
Following twenty-five years		
Monitoring per year	2	2
Cost per sample	$174	$174
Cost (following twenty-five years)	$8,698	$8,698
Total	$19,135	$19,135

Ground water monitoring		
Samples per year	2	2
Cost per sample	$99	$99
Total cost	$5,940	$5,940

Appendix G
Input to Monofill Costs - Option C Process

This appendix provides input that was used to estimate the capital and O&M costs for the monofill associated with the Option C treatment process.
Any costs quoted in this appendix are point estimates.
They were subsequently assigned uncertainty distributions as described in Section 4.5 and run through a Crystal Ball Monte Carlo analysis.

Dimensions

Dimensions required for a five year cell:	Without macroencapsulation		With macroencapsulation	
Length of disposal area	223	ft	210	ft
Width of disposal area	223	ft	203	ft
Area required for storage	49,618	ft^2	42,611	ft^2
	1.14	acres	0.98	acres
Storage volume depth	15	ft	15	ft
Depth below grade	7.5	ft	7.5	ft
Bottom liner thickness	7	ft	7	ft
Run-off ditch depth	6	ft	6	ft
Width at bottom of run-off ditch	1	ft	1	ft
Run-off ditch length	915.0	ft	849.9	ft
Run-off ditch volume	38,430	ft^3	35,694	ft^3
	1,423	yd^3	1,322	yd^3

Size of a cell without macroencapsulation		
Height of one 22-gallon drum	13.6	in
Diameter of one 22-gallon drum	23	in
Fill above and below each layer	6	in
Height of a layer	25.6	in
Stack drums	7	high
Thickness of waste layer	14.9	ft
Thickness alloted for waste layer	15	ft
Barrels per year	13,724	
Barrels in five years	68,620	
Barrels per layer required in the cell	9,802.86	
One layer is:	99	by
	99	barrels
Distance between barels in the square	4	in
Distance one barrel occupies	27	in
Length of the side of a cell	223	ft

Size of a cell with macroencapsulation		
Barrels per Arrow-Pak tube	9	
Length of one Arrow-Pak tube	10.7	ft
Diameter of one Arrow-Pak tube	26	in
Fill above and below each layer	5	in
Height of a layer	36	in
Stack tubes	5	high
Thickness of waste layer	15.0	ft
Thickness alloted for waste layer	15	ft
Barrels per year	13,724	
Barrels in five years	68,620	
Tubes in five years	7,624	
Required tubes per layer	1,525	
Distance between tubes	4	in
Area one tube occupies	11.1	ft by
	30	in
One layer is:	19	tubes long by
	81	tubes wide
Lengths of the sides of the cell	210	ft by
	203	ft

Labor & Materials

Summary of construction costs	Without macroencapsulation	With macroencapsulation
Disposal volume excavation	$127,088	$110,139
Run-on, run-off controls	$12,013	$11,158
Bottom Liner	$779,591	$678,144
Waste and Fill Layer	$15,933	$13,683
Top Liner	$253,461	$220,478
Groundwater Monitoring Wells	$96,670	$96,670
TOTAL	**$1,284,755**	**$1,130,271**

Disposal Volume Excavation						
Excavation required for disposal voume		813,121	ft^3		704,678	ft^3
		30,116	yd^3		26,099	yd^3
Unit cost for excavation		4.22	$/yd^3		4.22	$/yd^3
Cost	$	127,087.81		$	110,138.54	

Run-on, run-off controls						
Run-off ditch						
Excavation required for run-off ditch		38,430	ft^3		35,694	ft^3
		1,423	yd^3		1,322	ft^3
Unit cost for excavation		4.22	$/yd^3		4.22	$/yd^3
Cost	$	6,006.47		$	5,578.79	
Cost of building berm						
Assume excavated soil for run-off ditch is used for berm						
Berm volume		1,423	yd^3		1,322	yd^3
Unit cost for building		4.22	$/yd^3		4.22	$/yd^3
Berm cost	$	6,006.47		$	5,578.79	

Labor & Materials

Bottom Liner						
Area required for storage + liner slope		59,153	ft^2		51,455	ft^2
Cost of compacted clay						
Clay thickness		3	ft		3	ft
Clay volume		177,459	ft^3		154,366	ft^3
		6,573	yd^3		5,717	yd^3
Unit cost		27.63	$/yd^3		27.63	$/yd^3
Cost of compacted clay	$	181,599.40		$	157,968.01	
Geotextile support fabric						
Layers required		3			3	
Area required		59,153	ft^2		51,455	ft^2
Unit cost		0.26	$/ft^2		0.26	$/ft^2
Cost for geotextile support fabric	$	46,139.26		$	40,135.19	
Geotextile filter fabric						
Layers required		1			1	
Area required		59,153	ft^2		51,455	ft^2
Unit cost		0.13	$/ft^2		0.13	$/ft^2
Cost for geotextile filter fabric	$	7,689.88		$	6,689.20	
HDPE liners						
Layers required		2			2	
Area required		59,153	ft^2		51,455	ft^2
Unit cost		0.53	$/ft^2		0.53	$/ft^2
Cost for HDPE liner	$	62,702.07		$	54,542.70	
Gravel drainage layers						
Layers required		2			2	
Thickness of each layer		1	ft		1	ft
Area required		59,153	ft^2		51,455	ft^2
Volume required		118,306	ft^3		102,911	ft^3
		4,382	yd^3		3,812	yd^3
Unit cost		12.57	$/yd^3		12.57	$/yd^3
Cost for compacted gravel	$	55,077.92		$	47,910.67	
Compacted fill soil						
Layers required		1			1	
Thickness of each layer		2	ft		2	ft
Area required		59,153	ft^2		51,455	ft^2
Volume required		118,306	ft^3		102,911	ft^3
		4,382	yd^3		3,812	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost for compacted soil	$	25,326.20		$	22,030.52	
Leachate collection and removal system						
Area required		59,153	ft^2		51,455	ft^2
Installed unit cost		3.39	$/ft^2		3.39	$/ft^2
Cost	$	200,528.32		$	174,433.73	
Leak detection system						
Area required		59,153	ft^2		51,455	ft^2
Installed unit cost		3.39	$/ft^2		3.39	$/ft^2
Cost	$	200,528.32		$	174,433.73	

Waste and Fill Layer						
Volume of fill required		74,426	ft^3		63,917	ft^3
		2,757	yd^3		2,367	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost of flowable fill	$	15,932.75		$	13,682.89	

Labor & Materials

Top Liner						
		Without macroencapsulation			With macroencapsulation	
Area required for storage + liner slope		59,153	ft^2		51,455	ft^2
Cost of compacted clay						
Clay thickness		1.5	ft		1.5	ft
Clay volume		88,729	ft^3		77,183	ft^3
		3,286	yd^3		2,859	yd^3
Unit cost		27.63	$/yd^3		27.63	$/yd^3
Cost of compacted clay	$	90,799.70		$	78,984.00	
Geotextile support fabric						
Layers required		2			2	
Area required		59,153	ft^2		51,455	ft^2
Unit cost		0.26	$/ft^2		0.26	$/ft^2
Cost for geotextile support fabric	$	30,759.51		$	26,756.80	
Geotextile filter fabric						
Layers required		1			1	
Area required		59,153	ft^2		51,455	ft^2
Unit cost		0.13	$/ft^2		0.13	$/ft^2
Cost for geotextile filter fabric	$	7,689.88		$	6,689.20	
HDPE liners						
Layers required		1			1	
Area required		59,153	ft^2		51,455	ft^2
Unit cost		0.53	$/ft^2		0.53	$/ft^2
Cost for HDPE liner	$	31,351.04		$	27,271.35	
Gravel drainage layers						
Layers required		1			1	
Thickness of each layer		0.5	ft		0.5	ft
Area required		59,153	ft^2		51,455	ft^2
Volume required		29,576	ft^3		25,728	ft^3
		1,095	yd^3		953	yd^3
Unit cost		12.57	$/yd^3		12.57	$/yd^3
Cost for compacted gravel	$	13,769.48		$	11,977.67	
Compacted fill soil						
Layers required		1			1	
Thickness of each layer		3	ft		3	ft
Area required		59,153	ft^2		51,455	ft^2
Volume required		177,459	ft^3		154,366	ft^3
		6,573	yd^3		5,717	yd^3
Unit cost		5.78	$/yd^3		5.78	$/yd^3
Cost for compacted soil	$	37,989.31		$	33,045.79	
Compacted top soil						
Layers required		1			1	
Thickness of each layer		1	ft		1	ft
Area required		59,153	ft^2		51,455	ft^2
Volume required		59,153	ft^3		51,455	ft^3
		2,191	yd^3		1,906	yd^3
Unit cost		17.68	$/yd^3		17.68	$/yd^3
Cost for compacted soil	$	38,734.19		$	33,693.74	
Vegetation to stabilize topsoil						
Area required		59,153	ft^2		51,455	ft^2
		1.36	acres		1.18	acres
Unit cost		1743.40	$/acre		1743.40	$/acre
Cost	$	2,367.47		$	2,059.40	

Groundwater Monitoring Wells				
Clusters (three wells) required		4		4
Cost per cluster	$	24,167.48	$	24,167.48
Cost	$	96,669.92	$	96,669.92

Direct O&M (filling)

Summary of Annual Direct O&M Costs (filling)	**Without macroencapsulation**		**With macroencapsulation**
Staff	$724,561		$708,305
Groundwater Monitoring	$4,752		$4,752
Utilities	$10,000		$10,000
Fee	$110,897		$108,459
TOTAL	$850,210		$831,516

			Without macroencapsulation		**With macroencapsulation**	
Staff	**Burdened Annual Salary**	**Qty**	**Annual utilization**	**Total**	**Annual utilization**	**Total**
Operators	$45,227	4	1.20	$217,089.60	1.17	$212,219
Maintenance Tech	$66,162	1	1.20	$79,394.40	1.17	$77,613
Logistics/Shipping	$37,306	1	1.20	$44,767.20	1.17	$43,763
Operations Supervisor	$73,664	1	1.20	$88,396.80	1.17	$86,414
Administrative Assistant	$45,727	1	1.20	$54,872.40	1.17	$53,641
Plant Manager	$133,022	1	1.20	$159,626.40	1.17	$156,045
QA / Health & Safety Coordinator	$67,012	1	1.20	$80,414.40	1.17	$78,610
			Totals:	$724,561.20		$708,305

Groundwater Monitoring		
Number of groundwater monitoring wells	4	4
Samples per year from each well	12	12
Cost for sample analysis	$99	$99
Annual Cost	$4,752	$4,752

Shipments per year without macroencapsulation		
Truck weight limit	40,000	lb
Weight of one barrel loaded with treated mercury	892	lb
Barrels per truck delivery	44	barrels
Flat bed trailer width	8	ft
Flat bed trailer length	40	ft
Area available on flat bed trailer	320	ft^2
Area required by one barrel	2.2	ft^2
Area required by barrels in one shipment	96	ft^2
Barrels per year	13724	
Shipments per year	312	

Shipments per year with macroencapsulation		
Truck weight limit	40,000	lb
Barrels per Arrow-Pak	7	
Weight, one tube w/barrels of treated Hg (empty tube is 950 lb)	7194	lb
Arrow-Pak tubes per truck delivery	5	tubes
Area required by one Arrow-Pak tube	23.3	ft^2
Area required by tubes in one shipment	116	ft^2
Area available on flat bed trailer	320	ft^2
Tubes per year	1525	
Shipments per year	305	

O&M (post-closure)

Summary of Post-Closure Costs	Without macroencapsulation	With macroencapsulation
Leachate collection and removal system	$10,437	$10,437
Leak detection system	$19,135	$19,135
Ground water	$5,940	$5,940
Utilities	$30,000	$30,000
License and bonding fees	$300,000	$300,000
Fee	$54,827	$54,827
Contingency	$42,034	$42,034
Total 30-year Cost	$462,372	$462,372

Cost for one day of operator time for each inspection	$174

Leachate collection and removal system		
First five years		
Monitoring per year	12	12
Cost per sample	$174	$174
Total cost	$10,437	$10,437

Leak detection system		
First five years		
Monitoring per year	12	12
Cost per sample	$174	$174
Cost (first five years)	$10,437	$10,437
Following twenty-five years		
Monitoring per year	2	2
Cost per sample	$174	$174
Cost (following twenty-five years)	$8,698	$8,698
Total	$19,135	$19,135

Ground water monitoring		
Samples per year	2	2
Cost per sample	$99	$99
Total cost	$5,940	$5,940