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

EXECUTIVE SUMMARY

Draft Report

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April 22, 2002

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EXECUTIVE SUMMARY

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

S.1 Background

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

S.2 Approach

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

S.3 Sources of Information

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

Canadian Study: SENES Consultants (SENES, *The Development of Retirement and Long Term Storage Options of Mercury*, prepared for Environment Canada, 2001) has produced a draft report for Environment Canada on the development of retirement and long-term storage options for

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

mercury. The report provides comprehensive identification of the range of technologies that are potentially available for mercury storage or retirement, together with a wealth of references.

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

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

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

S.4 Limitation of Scope

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

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

elemental mercury. For example, the treatment of wastewater streams is excluded for this reason.

- Retorting is excluded as merely being a well-established prior step for producing elemental mercury, some of which may end up in the pool of surplus mercury
- Deep-sea disposal is excluded because obtaining the necessary modifications to international laws and treaties is regarded as too onerous a task
- Storage in pipelines is excluded because the project team could not find information about this option.

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

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

S.5 Goals, Criteria and Intensities

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

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

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

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

Intensities were then assigned to each of these criteria and sub-criteria. For example, three intensities were assigned to the sub-criterion “State of maturity of the treatment technology”: a) experience with full-scale operation; b) pilot treatment technology with full-scale operation of disposal option; and c) pilot treatment technology with untested disposal. Brainstorming about the relative importance of each pair of these three intensities (“pairwise comparison”) leads to the following relative ranking of the importance of these intensities: 0.717. 0.205, and 0.078 respectively. These are numerical weights that factor into the final AHP calculations. Details on the development of intensities for all criteria and sub-criteria are given in Chapter 2 of the main report. The assignment of individual retirement options to intensities is provided in Chapter 3. Pairwise comparison judgments made for intensities, criteria, and sub-criteria are provided in Appendix A.

S.6 Results

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

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

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

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

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

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

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

Finally, a limited number of analyses were performed to address uncertainties in the assignment of the retirement options to each intensity. These analyses are discussed in Section 4.3 of the main report. Examples include increasing implementation costs for storage in a mine from

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

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

S.7 Conclusions and Recommendations

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

1. Involve additional experts in the process of assigning weights to the various criteria. This would ensure that a wider range of expertise and interests is incorporated into the analysis. As discussed above, differences in the importance of the criteria relative to one another can change the results.
2. The alternatives considered in this report were limited to elemental mercury. Additional alternatives could be considered for mercury-containing wastes.
3. Additional Expert Choice analyses could be conducted in which certain alternatives are optimized. For example, within the general alternative of stabilization/ amalgamation treatment followed by landfill disposal are potential sub-alternatives addressing individual treatment technologies or landfill locations.
4. Revisit the available information periodically to determine if changes in criteria, or changes in intensities, are required. For example, some candidate criteria were not considered because insufficient information was available. One example is volatilization of mercury during long-term management. Very little data are available at this time to adequately address this as a possible criterion.
5. Consider performing a formal uncertainty analysis utilizing Monte-Carlo-based techniques.

Table S-1 Summary of Results for 11 Evaluated Alternatives

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

Shading indicates the highest ranking alternative.

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

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

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

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

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

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

[b] Scores normalized to total 1,000.