CRESP

Consortium For Risk Evaluation with Stakeholder Participation

Consortium Universities: **Vanderbilt University**, Georgia Tech, Howard University, New York University, Oregon State University, Rutgers University, University of Virginia

Review and Recommendations for the On-Site Disposal of Mercury-Contaminated Building Debris Waste from the Y-12 National Security Complex

Tasks 4A & 4B

Project Report

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Acknowledgment and Disclaimer

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EXECUTIVE SUMMARY

PROJECT OBJECTIVE AND SCOPE

In September 2018, the Department of Energy's (DOE) Oak Ridge Office of Environmental Management (OREM) presented its preferred alternative for the disposal of waste generated from Comprehensive Environmental Response, Compensation and Liability Act[2] (CERCLA) cleanup activities (DOE, 2018). That alternative is the construction of a new on-site CERCLA disposal facility known as the Environmental Management Disposal Facility (EMDF). Under the proposed plan, approximately 1.5 million cubic yards of the total waste volume to be placed into this new facility are expected to be debris and soils that will be generated from remediation of the Y-12 National Security Complex (Y-12 or Y-12 complex). Four former processing buildings within the Y-12 complex are known to be contaminated with mercury, and approximately 383,000 cubic yards (cy) of debris are expected to be generated from the demolition of these four buildings and their ancillary facilities. OREM also estimates that up to 100,000 cy of this debris may meet the regulatory definition of hazardous waste based on the level of mercury contamination and, thus, will require treatment before final disposal (UCOR, 2015).

Disposal of hazardous wastes is permitted under the Resource Conservation and Recovery Act of 1976[3] (RCRA) only as long as the wastes are first treated to meet applicable treatment standards. These treatments standards, known as "land disposal restrictions" (LDRs), were established by the Environmental Protection Agency (EPA) to ensure that hazardous waste cannot be placed on the land until the waste meets specific treatment standards to reduce the mobility or toxicity of the hazardous constituents in the waste. Treatment standards have been established for all mercury-bearing wastes[4]. However, alternative treatment standards, which are based on performance standards and specified technologies, are generally applied to the treatment of hazardous debris[5] because of the technical challenges associated with treating large debris-like objects (EPA, 2003).

In 2016, OREM issued a revised remedial investigation/feasibility study (RI/FS) (DOE, 2016) that evaluated disposal alternatives for future waste generated by cleanup actions at ORR. Appendix C: *Treatment and Disposal Options for Mercury-Contaminated Waste* described options for treatment and disposition of mercury-contaminated debris from demolition of the Y-12 building complex[6]. Options considered included treatment of the mercury-contaminated building debris directly at a disposal facility using immobilization by macroencapsulation. Options considered also included on-site disposal of treated Y-12 debris at EMDF, versus transporting the debris to an off-site commercial disposal facility. OREM noted that the ability to macroencapsulate the debris within the EMDF cells would enhance operational control, staging, and safety, and reduce treatment costs. However, such an approach would constitute "placement" of RCRA hazardous waste in a disposal facility prior to the applicable LDR treatment standards for the debris having been met. Therefore, designation of the disposal area as a corrective action management unit (CAMU) was determined to be the preferred regulatory path to allow macroencapsulation in-cell at EMDF (see CRESP, 2018 for information regarding the possible designation of EMDF as CAMU).

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[2] CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act, as amended by the Superfund Amendments and Reauthorization Act of 1986, Pub. L. 99-499 (SARA), 42 USC §§9601 *et seq.*

[3] RCRA. Resource Conservation and Recovery Act of 1976, Subtitle C, 42 U.S.C. §§ 6921, *et. seq.*

[4] A description of the standards associated with soils are discussed below on pages 7-8 of this report.

[5] 40 CFR 268.45

[6] In 2017, DOE issued a revised RI/FS (DOE, 2017) that deleted all of Appendix C's content.

In July 2018, OREM asked the Consortium for Risk Evaluation and Stakeholder Participation (CRESP) to explore options available for the management and disposal of the Y-12 mercury-contaminated building debris. The scope of work for this project, which began in September 2018, has been divided into six Tasks. To date, CRESP has completed work on three of the tasks.[7]

To help inform decisions on disposition of the Y-12 mercury contaminated debris and underlying contaminated soils, OREM requested that under project Task 4, CRESP develop and initiate implementation of a technical strategy to demonstrate methodologies for assuring adequate protectiveness when mercury-contaminated materials are disposed in a CAMU, or the technical basis necessary to support disposal using alternate methods/technologies. This fourth project Task was subdivided into subtasks, including the following two subtasks, which are the subject of this report:

Task 4A: "Document a strategy for evaluating and demonstrating adequate protectiveness of the disposed materials on a technical basis, including treatment effectiveness and defense-in-depth through the disposal cell configuration (which may include advanced liner materials)."

Task 4B: "Review literature and other documentation (*e.g*., technical reports, *etc*.) of the current state-of-the-art and practice regarding technology for preventing mercury releases from disposal sites. Technologies may include microencapsulation, macro-encapsulation, solidification/ stabilization and sequestration formulations, specific agents for mercury retention, and advanced liners and leachate treatment/collection layers. Recommendations will be made regarding specific technologies for further evaluation."

This report provides:

- A discussion of relevant sections of the UCOR report on the disposition of Y-12 mercury-contaminated debris (UCOR, 2015) that describe: the current physical condition of the four mercury-contaminated Y-12 buildings (*i.e*., Alpha-2, Alpha-4, Alpha-5 and Beta-4 and their ancillary facilities), proposed methods for estimating the level of mercury contamination, the types of mercury expected to be found in the buildings, possible pre-demolition methods of reducing and/or controlling the amount of elemental mercury that would be present in the building debris, and the targeted removal of sensitive and highly contaminated items;
- An overview of federal EPA regulatory requirements for the macroencapsulation and microencapsulation of mercury contaminated debris, and a review of the methods and procedures that the largest U.S. commercial hazardous waste facilities use to macroencapsulate inorganic heavy metal contaminated debris, as well as the methods and procedures suggested by the UCOR evaluation study (UCOR, 2015); and,
- A discussion of the multiple pathways and forms that mercury can take to reach the environment, based on a review of the literature and other documentation (*e.g*., technical reports, *etc*.) on the current state-of-the-art and practices regarding methods for preventing such mercury releases from the disposal of Y-12 mercury contaminated debris. Conceptual models, representing different options of macroencapsulation are used to graphically demonstrate these challenges.

[7] CRESP has submitted a Final Report on Tasks 1 & 2: *History and Application of Corrective Action Management Units (CAMUs) With Remediation Projects*, and a Draft Report on Task 3: *Recommendation on Whether DOE Should Pursue Establishment of a CAMU at EMDF*.

Preliminary Observations and Information Gaps

Handling and Disposition Pathways for Mercury Contaminated Debris

The likely presence of elemental mercury in or on the Y-12 building demolition debris and the multiple mechanisms for mercury release into the environment suggest the following:

- Treatment of debris, through immobilization of residual elemental mercury and/or encapsulation of debris while it is still located at Y-12 may be required to prevent separation of elemental mercury from the building demolition debris (BDD) and dispersion or volatilization of mercury during loading, transport to, and handling at EMDF. Options for immobilization and/or encapsulation include sprays, grout, fixatives, *etc*.
- Selection of initial treatment and/or separation processes (*e.g*., use of cleaners, coatings) to isolate mercury on debris or separate residual mercury from debris may have a significant impact on the release and dispersion of mercury from the waste. The reaction of elemental mercury with inorganic additives to form inorganic mercury compounds (*e.g*., adding sulfur to form mercury sulfide or HgS) would reduce the overall volatility and mobility of mercury; however, organic additives introduced through these initial treatment and/or separation processes may increase the overall mobility of mercury due to complexation, methylation, or sorption to soluble organic compounds (see conceptual model discussion).
- Mercury contaminated debris dumped into/onto an open pad as a process toward large-scale macroencapsulation has the potential for mercury vaporization into the air and disposition onto surrounding materials. Monitoring and protection of site workers at EMDF from mercury exposure will be needed, if such a disposal method is used.

UCOR Macroencapsulation Option Concerns

UCOR's 2015 evaluation includes a discussion of six macroencapsulation and disposition alternative options for the mercury contaminated debris that would be created from future demolition of the Y-12 complex of buildings. The primary objectives of each option discussed in UCOR the evaluation are (i) to allow for on-site disposal of the debris in the existing Environmental Management Waste Management Facility (EMWMF) and/or the proposed EMDF waste disposal facilities; (ii) to plan, to the extent possible, the macroencapsulation treatment within the disposal facility cell; and (iii) to provide OREM with a rough-order-of-magnitude comparison of anticipated costs of each alternative.

The first three options proposed by UCOR are to macroencapsulate the BDD entirely within an EMDF disposal cell. Thus, mercury contaminated debris would be placed in a disposal cell before being treated to meet the LDR treatment standards for mercury-bearing wastes. These options will necessitate that either EMDF disposal cell be designated as a CAMU, or OREM seek and obtain a CERCLA waiver of the prohibition against land disposal of wastes not meeting applicable LDR treatment standards (even if the waste is subsequently treated to meet LDR standards).

In addition to the above, there are several observations that can be made about the macroencapsulation methods proposed in Options 1 and 2. These observations are based on knowledge of the on-site transportation and hazardous waste disposal methods at Hanford's Environmental Restoration Disposal Facility (ERDF), and also on the mercury chemistry and methods of mercury transport discussed in this report:

- Any container used to transport the mercury contaminated debris from Y-12 to EMDF would need to be lined, to prevent the transporting vehicle from becoming contaminated and this liner would likely need to be dumped with the debris onto the concrete vault floor. Dumping of the liner may result in the liner becoming entangled in the debris (*e.g.*, while being moved around within the vault by the dozer or trackhoe) and may affect whether the debris can be fully encapsulated;

- There is a high risk that the crushing of the mercury contaminated debris and the movement of construction equipment within the vault will disperse mercury into the air, possibly contaminating areas outside the concrete vault where the debris is being placed. There is also the possibility that the proposed crushing of debris could dislodge elemental mercury liquid from inside the debris, which could coalesce on the vault floor or on surrounding surfaces; and,
- There is also the possibility that the dozer or trackhoe operator will be exposed to inhalation of mercury released in the air from the work being conducted to crush and move the mercury contaminated debris. The dozer and trackhoe will also become contaminated with mercury and require macroencapsulation with the debris.

Potential Use of Waste Management's High-Density Polyethylene Vaults

Consideration should be given to replacing the Sealand containers[8] that are proposed for use in macroencapsulation Options 3, 4 and 5 (UCOR, 2015) with the specially designed, patented 100mil high-density polyethylene (HDPE) vaults that Waste Management (WM) could provide to OREM[9]. Instead of the sand that WM places in the bottom of the disposal vault for stability before the debris is added, OREM might consider using a reactive or absorbent pad on the HDPE vault floor to capture any elemental mercury that might dislodge from the debris during loading at the Y-12 site and transportation to EMDF. A grout mix would then be poured into the debris-filled HDPE vault, fully encapsulating the debris. The combination of the 100mil thick HDPE vault walls and grout encapsulation of the debris would create a double layer of environmental protectiveness. After the grout has hardened, the vault would be welded shut, and gently dropped off the dumpster onto the ground in an EMDF cell.

The dumpster would then receive a new empty HDPE vault unit with reactive or absorbent pad on its floor and be returned to the Y-12 demolition site to receive a new load of mercury contaminated debris.

Although the HDPE vaults only have a 20cy capacity, which is less than half that of the 43cy capacity of the Sealand container proposed in the 2015 UCOR evaluated Options 3, 4 and 5, the overall costs of using the HDPE vault seem to be much less than a similarly outfitted Sealand containers. The equivalent cost of HDPE vaults for the Sealand container volume of 43 cy is estimated at about $5,000[10] compared to $17,000[11] for each Sealand container as suggested by UCOR Option 5.

The use of the HDPE vaults in place of the Sealand containers, would have the similar requirements of Option 3 with regard to needing to have EMDF be designated a CAMU or that a CERCLA waiver be obtained, if the final grout layer is added inside the disposal cell, or with Options 4 and 5 that a staging area outside of EMDF be constructed for the HDPE vaults if they are filled with grout and allowed to cure outside the cell. However, robust equipment (such as cranes) would not be needed at the disposal

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[8] Containers designed and built for intermodal freight transport.

[9] Email to Henry Mayer from Jennifer Sweeney, Hazardous Waste SME, Waste Management, Emelle, AL. October 10, 2019. Proposed cost of $2,275 per vault delivered to ORR.

[10] $2,275 HDPE vault purchase cost multiplied by the 43cy Sealand capacity and divided by 20 cy HDPE capacity = $4,891.25.

[11] $94,571,007 estimated cost of purchasing and modifying Sealand containers under Option 5 (UCOR, 2015), divided by the 5,405 containers required in this option.

facility to lift and move the HDPE vaults filled with grout, since they would be gently dropped onto the disposal cell floor by the dumpster transport vehicle.

Gaps in Data and Other Information

Based on review of UCOR and alternative treatment options for BDD containing mercury, the following gaps have been identified:

- The performance standard for macroencapsulation of hazardous debris under 40 CFR 268.45 requires that the encapsulating material be resistant to degradation by the debris itself and the case-specific disposal environment. Research conducted for this report, however, did not find any longevity stipulation or requirement that the macroencapsulation should meet (*i.e*., that such degradation not occur in 10, 100, or 1,000 years), nor specific procedures that should be used to test and prove the efficacy of the macroencapsulating method;
- UCOR's proposed criteria for determining which debris materials will require treatment are uncertain. UCOR's 2015 evaluation report discusses screening based on the "Rule of 20". The Rule of 20 assumes that the total elemental content of mercury will leach as a means to determine passage of the Toxicity Characteristic Leaching Procedure (TCLP). In itself, TCLP is an unreliable indicator of future leachability in scenarios other than the disposal of waste in municipal landfills (SAB, 1991; 1999). Additionally, representative subsampling of intact materials for total mercury content analysis or TCLP is challenging due to the spatial variability of contamination and the nature and scale of the materials involved. The uncertainty surrounding the criterion used to determine which debris will require treatment suggests the need for the development and specification of screening and sampling protocols for Y-12;
- As part of their waste acceptance criteria, the four large commercial hazardous waste disposal facilities discussed in this report do not allow for the presence of elemental mercury. Therefore, the macroencapsulation methodologies and encapsulating materials used at these four facilities have not been proven to be suitable for debris wastes with a potential for the presence of elemental mercury such as is expected to be present at Y-12;
- The impact of unreacted elemental mercury vaporization and transport is unknown. Residual elemental mercury within the waste package may vaporize, transport as a vapor through a continuous pore space, and condense to elemental mercury outside of the waste package;
- The selection of specific reactive barrier materials (*e.g*., cementitious blends, absorption mats, reactive/adsorptive disposal cell liner) may significantly impact the feasibility of mercury treatment to allow disposal at EMDF, the projected costs, and the process for deconstruction, treatment, transport, and disposal of the building demolition waste. The effective treatment of metallic mercury has been demonstrated at the laboratory scale using sulfur-polymer cements (Kalb et al, 2011; Adams and Kalb, 2002; Wang, 2012) and chemically-bonded phosphate ceramics (Singh et al, 1998; Wagh and Singh, 1999; Wagh et al, 2000). However, each of these processes has disadvantages for macroencapsulation at field scale, such as requirements to preheat the macroencapsulating mixture up to 140 °C and for process optimization only in well-mixed systems;
- There is likely a balance between microencapsulation of smaller, finer particle-sized waste materials (*e.g*., soils, concrete fines, and rubble) that could be separated or segregated from the large debris items, and the macroencapsulation of the larger debris. Microencapsulation should provide a higher degree of mercury retention than macroencapsulation, because wastes with a fine particle size could be thoroughly mixed with reactive treatment materials.

Macroencapsulation of oversized debris will rely on flowability of the reactive barrier material to fill gaps that otherwise would not be present with microencapsulation; and,

- Macroencapsulation is a key component of any EMDF disposal process for building demolition debris waste. However, the rate of transport of mercury, in all forms, through barrier components is unknown. These barrier components could include HDPE used to contain waste packages (*e.g*., Supersack material or WM's special HDPE vault), steel barriers (*e.g*., roll-off dumpster or Sealand container), and reactive cementitious materials (*e.g*. sulfur-polymer cements or sulfate resistant cements).

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LIST OF ABBREVIATIONS AND ACRONYMS

ARAR	applicable or relevant and appropriate requirements
BDD	building demolition debris
CAMU	corrective action management unit
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFR	Code of Federal Regulations
CHMM	Certified Hazardous Materials Manager
CLSM	controlled low strength material
COLEX	column exchange process
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
Cy	cubic yards
D&D	decontamination and demolition
DNAPL	Dense non-aqueous phase liquid
DOE	U.S. Department of Energy
EMDF	Environmental Management Disposal Facility
EMWMF	Environmental Management Waste Management Facility
EPA	Environmental Protection Agency
ERDF	Environmental Restoration Disposal Facility (at Hanford)
ES	Energy Solutions, Salt Lake City, UT
ETTP	East Tennessee Technology Park
FFA	Federal Facility Agreement
FWDF	Federal Waste Disposal Facility
GM	Clean Harbors Grassy Mountain facility, Clive, UT
HDPE	high- density polyethylene
LDR	Land Disposal Restrictions
MLLW	mixed low-level waste
OREM	Oak Ridge Office of Environmental Management
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
PIDAS	Perimeter Intrusion Detection and Assessment System
RCRA	Resource Conservation and Recovery Act
RI/FS	Remedial Investigation-Feasibility Study
ROD	Record of Decision
SME	subject matter expert
TCLP	Toxicity Characteristic Leaching Procedure
TDEC	Tennessee Department of Environment and Conservation
TSCA	Toxic Substances Control Act of 1976
UCOR	AECOM-led partnership with Jacobs Engineering
UTS	universal treatment standard
WCS	Waste Control Specialists
WM	Waste Management, Emelle, AL
Y-12	Y-12 National Security Complex

I. Introduction

In 2018, the Department of Energy's (DOE) Oak Ridge Office of Environmental Management (OREM) asked the Consortium for Risk Evaluation and Stakeholder Participation (CRESP) to explore options available for the management and disposal of the mercury-contaminated building debris[1] and soils that will be generated from remediation of the Y-12 National Security Complex (Y-12 or Y-12 complex). OREM proposes to retrieve, isolate and store for offsite disposal the vast majority of the elemental mercury collected during demolition; however, debris and soils containing residual levels of mercury are being considered for on-site disposal. OREM has asserted a preference for disposal of this waste in an on-site, engineered disposal facility compliant with the Comprehensive Environmental Response Compensation and Liability Act[2] (CERCLA)[3] specifically designed to eliminate ongoing environmental impacts (DOE, 2018).

Toward this end, OREM has proposed to construct a new CERCLA on-site disposal facility known as the Environmental Management Disposal Facility (EMDF), which will have a capacity of 2.2 million cubic yards (cy) of waste. Approximately 30 percent of the waste volume destined for this new facility is expected to come from remediation at the Oak Ridge National Laboratory (ORNL) and the balance (estimated 1.5 million cy) from remediation of the Y-12 complex. Within the Y-12 complex, four former processing buildings are known to be contaminated with mercury, and approximately 383,000 cy of debris are expected to be generated from the demolition of these buildings and their ancillary facilities. OREM estimates that up to 100,000 cy of the total debris volume may meet the regulatory definition of hazardous waste based on the anticipated level of mercury contamination.

Under the Resource Conservation and Recovery Act[4] (RCRA), land disposal of hazardous wastes is permitted only as long as the wastes are first treated to meet applicable treatment standards, known as "land disposal restrictions" (LDRs). The Environmental Protection Agency (EPA) established the LDRs as a

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[1] "Debris" is defined under 40 Code of Federal Regulations (CFR) 268.2(g) as solid material exceeding a 60 mm particle size that is intended for disposal and that is: a manufactured object; or plant or animal matter; or natural geologic material. The regulations further state that the following is not debris: any material for which a specific treatment standard is provided in 40 CFR Subpart D, Part 268 (*i.e.*, lead acid batteries, cadmium batteries, and radioactive lead solids); process residuals such as smelter slag and residues from the treatment of waste, waste water, sludges, or air emission residues; and intact containers of hazardous waste that are not ruptured and that retain at least 75% of their original volume.

[2] CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act, as amended by the Superfund Amendments and Reauthorization Act of 1986, Pub. L. 99-499 (SARA), 42 USC §§9601 et seq.

[3] Cleanup at the Oak Ridge Reservation (ORR) has been governed by the provisions of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 42 U.S.C. 9601, et seq., as amended by the Superfund Amendments and Reauthorization Act of 1986, Pub. L. 99-499 (jointly referred to as CERCLA) since the EPA placed the site on the National Priorities List in 1989. In compliance with section 120 of CERCLA, OREM, EPA, and Tennessee Department of Environment and Conservation (TDEC) entered into a Federal Facility Agreement (FFA) in November 1991 to "ensure that the environmental impacts associated with past and present activities at the Site are thoroughly investigated and that appropriate remedial action is taken as necessary to protect the public health and welfare and the environment". The agreement also assures coordination of both CERCLA response measures and corrective actions under RCRA (Resource Conservation and Recovery Act of 1976 and Toxic Substances Control Act of 1976 (TSCA), by explicitly stating that both "will be deemed to achieve compliance with CERCLA. Implementation of CERCLA actions would be in compliance with RCRA as ARARs to be specified in CERCLA decision documents.

[4] RCRA. Resource Conservation and Recovery Act of 1976, Subtitle C, 42 U.S.C. §§ 6921, et. seq.

further measure of protection from threats posed by hazardous waste disposal by ensuring that hazardous waste cannot be placed on the land until the waste meets specific treatment standards to reduce the mobility or toxicity of the hazardous constituents in the waste. Treatment standards, based on best demonstrated available technology (BDAT), have been established for mercury-bearing wastes based on retorting and recovery of elemental mercury[5]. However, alternative treatment standards, which are based on performance standards and specified technologies, are generally applied to the treatment of hazardous debris[6] because of the technical challenges associated with retorting high volumes and large debris-like objects (EPA, 2003).

OREM summarized these alternative treatments in its 2016 Remedial Investigation/Feasibility Study (RI/FS) (DOE, 2016) as follows:

> "For mercury-contaminated debris that is considered hazardous (D009) according to the TCLP [Toxicity Characteristic Leaching Procedure] toxicity threshold of the LDRs, potentially effective treatment technologies include thermal extraction and recovery (including retort and thermal desorption), liquid-phase chemical extraction, and immobilization methods. For mixed low-level radioactive debris that requires treatment for mercury, thermal and chemical extraction methods typically generate secondary radioactive waste streams (both liquid and gaseous), are costly due to the pre-treatment requirements and high energy usage, and generally applied only to smaller volumes of waste. Immobilization methods such as macroencapsulation, which may incorporate mercury S/S [solidification/stabilization] as part of the treatment process, are arguably the most practically applicable treatment technology for large volumes of mercury-contaminated demolition debris.
>
> Of these possible treatment technologies, the only feasible option for treatment of D009 debris directly at a disposal facility would be immobilization by macroencapsulation. Macroencapsulation can be accomplished outside of the landfill footprint and the stabilized form moved into the landfill footprint for final disposal, or it can be accomplished "in-cell" as an integral part of the disposal. As well, macroencapsulation could be accomplished at the project/demolition site prior to the waste being disposed, requiring transport of the macroencapsulated waste to the disposal facility.
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> Designation of the disposal area (or treatment area, if treatment is not performed in the disposal area footprint) as a Corrective Action Management Unit (CAMU) is the preferred regulatory path to allow macroencapsulation at a future on-site disposal facility."

In 2018, OREM requested that CRESP explore options available for the management and disposal of the Y-12 mercury-contaminated building debris. Work on the project began in September 2018. To meet this objective, OREM and CRESP developed a project scope that has been divided into six project scope tasks (CRESP, 2018), the first three of which have been completed. The objective of the fourth task is to help inform OREM's decisions regarding on-site disposition of the Y-12 complex mercury contaminated debris and soils, through the development and initial implementation of a technical strategy for evaluating the protectiveness of and/or risks of alternate methods/technologies used for disposal of mercury-contaminated materials at EMDF.

[5] A description of the standards associated with soils are discussed below on pages 6-7 of this report.

[6] 40 CFR Part 268

This report is organized into five sections:

1. **Anticipated Mercury Contamination at the Y-12 Complex**: A discussion of the relevant sections of UCOR 2015 evaluation that describe: the current physical condition of the four mercury-contaminated Y-12 buildings (*i.e*., Alpha-2, Alpha-4, Alpha-5 and Beta-4 and their ancillary facilities), proposed methods for estimating the level of mercury contamination, the types of mercury expected to be found in the buildings, possible pre-demolition methods of reducing and/or controlling the amount of elemental mercury that would be present in the building debris, and the targeted removal of sensitive and highly contaminated items;
2. **Alternative Treatment Methods for Mercury Contaminated Debris**: An overview of federal EPA regulatory requirements for the macroencapsulation and microencapsulation of mercury contaminated debris, and a review of the methods and procedures that the largest U.S. commercial hazardous waste facilities use to treat inorganic heavy metal contaminated debris by macroencapsulation, as well as the methods and procedures suggested by the UCOR evaluation study (UCOR, 2015);
3. **The Challenges of Mercury Encapsulation**: A discussion of the multiple pathways and forms that mercury can take to reach the environment and result in human health and ecological risks, based on an extensive review of the literature and other documentation (*e.g*., technical reports, *etc*.) on the current state-of-the-art and practice regarding methods for preventing such mercury releases from the disposal of Y-12 mercury contaminated debris. Conceptual models, representing different phases of macroencapsulation are used to graphically demonstrate these challenges;
4. **Preliminary Observations**: A list of the preliminary observations that have emerged from the results of the research conducted on project Tasks 4A and B, which relate to the impacts of mercury chemistry on alternative macroencapsulation methods; concerns regarding UCOR's proposed in-cell macroencapsulation Options 1 and 2; and a macroencapsulation variation that would replace the Sealand containers proposed in UCOR's Options 3, 4 and 5 with the high-density polyethylene (HDPE) vault developed by Waste Management (WM); and,
5. **Gaps in Data & Other Information**: A discussion of the gaps in scientific data and technical information on the macroencapsulation methods currently in commercial use and the large-scale testing of the rates of mercury transport through different macroencapsulate media (i.e. reactive cementitious blend, HDPE (*e.g*., Super Sacks®[7], liners).

II. ANTICIPATED MERCURY CONTAMINATION IN THE Y-12 COMPLEX

In 2015, UCOR completed an extensive evaluation of the current condition of four mercury-contaminated Y-12 buildings, identified as Alpha-2, Alpha-4, Alpha-5 and Beta-4, "to gain a better understanding of the extent of mercury contamination within these four complexes, to identify strategies to reduce the quantity and concentration of mercury in the decontamination and demolition (D&D) debris prior to disposal, and to evaluate disposition options for the mercury-contaminated debris that are protective of human health and the environment." UCOR's evaluation also included several observations:

[7] A Super Sack® container is a flexible intermediate bulk container manufactured by BAG Corp. These polypropylene containers are available in sizes from 4 – 85 cy, with specific designs for different applications (http://www.bagcorp.com/sites/default/files/supersack_catalog.pdf).

- The Alpha-5 building has degraded to the point that many areas within the building are not structurally sound, which will limit future access for characterization and pre-demolition activities;
- The four buildings and their ancillary facilities are located in a congested area at the Y-12 complex with no areas currently available for laydown, equipment, or staging yards;
- Currently, there is no unimpeded traffic pattern to transport waste from the generating site at Y-12 to the onsite disposal facility at EMDF because the mercury contaminated buildings are so close to one another and the surrounding active operational facilities;
- The operational facilities within the Y-12 complex are located directly adjacent to three of the boundaries of the proposed D&D area;
- Mercury contamination is not only present inside the building structures, but also in the soils under and adjacent to the structures;
- Beryllium contamination is present in Alpha-5, so D&D activities within Alpha-5 will require implementation of DOE's rigorous chronic beryllium disease prevention program; and,
- Several buildings in the Y-12 complex are located within the Perimeter Intrusion Detection and Assessment System (PIDAS) security area, which requires stringent access and security controls.

Determining Level of Mercury Contamination

In its review, UCOR proposed that a limit of 4 mg/kg of total mercury be used to determine which Y-12 debris and soils exceed RCRA LDR limits for mercury, and thus require treatment prior to disposal in the existing Environmental Management Waste Management Facility (EMWMF) or proposed EMDF. The RCRA hazardous waste limit for mercury using the Toxicity Characteristic Leaching Procedure (TCLP) extraction is 0.2 mg/L. RCRA authorizes the use of a "Rule of 20" for comparing total mercury to the hazardous waste limit where the TCLP limit is multiplied by 20 to yield a total mercury content of 4 mg/kg. If the measured total mercury in debris is less than 20 times the RCRA limit, treatment is not required. Where visible liquid elemental mercury is found, total mercury results will likely be significantly higher than this 4 mg/kg limit and, therefore the debris will likely be required to be treated prior to disposal. The 4 mg/kg limit may also be exceeded when visible elemental mercury is not observed (e.g., if elemental mercury is present in pores or occluded in material, or where mercury is present in forms other than liquid elemental mercury).

However, this proposed criterion for determining which debris materials require treatment is uncertain. The RCRA "Rule of 20" assumes that the total elemental content of mercury will leach as a means to determine passage of TCLP. In itself, TCLP is an unreliable indicator of future leachability in scenarios other than the disposal of waste in municipal landfills (SAB, 1991; 1999). Additionally, representative subsampling of intact materials for total mercury content analysis or TCLP is challenging due to the spatial variability of contamination and the natural and scale of the materials involved. The uncertainty surrounding the criterion that is to be used to determine the debris that will require treatment suggests the need for the development and specification of screening and sampling protocols for Y-12.

UCOR's evaluation also notes that the routine laboratory analytical method for total mercury[8] is not amenable to some debris samples such as coupons or sections of structural steel, tanks, equipment, and piping because of the approximately 0.5 g sample size required. Most representative samples of metal weigh over 100 g, substantially more than the requirement for sampling. Smaller-sized sample pieces, such as metal shavings, could be collected but these samples would not be representative. Options for

[8] EPA Method 7471B (SW-846) Mercury in solid or semisolid wastes.

analysis include: (i) analysis by TCLP, which uses a 100-g sample; (ii) collection of solvent-wetted wipes from a known area for total mercury analysis; and (iii) use of field methods for measurement of total mercury surface contamination.

FORMS OF MERCURY IN BUILDING DEBRIS

Within the building demolition debris, mercury is likely to be present as both elemental mercury (Hg^0) and divalent mercury as an aqueous ion (Hg^{+2}). Treated materials may also contain precipitated mercury after stabilization with fixatives such as sulfur (Yee et al, 2013). Where sufficient organic matter is present to support biological activity (*e.g.*, soils), methylated mercury (CH_3Hg) and mercury in aqueous solution chelated with organic ligands ($Hg_{organic}$) may be present. Table 1 shows the relative aqueous solubility of selected forms of mercury. The most stable and least soluble form of mercury is mercury sulfide (HgS), also known as the mineral cinnabar.

Although the majority of elemental mercury may be collected and disposed of separately from mercury contaminated building demolition debris (BDD), the potential vaporization and transport of residual elemental mercury trapped within the disposed BDD makes the management of BDD different than typical inorganic wastes. Elemental mercury is relatively insoluble in water ($5.6x10^{-2}$ mg/L) which may be present as a dense non-aqueous phase liquid (DNAPL). Elemental mercury may also oxidize to form the more soluble Hg^{+2} ion (1.284 mg/L at 25 °C) or evaporate into gaseous pore space as mercury vapor (Clarkson and Magos, 2006). The vapor pressure of elemental mercury is relatively low (0.16 Pa) compared to organic forms of mercury, while mercuric sulfide has a very low vapor pressure (Table 1).

Table 1. Properties of Mercury Compounds (after Rodriguez et al., 2012)

Compound	Chemical Formula	Hg Redox	Solubility (g/L)	Density (g/cm^3)	Vapor Pressure (Pa)
Elemental mercury	Hg^0	0	5.6×10^{-5}	13.53	0.16
Mercurous chloride	Hg_2Cl_2	+1	2×10^{-3}	7.15 (19 °C)	
Mercuric chloride	$HgCl_2$	+2	69 (20 °C)	5.40	0.1 (20^0 C)
Mercuric sulfide	HgS	+2	2×10^{-53} [a] 2×10^{-32} [b]	8.17 [a] 7.70 [b]	
Methyl-mercuric chloride	CH_3HgCl	+2	0.100 (20 °C)	4.06	1.13
Dimethyl mercury	C_2H_6Hg	+2	1 (21 °C)	3.19	8,800

Notes: All values determined at 25 °C unless noted.
[a] cinnabar;
[b] metacinnabar;
[c] vapor pressure data from PubChem database (https://pubchem.ncbi.nlm.nih.gov/)

MERCURY TRANSPORT IN POROUS MEDIA

Mercury may transport through porous media via one of several mechanisms including the following:

- Diffusion of elemental mercury or Hg^{+2} within porewater;
- Volatilization and transport through gas-filled pores and cracks; and,
- Movement of elemental mercury as a DNAPL.

Elemental mercury present as a DNAPL may be transported by gravity forces or may condense within the pore structure of porous materials or collect in air gaps in poorly macroencapsulated materials. The primary pathway for transport of Hg^{+2} is diffusion through a continuous water-filled pore network from areas of high concentration (*e.g.*, near elemental mercury lenses) to areas of lower concentration. When porous materials (*e.g.*, soils, concrete) are exposed to infiltration, infiltrating water may displace an equal volume of pore water containing mercury at the solubility concentration. Therefore, a primary purpose of disposal in a RCRA-compliant landfill is to limit the amount of infiltration to which materials are exposed.

PRE-DEMOLITION ACTIVITIES

UCOR's evaluation, using lessons learned from its research on the cleanup of private sector chlor-alkali plants and the demolition of the K-25 and K-27 buildings at the East Tennessee Technology Park (ETTP), proposes that the pre-demolition activities described below be considered. The evaluation also anticipates that the identified activities would be refined as additional information becomes available on both the Y-12 complex and the potential new on-site disposal facility.

- Several tanks, flasks, and components within the Y-12 complex are currently storing elemental mercury. These storage vessels would be drained, or the containers/components shipped off-site "as-is" for appropriate treatment and disposal.
- Accessible elemental mercury in the Y-12 process equipment, process piping, and building hold-up areas would be aggressively removed. Techniques that UCOR indicated may be used to collect elemental mercury include:
    - Tap and drain low spots in process equipment, piping, and tanks, followed by capping. It is assumed that tapping and draining will remove much of the elemental mercury. Final determination of mercury concentrations for piping and equipment would be made by mass balance calculations[9];
    - Clean interior cavities of pipes and equipment using brushes or rubber scrapers;
    - Flush or rinse equipment, pipes, or components with nitric acid, boric acid, or similar solutions, if cost-beneficial after considering the required treatment of secondary wastes;
    - Collect elemental mercury by draining, vacuuming using a mercury-recovery vacuum, or sweeping; and,
    - Transfer elemental mercury to an appropriate storage container and send off-site for treatment and disposal.

UCOR's evaluation indicates that limited mercury characterization may be needed for drained piping and equipment to provide results that can be used in support of the mass balance calculation (mercury remaining compared to total mass of waste) for RCRA compliance. However, UCOR does not anticipate that widespread statistical sampling of piping and equipment for disposal would be required. Likewise, limited mercury characterization for vent duct and non-process equipment and piping is anticipated, assuming that removal of visible mercury and a mass balance is performed.

Areas of known or suspected surficial mercury contamination may need to be decontaminated or sprayed with fixatives to minimize mercury vapors and limit contaminant transfer during dismantlement and/or demolition. Fixatives may also be used to lock down beryllium contamination on equipment and structures.

As soils under and around the Y-12 complex are contaminated with mercury and likely to be disturbed during D&D of the buildings, site preparation methods will need to minimize the release of mercury from these soils when they are disturbed by heavy equipment, and to minimize further contamination of building debris and/or soil through contact with adjacent soils. Activities that may be taken during site

[9] It is unclear how proposed mass balances would be calculated.

preparation include paving (or coating) the grounds around the perimeter of the complexes and installing berms or other run-off controls (UCOR 2015).

TARGETED REMOVAL OF CONTAMINATED ITEMS

UCOR's evaluation proposes that three categories of materials be removed from the Y-12 complex prior to building demolition:

1. **Highly contaminated non-structural, equipment and building materials.** These items could be contaminated with mercury, beryllium, uranium, or a combination of contaminants, and their removal could reduce the volume of mixed waste generated from demolition. These highly contaminated materials would be segregated for treatment and disposal, based on their contaminants. Highly contaminated materials that cannot be removed prior to mass building demolition, may be painted or otherwise marked; to allow identification, removal and segregation from other debris after demolition;
2. **Classified equipment and/or components that would require rigorous safeguards and security controls during D&D.** Removal of these items before demolition begins likely would result in security controls being downgraded during the remainder of the project; and,
3. **Aluminum bus bars and copper bus bars with silver plating that are not anticipated to be contaminated with radionuclides, as well as mercury and nickel anodes with minimal surface mercury contamination.** UCOR's evaluation indicates that these items are located in Alpha 4 building and could be evaluated for their potential to be recycled prior to D&D activities and to determine whether recycling is economically beneficial[10].

III. ALTERNATIVE TREATMENT METHODS FOR MERCURY CONTAMINATED DEBRIS

The EPA requires that hazardous contaminated soils, which will be land disposed, are to be treated to reduce the TCLP concentrations of the hazardous constituents by 90% or meet hazardous constituent concentrations that are 10 times the universal treatment standard (UTS). This is commonly referred to as ''90% capped at 10 times UTS.'' A number of commenters to the 1998 proposed *Land Disposal Restrictions Phase IV: Final Rule*[11] expressed concern about the achievability of the soil treatment standards and/or the methodology EPA used to develop them, but EPA's position was that the new standards were sufficiently stringent to satisfy the core requirement of RCRA Section 3004(m), which is to minimize threats to human health and the environment posed by land disposal. It should be noted that the CAMU minimum national treatment standards also require a 90% reduction in TCLP constituent concentrations, capped at 10 times the UTS. However, CAMU regulations also allow flexibility for alternative leaching tests and approaches for demonstrating treatment effectiveness.

Under 40 CFR 268.49(c), *Treatment standards for contaminated soils*, metals must achieve a 90% reduction, as measured in leachate from the treated soil (testing is according to the TCLP) when a metal stabilization treatment technology is used, and as measured in total constituent concentrations when a metal removal technology is used. Treatment for non-metals must achieve 90% reduction in total constituent concentrations. If the soil is treated to achieve the 90% reduction standard, or the

[10] Contamination within or on the property is in compliance with applicable DOE Authorized Limits of DOE Order 458.1(4)(k)(6).

[11] Federal Register*, Land Disposal Restrictions Phase IV: Final Rule Promulgating Treatment Standards for Metal Wastes and Mineral Processing Wastes; Mineral Processing Secondary Materials and Bevill Exclusion Issues; Treatment Standards for Hazardous Soils, and Exclusion of Recycled Wood Preserving Wastewaters,* Vol.63, No 100, 28605-6 (1998).

treatment reduces constituent concentrations to levels that achieve the standard of 10 times the UTS, then further treatment is not required.

EPA requires that hazardous wastes that meet the toxicity characteristics for mercury (D009 wastes) and which are not classified as debris, wastewaters, or mixed (radioactive and hazardous) wastes, be treated to meet RCRA LDRs through one of four treatment standards[12]. The mercury waste has been further divided into two subcategories: (1) "low mercury subcategory" (*i.e*., containing less than 260 mg/kg total mercury), and (2) "high mercury inorganic subcategory" (*i.e*., containing more than 260 mg/kg total mercury). The treatment standard for "low mercury subcategory" waste requires that leachate from treatment residuals, using the TCLP, have a mercury concentration of less than 0.025 mg/L (or 0.20 mg/L for residues from retorting). Treatment by stabilization can be generally used to achieve this standard. The treatment standard for "high mercury inorganic category" waste is mercury recovery in a thermal processing unit that volatilizes and subsequently condenses the mercury. These units are commonly referred to as "retorters", and the recovery process as "retorting." (40 CFR, 268.42, Table 1).

EPA recognized the technical challenges of treating debris-like objects and cleaning up remediation sites, and in 1992 promulgated alternative treatment requirements for hazardous debris[13], which are based on performance standards and specified technologies that reflect these challenges (40 CFR 268.45). Table 1 of 40 CFR 268.45, *Alternative Treatment Standards for Hazardous Debris*, contains technology descriptions, performance and/or design, and operating standards for each specified technology, and restrictions on contaminants for specific technologies. Table 1 categorizes technologies into three groups: (i) extraction (physical and chemical), (ii) destruction (biological and chemical), and (iii) immobilization (macroencapsulation, microencapsulation, and sealing). Because of the technical challenges associated with treating mercury, which can be difficult to stabilize and has the potential to become volatile at ambient conditions, the treatment technologies that generally apply to mercury contaminated debris are microencapsulation and macroencapsulation. *These technology options do not distinguish between debris containing high and low levels of mercury* [emphasis added].

The definition of debris under 40 CFR 268.2(g) specifically identifies certain materials as not being "debris." One identified material is relevant to mercury-containing wastes: "intact containers of hazardous waste that are not ruptured and that retain at least 75% of their original volume." EPA considers certain manufactured objects that hold liquids, including mercury-containing pumps and batteries, to be "containers." Under 40 CFR 260.10, containers are defined as "any portable device in which a material is stored, transported, treated, disposed of, or otherwise handled." Under this definition, mercury-containing items such as thermometers, pumps, manometers, thermostats, jars of elemental mercury, batteries, dental amalgam collection devices, and ampules are considered "containers". As such, these items are not considered "debris" and are subject to the non-debris mercury treatment standards described above.

Source separation[14] is not listed as a specific technology under the debris standards on Table 1. However, in many circumstances it may be highly beneficial to remove mercury-containing devices such as containers or other items with readily identifiable mercury from the debris. This could result in

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[12] 40 CFR 268.40

[13] Under 40 CFR 268.2(h), *hazardous debris* means debris that contains a listed hazardous waste or exhibits a characteristic of hazardous waste. Deliberately mixing prohibited waste with debris to change the treatment classification from waste to hazardous debris is not allowed under the dilution prohibition in 40 CFR 268.3.

[14] The process of removing mercury contaminated material from the bulk of the debris.

removing the mercury characteristic (D009 waste) from the debris as a whole, or at least reduce the volume of hazardous debris with the D009 classification and related treatment requirements.

Macroencapsulation

OREM, in its 2016 RI/FS (DOE, 2016) chose macroencapsulation as the preferred treatment method for the majority of the Y-12 mercury contaminated debris, due to the expected large sized steel, concrete and other debris that will be created during demolition of the buildings. EPA's performance standard imposed for macroencapsulation (Table1, 40 CFR 268.45) is as follows: the "encapsulating material must completely encapsulate debris and be resistant to degradation by the debris and its contaminants and materials into which it may come into contact after placement (leachate, other waste, microbes)." Approved methods for ensuring that the encapsulating material completely encapsulates the waste include either the application of surface coating materials such as polymeric organics (*e.g*., resins and plastics) or use of a jacket of inert inorganic materials to substantially reduce surface exposure to potential leaching media. Visual inspection may be appropriate for verifying that sprayed-on or applied coatings have complete integrity, without cracks, voids or protruding waste to ensure that the hazardous debris is completely encapsulated (EPA, 2003).

The October 2003 internal EPA Memorandum on *Treatment Standards for Mercury-Containing Debris* notes that,

> "Another measure of the ability of a macroencapsulation technology to substantially reduce surface exposure to potential leaching media is the structural integrity of the waste form produced by the technology. This factor is especially significant for mercury-bearing wastes, as mercury is volatile at disposal temperatures, and if present in liquid form, is directly mobile… An assessment of structural integrity will depend upon the specifics of the encapsulating technology and the case-specific disposal environment. Note that the disposal environment may include significant short-term stresses from management in the disposal cell, including driving of heavy equipment over disposed wastes. Disposed waste forms also will be subjected to burial stresses, which can result in compression and long-term creep; these stresses can be significant, especially if load-bearing will be accommodated at pressure points."

Commercial Macroencapsulation Methods

The 2015 UCOR evaluation includes a discussion of a benchmarking study UCOR performed "to determine current methods being used to macroencapsulate hazardous and radioactive waste debris prior to disposal." As part of the study, discussions were held with "waste management representatives from other DOE facilities, conversations with vendors, and site visits to commercial and government facilities performing macroencapsulation." This study included two large commercial hazardous waste facilities: Waste Control Specialists (WCS) in Dallas, Texas and Energy Solutions (ES) in Salt Lake City, Utah, both of which DOE has used in the past for disposal of radiologically contaminated building and equipment debris, classified as mixed low-level radioactive waste (MLLW).

Both WCS and ES facilities, who had been contacted previously as part of this project's Task 1 and Task 2 research on CAMUs (CRESP, 2019), were contacted to learn more about their macroencapsulation processes and procedures. In addition, CRESP obtained information from OREM on how the Y-12 mercury-contaminated COLEX debris had recently been handled at the site and shipped to the Clean Harbors Grassy Mountain facility (GM) in Clive, Utah for disposal. GM was contacted to obtain additional information (including photos) about its macroencapsulation of the COLEX debris. CRESP also conducted an extensive search of the Internet to identify other commercial hazardous waste facilities in the U.S. and Canada that appeared capable of accepting and managing the disposal of large quantities of mercury and other heavy metal contaminated building debris. The only other commercial facility identified through this research was Waste Management (WM) in Emelle, Alabama.

As noted in UCOR's evaluation, its discussions with the two commercial facilities related to macroencapsulation of "hazardous and radioactive waste debris" (UCOR 2015).. At WCS[15], MLLW from DOE sites must go into the dedicated Federal Waste Disposal Facility (FWDF), which WCS manages, but for which DOE is responsible for all environmental risks. Hazardous wastes not having a radiological component would be placed in WCS's Subtitle C hazardous waste landfill, where it would be macroencapsulated in a grout/cement type mix.

In September 2019, CRESP spoke with the same representative of ES at its Clive, UT facility who had been contacted in November 2018 as part of its CAMU project research, to learn more about ES's macroencapsulation methods.[16] At ES, MLLW is managed in its Class A disposal cell, with other hazardous waste going into a separate disposal area. Mixed waste hazardous debris is placed in a large metal form that provides spacing from the ground so that the debris can be fully encapsulated. When possible, unusually large items are shredded to reduce their size. As shown in the photographs below (Energy Solutions 2010), the debris is encapsulated with a proprietary blend grout type material, that when cured, becomes a highly stable, rigid vault for the debris. At least 4 inches of grout surrounds all sides of the debris. According to the ES representative, its macroencapsulation process accommodates any size or weight of hazardous debris, with special procedures and methods used for unusually large items and/or those weighing more than 20,000 lbs. Visual testing during the process ensures that the debris is fully encapsulated, but no other testing of the resulting monolith is required.

Figure 1. Energy Solutions' Macroencapsulation Process

Y-12 COLEX Disposal Process – Clean Harbors

The Y-12 COLEX debris was macroencapsulated and disposed of at the Clean Harbors GM facility, utilizing the large intermodal container that the debris was transported in from the Y-12 site to create a structurally sound permanent vault. Super Sacks® were used to line the intermodal containers, with plywood being placed around and under the supersacks to separate the supersacks from the walls of the container. A piece of plywood was added to the top after filling the supersack with the COLEX debris; the intermodal top was then closed and shipped to Utah.[17] After arriving at the Grassy Mountain

[15] Henry Mayer exchanges with Elizabeth Broda, Vice President, Business Development, Waste Control Specialists, Andrews, TX , occurred between July 15 and July 29, 2019.

[16] Henry Mayer exchanges with Johnny Bowne, Vice President, Business Development, Energy Solutions, Clive, UT, occurred in November 2018 and September 16, 2019.

[17] Email from Michael Kane to Susan DePaoli with attached photos, December 6, 2018; and email from Susan DePaoli to Henry Mayer, July 1, 2019.

facility[18] (see Figure 2):

- The top of the intermodal was removed, as well as the plywood layer;
- The intermodal was then placed in an open “vault” of pozzolanic material, located in its triple-lined landfill compliant with the Toxic Substance Control Act (TSCA)[19] and RCRA;
- The Super Sacks were opened and inspected to ensure that no elemental mercury was visible on the debris or in the supersack;
- Pozzolanic material was transferred into the supersack and intermodal to fill the void spaces;
- The intermodal lid was put back on; and,
- The intermodal was then covered with additional pozzolanic material.

The pozzolanic material used by Clean Harbors is cement kiln dust, which is a fine, powdery material, portions of which generally contain some reactive calcium oxide. The GM representative noted that this procedure of macroencapsulating the COLEX debris in the intermodal container and then burying it, was not its standard macroencapsulation method, but that they and UCOR agreed that it would be the most cost effective and environmentally protective. GM’s normal method is similar to that of ES and WCS, which is to place the debris in a form and then encapsulate it with a cement mix. Grassy Mountain is much more aggressive though in terms of ensuring that the resulting monolith is structurally stable and environmentally protective. GM generally requires at least 8-inches of grout surrounding the debris, but it has used grout as much as 20 inches thick to ensure structural stability.

Figure 2. Macroencapsulation of COLEX Debris

High-density polyethylene vault

WM utilizes a specially designed and patented 100 mil thick one-piece HDPE vault to macroencapsulate hazardous waste and MLLW at its Emelle facility[20]. The HDPE vault was approved by the EPA in 1995 as a conceptual method for macroencapsulating hazardous debris, and later by several State environmental

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[18] Telephone discussion between Henry Mayer and Shane Whitney, General Manager, Clean Harbors Environmental Services, Grassy Mountain Facility, August 14, 2019.

[19] Toxic Substances Control Act of 1976, 15 U.S.C. ch. 53, subch. I §§ 6601-2629

[20] Telephone conversations and email exchanges between Henry Mayer and Jennifer Sweeney, CHMM, Hazardous Waste SME, Waste Management, Emelle, AL occurred between September 13 and October 10, 2019.

agencies as meeting the RCRA macroencapsulation "no degradation" performance standard (Table 1, 40 CFR 268.45).

The unit can be placed in a 20cy intermodal or roll-off container to receive and transport hazardous debris from a demolition or cleanup site to the WM Emelle facility. As an example, WM would provide a 20cy roll-off container to the Y-12 site, with the HDPE vault already installed. A small amount of sand or other inert material is placed in the bottom of the vault for stability. The vault would be filled with debris, covered with a temporary cover provided by WM, and transported to Emelle. There, WM would fill the HDPE vault with additional sand or inert material to further stabilize it and ensure that the debris is fully encapsulated. WM does not add this material to provide any further environmental protectiveness and is thus relying solely on the 100mil thick HDPE vault walls to meet the "no degradation" performance standard. The vault is then welded shut, gently dropped off the dumpster onto the ground, and transferred to one of its RCRA Subtitle C landfill cells (see photos below). A new HDPE vault unit would be installed in the dumpster and returned to Y-12 for a new shipment of contaminated debris.

Figure 3. Macroencapsulation Using HDPE Vault

Layered Protection System

CRESP interviews with these four large commercial hazardous waste disposal facilities suggest that each facility and its state regulator relied on the combined protectiveness of three integral components in approving their macro methods of encapsulating mercury containing hazardous debris. These three components are:

- *Structural Stability*: Each of the four facilities uses grout cement, pozzolanic material, and/or metal, concrete or HDPE containers to create a robust, structurally stable encapsulation of the hazardous debris. All gaps and spaces in the debris are filled, and the outer wall material and depth have been tested to show that they will not degrade over some minimum time period from contact with the debris and its hazardous constituents. None of the officials interviewed would provide the test procedures and temporal requirements applied to their macroencapsulation method;
- *Disposal Cell Design*: All four commercial disposal facilities boast of having double or triple lined disposal cells constructed of 60-80mil HDPE, and sometimes including a liner of up to 3 feet of clay, which meet or exceed TSCA and RCRA requirements. In addition, all four have installed leachate collection/leak detection systems to meet the requirements of 40 CFR 264.301(c)(2) and (3) between the liners; and,

- *Geographic Location*: Three of the commercial facilities are located in areas that experience low precipitation, have naturally poor groundwater, and were constructed on low-permeability clay soils. The location of the WM facility in Emelle was chosen for its 650-750 feet of impermeable "Selma Chalk" limestone above the aquifer. The location chosen for each facility was an important consideration to help ensure that if the disposal cell liners and leachate collection system fail, the risk that the hazardous contaminants reach critical groundwater aquifers is minimal.

Macroencapsulation Alternatives Suggested by UCOR

UCOR's 2015 evaluation includes a discussion of six macroencapsulation and disposition alternative options for the mercury contaminated debris that would be created from future demolition of the Y-12 complex of buildings. The primary objectives of each option discussed in the evaluation are (i) on-site disposal of the debris in the existing EMWMF and/or the proposed EMDF waste disposal facilities; (ii) to the extent possible, conduct the macroencapsulation treatment inside the disposal facility cell; and (iii) provide OREM with a rough-order-of-magnitude comparison of anticipated costs of each alternative. The first three options proposed by UCOR would macroencapsulate the building debris within an EMDF disposal cell and would thus be placing the mercury contaminated debris in a disposal cell before being treated to meet the LDR treatment standards for mercury-bearing wastes. This will necessitate either the designation of the EMDF disposal cell as a CAMU, or that OREM seek and obtain a CERCLA waiver of the prohibition against land disposal of wastes not meeting applicable LDR treatment standards (even if the waste is subsequently treated to meet LDR standards).

UCOR's suggested approach is that vehicles/containers transporting mercury-contaminated waste be lined with impregnated mats or with mercury amalgamation powder (such as sulfur) prior to being loaded to allow any elemental mercury released during transport to be adsorbed or treated. Trucks and containers containing mercury-contaminated debris would be tarped during transport to minimize exposure to mercury vapors.

Option 1: Large scale in-cell macroencapsulation (OREM preferred method): In this first option, a large (550-ft long, 100-ft wide, 10-ft high walls), open-ended, concrete vault would be constructed on top of a new disposal facility liner system. Demolition debris would be loaded at the Y-12 site, transported to EMDF, dumped at the open of the large concrete vault, and pushed into the vault and compacted by a D-8 dozer (see Figure 4 below). After waste placement, the vault would be filled periodically with controlled low-strength material (CLSM) to eliminate void spaces. Water collected within the vault during waste placement would be removed and treated appropriately. UCOR estimates that seven such large-scale vaults would be required to accommodate the anticipated 100,000 cy of waste requiring treatment. UCOR believed that this option would require minimal size reduction at the Y-12 site and the most compaction within the disposal cell.

Figure 4. Proposed Large Scale In-Cell Macroencapsulation

Option 2: Medium scale in-cell macroencapsulation: This option is similar to the first option above, except the waste would be placed and compacted in smaller concrete cells, approximately 30-ft long by 30-ft wide, with 10-ft high walls. Demolition debris would be loaded at the Y-12 site, transported to the on-site disposal facility, and dumped into the medium scale concrete vaults from the side of the disposal facility. A trackhoe, working outside the cell would move and arrange the waste (see Figure 5 below). After each cell is full of debris, CLSM would be placed around the debris to fill void space. Water collected within the vault during waste placement would be removed and treated appropriately. Thirty-three concrete vaults, sectioned into eighteen 30-ft by 30-ft cells, would be required. UCOR believed that this option offers minimal size reduction at the Y-12 site, however the debris would not be compacted as efficiently as in the first option.

Figure 5. Proposed Medium Scale In-Cell Macroencapsulation

Option 3: Large containers filled with CLSM and placed in macro-bags in-cell: This option involves loading debris into top-loaded Sealand containers[21] at the Y-12 site and transporting the containers to EMDF. A macro-bag would be placed on the disposal facility cell floor. The container would be placed on the bag, voids in the container would be filled with CLSM or a lighter material, and the macro-bag would be closed around the container. With this option, debris would be sized-reduced at the Y-12 site to dimensions that would fit into Sealand containers.

As described, equipment would be needed at the Y-12 site to load the Sealand containers on the transport vehicle and at the disposal facility to unload the Sealand containers. UCOR estimated that over 4,600 Sealand containers and macro-bags would be required to encapsulate the estimated 100,000 cy of mercury contaminated debris.

Option 4: Large containers filled with CSLM and placed in macro-bags out of cell. This option also involves loading debris into top-loaded Sealand containers at the Y-12 site and transporting the containers to the on-site disposal facility. A macro-bag would be placed in a designated area outside of the disposal facility cell. The container would be placed on the bag, voids in the container would be filled with CLSM or a lighter material, and the macro-bag would be closed around the container. The container would then be placed in EMDF. This option would require construction of a staging area outside of EMDF for the Sealand containers while they are filled with CLSM and allowed to cure.

It is inferred that the initial stages of this option are the same as Option 3 for large containers filled with CSLM and placed in macro-bags in-cell. If so, extra care would be needed to ensure that the integrity of the macro-bags is maintained when the bagged Sealand containers are moved from the staging area into the disposal cell. More robust equipment (such as cranes) would be needed at the disposal facility

[21] For this purpose, a Sealand container is assumed to be 20-ft long x 8-ft wide x 8.5-ft high, with a capacity of 43 cy.

to lift and move the heavier Sealand containers filled with CLSM onto transport vehicles and place the Sealand containers in the disposal cell.

Option 5: Large containers filled with CLSM out of cell. This option also involves loading debris into top loaded Sealand containers at the Y-12 site. These Sealand containers would however be modified to have plastic pallets around the interior walls prior to loading in order to allow the CLSM to flow around and fully encapsulate the debris. This mimics the current practice at Environmental Restoration Disposal Facility (ERDF) at DOE's Hanford site. The loaded containers would be transported to the disposal facility and filled with CLSM outside of the disposal cell.

This option would also require construction of a staging area outside of EMDF for the Sealand containers while they are filled with CLSM and allowed to cure. More robust equipment (such as cranes) would be needed at the disposal facility to lift and move the heavier Sealand containers filled with CLSM onto transport vehicles and place the Sealands containers in the disposal cell.

Option 6: Small containers filled with CLSM and placed in macro-bags at generator site. This is an on-site disposal option that meets the current limitations of the EMWMF Record of Decision (ROD) (*i.e*., treatment is performed by the generator). In this option, the debris would be size-reduced at the Y-12 site to fit into a B-25[22] container. The container would be filled with CLSM and enclosed with a macro-bag at the Y-12 site. Once the CLSM has cured the container would be transported to EMDF and placed in the disposal cell.

With this option, significant waste handling and size reduction would be required at the Y-12 site. The site would also need to be equipped with a batch plant to produce the CLSM and a staging area for the B-25 containers while hardening. This option significantly increases the waste disposal volume due to the size reduction required for the debris to fit into the B-25 container and the lack of compaction.

MICROENCAPSULATION

Microencapsulation of smaller pieces of Y-12 debris is another option to be considered, because it has been suggested that it may have a lower cost[23] and that less stringent performance standards may be required.

40 CFR 268.45 defines microencapsulation as the "stabilization of the debris with the following reagents (or waste reagents) such that the leachability of the hazardous contaminants is reduced: (1) Portland cement; or (2) lime/pozzolans (*e.g*., fly ash and cement kiln dust). Reagents (*e.g*., iron salts, silicates, and clays) may be added to enhance the set/cure time and/or compressive strength, or to reduce the leachability of the hazardous constituents." All four commercial disposal facilities interviewed for this report offer microencapsulation of hazardous debris.

The microencapsulation process fully embeds the debris with often custom-tailored, proprietary encapsulation agents that are intended to permanently prevent the hazardous contaminates from leaching into the surrounding environment. This is generally accomplished by transferring the hazardous debris into large tanks containing fly ash, cement kiln dust and other reagents, and mixing the debris around so that the encapsulating agents reach and cover all debris surfaces. Once the waste has been effectively coated, it is transported to a RCRA Subtitle C approved landfill for permanent disposal. However, there are physical constraints of the process that prevent its use on large size debris. A

[22] A strong tight top loading container fabricated from carbon steel with the dimensions of 6-ft long x 3.8-ft wide x 3.9-ft high and a capacity of 3.3 cy.

[23] Estimated to be $60-$70 per cu. yd. lower than macroencapsulation by Shane Whitney, General Manager, Clean Harbors Environmental Services, Grassy Mountain Facility, August 14, 2019.

standard mentioned during conversations with several commercial facilities is that such debris must be smaller than 3 ft x 3 ft in size, and that the debris shape must enable the microencapsulation agents to fully coat all surfaces of the debris.

EPA has raised concerns about the ability to adequately microencapsulate mercury contaminated debris. An EPA study[24] related to treatment research conducted on non-debris mercury wastes and pure elemental mercury, found that,

> "treated wastes were subjected to a range of highly buffered pH liquids and were sampled to determine the amount of mercury in the subsequent leachate. We concluded that the waste forms that we examined were not sufficiently stable across the range of expected Subtitle C landfill conditions for the Agency to propose an alternative treatment standard for all hazardous non-debris mercury wastes. The Agency also concluded, however, that, on a site-specific basis, taking into consideration actual disposal conditions, mercury wastes could be potentially treated via microencapsulation and disposed of in a protective manner."

The October 2003 internal EPA memorandum mentioned earlier notes that "when assessing the appropriateness of microencapsulation for mercury-containing debris, the primary factors to keep in mind include the chemical composition of the leachates to which the stabilized waste will be exposed, including pH and major anions, cations and organic compounds. It is also important to consider what additional measures, if any (*e.g.*, macroencapsulation), will be put in place to prevent leachate from mobilizing the hazardous constituents."

However, there is likely a balance between the microencapsulation of smaller and even finer particle sized waste materials (*e.g.*, soils, concrete fines, and rubble[25]) that could be separated or segregated from the large debris items. Macroencapsulation is an un-mixed treatment that relies on the flowability of the treatment matrix to fill gaps in large debris. Any gaps in the treated material could provide a pathway for movement of elemental mercury or ingress of water. Because microencapsulation involves mechanical mixing of waste within a treatment matrix, microencapsulation could provide a higher degree contact between mercury and treatment additives than macroencapsulation and, hence, provide a better retention of mercury in the D&D waste.

IV. THE CHALLENGES OF MERCURY ENCAPSULATION

Within the Y-12 BDD, mercury is likely to be present as both elemental mercury (Hg^0) and divalent mercury as an aqueous ion (Hg^{+2}). Treated materials may also contain precipitated mercury after stabilization with fixatives such as sulfur (Yee et al, 2013). Where sufficient organic matter is present to support biological activity (*e.g*., soils), methylated mercury (CH_3Hg) and mercury in aqueous solution chelated with organic ligands ($Hg_{organic}$) may be present.

CONCEPTUAL WASTE PACKAGES AND DISPOSAL ENVIRONMENT

Although the majority of elemental mercury may be collected before and during demolition, and disposed of separately from the BDD waste, the potential vaporization and transport of residual elemental mercury trapped within the disposed BDD makes its management different than that of typical inorganic hazardous wastes. Depending upon waste types, the primary waste package could

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[24] NODA, 2003. *Notice of Data Availability*, 68 FR 4481, January 29, 2003.

[25] Waste or rough fragments of stone, brick, concrete, *etc*., especially as the debris from the demolition of buildings.

receive initial on-site pre-treatment through surface coatings of additives that substantially reduce surface exposure to potential leaching media.

A set of three conceptual models (see Figure 6) depicts the possible encapsulation options (physical encapsulation with or without chemical stabilization) that the mercury contaminated BDD may go through in preparation for final disposal in EMDF:

A. ***BDD waste package:*** The building demolition debris is placed on the ground or a pad, or contained in a flexible container that provides little to no resistance to contaminant transport. Examples include the initial stages of macroencapsulation portrayed in the ES and WM HDPE vaults. The transport of mercury out of the debris, or the presence of elemental mercury on the surface of the debris can occur in the waste package. This would result in mercury which could then dissolve in infiltrated water, react with oxygen, carbon dioxide, or any other elements present, and potentially transport out of the waste package. Elemental mercury dislodged during loading, transport, placement and compaction could move with gravity to gaps in the compacted waste. Since elemental mercury has a high surface tension (484.5 mN/m at 20 °C), mercury vapor could condense in smaller pores, forming a NAPL of mercury, which could move into larger pores within the debris. Capillary condensation is more likely within materials with larger, or more varied, pore structure (Moro and Bohni, 2001).

B. ***Physical encapsulation of the BDD waste package***: The BDD waste package is encapsulated with grout, pozzolanic or a similar material that is confined by the walls of a cement, polymer or steel container or barrier material. Examples include the macroencapsulation methods portrayed in the ES and WM HDPE vaults and GM COLEX disposal. This may begin with physical immobilization and/or encapsulation of the mercury in the debris during filling of the container while at Y-12 to prevent separation, dispersion or volatilization of mercury during loading, and transport to and handling at EMDF. Options for immobilization and/or encapsulation include sprays, grout, fixatives, *etc*. While the same transport mechanisms within the BDD waste package may occur, mercury would need to transport through the encapsulation material as well as the container walls in order to be released into the disposal cell environment. Physical encapsulation of BDD waste may provide a barrier to contain accumulated elemental mercury and minimize mercury transport from the waste package.

C. ***Chemical stabilization of BDD with physical encapsulation***: An option to the physical encapsulation of BDD waste described above would be to add reactive components to the waste that will minimize the solubility and mobility of mercury. Additives (*e.g.*, sulfur) could be added to the grout or other encapsulation mix or sprayed on the BDD waste package before physical encapsulation. Chemical stabilization will further immobilize elemental mercury in the disposal cell, reducing the potential for transport within the BDD waste package (Fuhrmann et al, 2002). However, HgS may oxidize to Hg^{2+} in the presence of oxygen. Additionally, since elemental mercury would be stabilized to insoluble inorganic forms (*e.g.*, HgS), the potential for accumulation of elemental mercury and capillary condensation of mercury in the pore structure would be minimized.

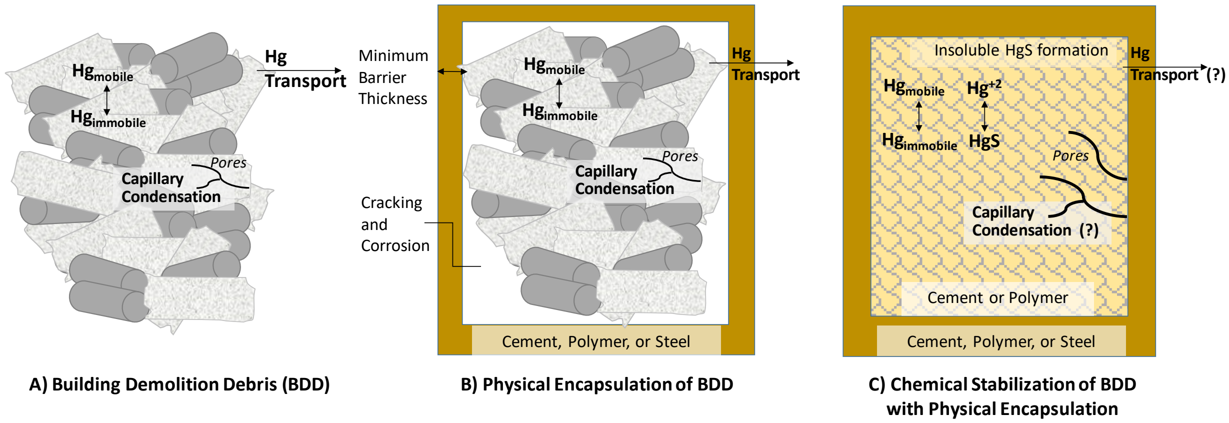

Figure 6. Conceptual BDD waste packages: A) BDD waste, B) physical encapsulation of BDD, and C) chemical stabilization and physical encapsulation of BDD.

The disposal of mercury-contaminated BDD waste from the Y-12 building complex could consist of a "defense in depth" approach (see Figure 7). At the disposal cell, the macroencapsulated BDD waste packages (physical encapsulation with or without chemical stabilization) could be off-loaded and stacked on a reactive mat installed above the disposal cell's RCRA compliant liner, in a manner that would allow fill or additional macroencapsulation material to encompass each package. This secondary macroencapsulation of the disposed BDD waste packages would encase the macroencapsulated BDD waste packages within one or more added protective barriers, so that any mercury released from the waste packages is contained or slowed from reaching the disposal cell liner or volatizing and escaping into the atmosphere. This two-part conceptual release model would allow for compartmentalized modelling of mercury release, in that the mercury that is released from the primary waste package is the source for transport through initially clean grout of the secondary barrier. The thickness of the secondary barrier would be a variable parameter to information waste package placement operations at the disposal cell.

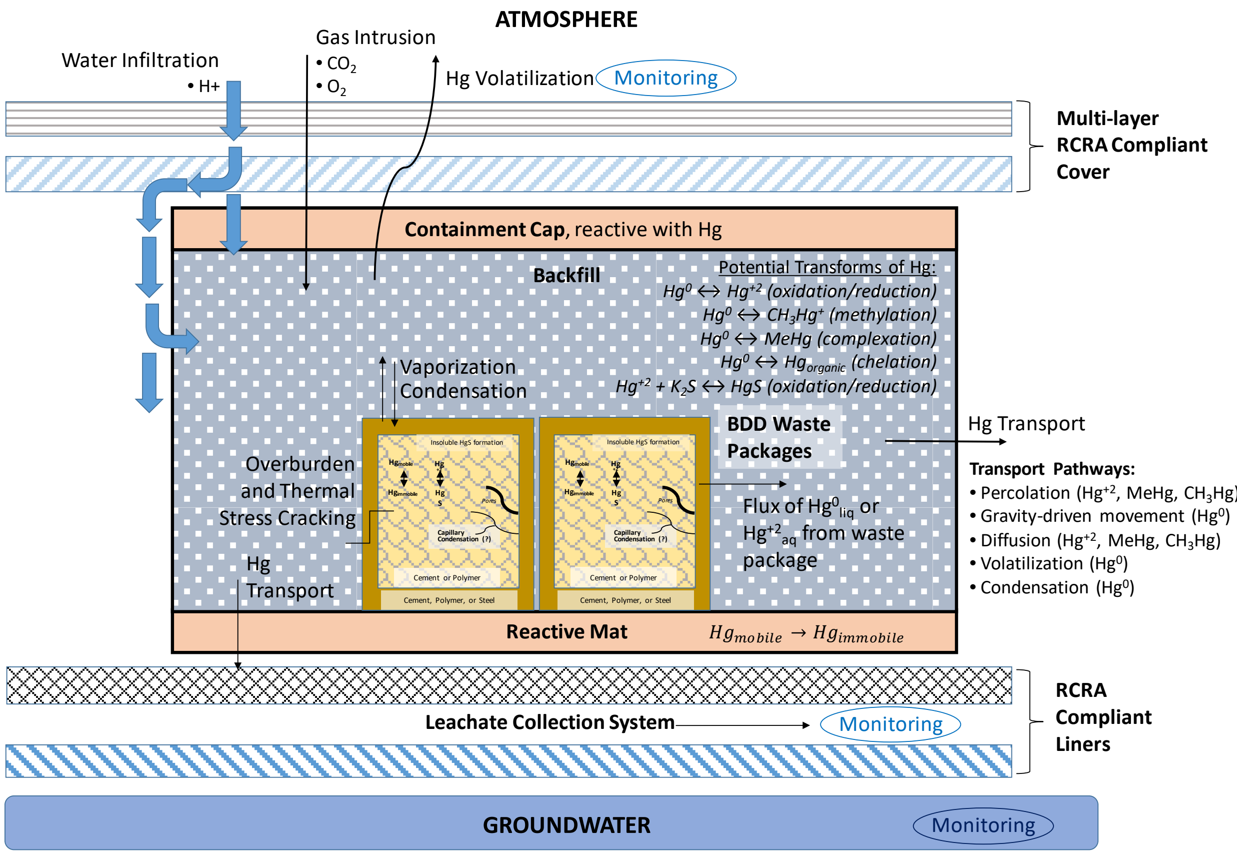

Figure 7. Conceptual model of EMDF cell containing encapsulated mercury-contaminated BDD waste packages.

Volatilization within the disposal cell and through the cap and liners is possible, as well as through the sides of the disposal cell; however, the rate of transport of mercury vapor through prototype materials is not well-documented. Mercury volatilization is a function of temperature and could vary seasonally, increasing up to three orders of magnitude or 1000 times between winter months (ca. 275° C) and summer months (up to 37° C) (Huber, M.L. et al, 2006). Therefore, volatilization of mercury from disposed debris prior to closure of the disposal cell, and during treatment when exothermic reactions occur, may be important. Transport of mercury vapor within porous media (*e.g.*, soils, concrete, wastes treated with cementitious or pozzolanic reactants, *etc.*) could result in localized condensation to elemental mercury away from the waste package.

V. PRELIMINARY OBSERVATIONS AND COMMENTS

HANDLING AND DISPOSITION PATHWAYS FOR MERCURY CONTAMINATED DEBRIS

The likely presence of elemental mercury in or on the Y-12 building demolition debris, and mercury's multiple mechanisms for release into the environment prior to being macroencapsulated suggest the following:

- Treatment of debris, through immobilization of residual elemental mercury and/or encapsulation of debris while it is still at Y-12 may be required to prevent separation of elemental mercury from the BDD and dispersion or volatilization of mercury during loading, transport to, and handling at EMDF. Options for immobilization and/or encapsulation include sprays, grout, fixatives, *etc.*;

- Selection of initial treatment and/or separation processes (*e.g*., use of cleaners, coatings) to isolate mercury on debris or separate residual mercury from debris may have a significant impact on the release and dispersion of mercury from the waste. The reaction of elemental mercury with inorganic additives to form inorganic mercury compounds (*e.g*. adding sulfur to form mercury sulfide or HgS) would reduce the overall volatility and mobility of mercury (see conceptual models); however, organic additives introduced through these initial treatment and/or separation processes may increase the overall mobility of mercury due to complexation, methylation, or sorption to soluble organic compounds; and,
- Mercury contaminated debris dumped into/onto an open pad as a process toward large-scale macroencapsulation has the potential for mercury vaporization into the air and disposition onto other surrounding materials. Monitoring and protection of site workers at EMDF from mercury exposure will be needed, if such a temporary storage method is used.

UCOR Macroencapsulation Option Challenges

UCOR's 2015 evaluation includes a discussion of six macroencapsulation and disposition alternative options for the mercury contaminated debris that would be created from future demolition of the Y-12 complex of buildings. The primary objectives of each option discussed in UCOR the evaluation are (i) to allow for on-site disposal of the debris in the existing Environmental Management Waste Management Facility (EMWMF) and/or the proposed EMDF waste disposal facilities; (ii) to plan, to the extent possible, the macroencapsulation treatment within the disposal facility cell; and (iii) to provide OREM with a rough-order-of-magnitude comparison of anticipated costs of each alternative.

The first three options proposed by UCOR are to macroencapsulate the BDD entirely within an EMDF disposal cell. Thus, mercury contaminated debris would be placed in a disposal cell before being treated to meet the LDR treatment standards for mercury-bearing wastes. These options will necessitate that either EMDF disposal cell be designated as a CAMU, or OREM seek and obtain a CERCLA waiver of the prohibition against land disposal of wastes not meeting applicable LDR treatment standards (even if the waste is subsequently treated to meet LDR standards).

In addition to the above, there are several observations that can be made about the macroencapsulation methods proposed in Options 1 and 2. These observations are based on knowledge of the on-site transportation and hazardous waste disposal methods at Hanford's ERDF, and the mercury chemistry and methods of mercury transport discussed in this report.

- The container used to transport the mercury contaminated debris from Y-12 to EMDF would need to be lined, to prevent the vehicle from becoming contaminated and this liner would likely need to be dumped with the debris onto the concrete vault floor. Dumping of the liner may result in the liner becoming entangled in the debris (*e.g*., while being moved around within the vault by the dozer or trackhoe) and also may affect whether the debris can be fully encapsulated.
- There is a high risk that the crushing of the mercury contaminated debris and the movement of construction equipment within the vault will disperse mercury into the air, possibly contaminating areas outside the concrete vault where the debris is being placed. There is also the possibility that the proposed crushing of debris could dislodge elemental mercury liquid from inside the debris, which could coalesce on the vault floor or on surrounding surfaces; and,
- There is also the possibility that the dozer or trackhoe operator will be exposed to inhalation of mercury released in the air from the work being conducted to crush and move the mercury

contaminated debris. The dozer and trackhoe will also become contaminated with mercury and require macroencapsulation with the debris.

POTENTIAL USE OF WM'S HDPE VAULTS

Consideration should be given to replacing the Sealand containers that are proposed for use in macroencapsulation Options 3, 4 and 5 (UCOR, 2015) with the specially designed, patented 100mil HDPE vaults that WM has offered to sell OREM[26]. Instead of the sand that WM places in the bottom of the disposal vault for stability before the debris is added, OREM might consider using a reactive or absorbent pad on the HDPE Vault floor to capture any elemental mercury that might dislodge from the debris during loading at the Y-12 site and transportation to EMDF. A grout mix would then be poured into the debris-filled HDPE vault, fully encapsulating the debris. The combination of the 100mil thick HDPE vault walls and grout encapsulation of the debris would create a double layer of environmental protectiveness. After the grout has hardened, the vault would be welded shut, and gently dropped off the dumpster onto the ground in an EMDF cell.

This dumpster would then receive a new empty HDPE vault unit with reactive or absorbent pad on its floor and returned to the Y-12 demolition site to receive a new load of mercury contaminated debris.

Although the HDPE vaults only have a 20cy capacity, which is less than half that of the 43cy capacity of the Sealand container proposed in the 2015 UCOR evaluated Options 3, 4 and 5, the overall costs of using the HDPE vault seem to be much less than a similarly outfitted Sealand containers. The equivalent cost of HDPE vaults for the Sealand container volume of 43cy is estimated at about $4,891[27] compared to $17,497[28] for each Sealand container as suggested by UCOR Option 5.

The use of the HDPE vaults in place of the Sealand containers, would have the similar requirements of Option 3 with regard to needing to have EMDF be designated a CAMU or that a CERCLA waiver be obtained, if the final CLSM layer is added inside the disposal cell, or with Options 4 & 5 that a staging area outside of EMDF be constructed for the HDPE vaults if they are filled with CLSM and allowed to cure outside the cell. However, robust equipment (such as cranes) would not be needed at the disposal facility to lift and move the debris and grout filled HDPE vaults, since they would be gently dropped onto the disposal cell floor by the dumpster transport vehicle. Gaps in Data and Other Information

Based on review of UCOR and alternative treatment options for BDD containing mercury, the following gaps have been identified:

- The performance standard for macroencapsulation of hazardous debris under 40 CFR 268.45 requires that the encapsulating material be resistant to degradation by the debris itself and the case-specific disposal environment. Research conducted for this report, however, did not find any longevity stipulation or requirement that the macroencapsulation should meet (*i.e*. that such degradation not occur in 10, 100, or 1,000 years), nor specific procedures that should be used to test and prove the efficacy of the macroencapsulating method;
- UCOR's proposed criteria for determining which debris materials will require treatment are uncertain. UCOR's 2015 evaluation report discusses screening based on the "Rule of 20". The

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[26] Email to Henry Mayer from Jennifer Sweeney, Hazardous Waste SME, Waste Management, Emelle, AL. October 10, 2019. Proposed cost of $2,275 per vault delivered to ORR.

[27] $2,275 HDPE vault purchase cost multiplied by the 43cy Sealand capacity and divided by 20 cy HDPE capacity = $4,891.25.

[28] $94,571,007 estimated cost of purchasing and modifying Sealand containers under Option 5 (UCOR, 2015), divided by the 5,405 containers required in this option.

Rule of 20 assumes that the total elemental content of mercury will leach as a means to determine passage of the TCLP. In itself, TCLP is an unreliable indicator of future leachability in scenarios other than the disposal of waste in municipal landfills (SAB, 1991; 1999). Additionally, representative subsampling of intact materials for total mercury content analysis or TCLP is challenging due to the spatial variability of contamination and the nature and scale of the materials involved. The uncertainty surrounding the criterion used to determine which debris will require treatment suggests the need for the development and specification of screening and sampling protocols for Y-12;

- As part of their waste acceptance criteria, the four large commercial hazardous waste disposal facilities discussed in this report do not allow for the presence of visible mercury. Therefore, the macroencapsulation methodologies and encapsulating materials used at these four facilities have not been proven to be suitable for debris wastes with a potential for the presence of liquid mercury (visible or occluded) such as is expected to be present at Y-12;
- The impact of mercury vaporization and transport is unknown. Residual elemental within the waste package may vaporize, transport as a vapor through a continuous pore space, and condense to elemental mercury outside of the waste package;
- The selection of specific reactive barrier materials (*e.g*. cementitious blends, absorption mats) may significantly impact the feasibility of mercury treatment to allow disposal at EMDF, the projected costs, and the process for deconstruction, treatment, transport, and disposal of building demolition debris waste. The effectiveness for metallic mercury has been demonstrated at the laboratory scale for sulfur-polymer cements (Kalb et al, 2011; Adams and Kalb, 2002; Wang, 2012) and chemically-bonded phosphate ceramics (Singh et al, 1998; Wagh and Singh, 1999; Wagh et al, 2000). However, each of these processes have disadvantages for macroencapsulation at field scale, such as requirements for preheating the macroencapsulating mixture up to 140 °C and for process optimization only in well-mixed systems;
- There is likely a balance between microencapsulation of smaller, finer particle sized waste materials (*e.g*., soils, concrete fines, and rubble) that could be separated or segregated from the large debris items, and the macroencapsulation of the larger debris. Microencapsulation should provide a higher degree of mercury retention than macroencapsulation because the finer, smaller sized waste would be thoroughly mixed with reactive treatment materials. Macroencapsulation of oversized debris will rely on flowability of the reactive barrier material to fill gaps that would otherwise not be present with microencapsulation; and,
- Macroencapsulation is a key component of any EMDF disposal process for building demolition debris waste. However, the rate of transport of mercury, in all forms, through barrier components is unknown. These barrier components could include HDPE used to contain waste packages (*e.g*., supersack material or WM's special HDPE vault), steel barriers (*e.g*., Sealand containers or roll-off boxes), and reactive cementitious materials (e.g. sulfur-polymer cements or sulfate resistant cements).

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VII. SUPPLEMENTAL INFORMATION – EPA 2003 MEMORANDUM

Found to have been issued October 23, 2003

MEMORANDUM

SUBJECT: Treatment Standards for Mercury-Containing Debris

FROM: Robert Springer, Director
Office of Solid Waste

TO: RCRA Senior Policy Advisors
State Waste Managers

This memorandum discusses issues pertaining to the treatment and disposal of mercury-containing debris subject to the RCRA land disposal restrictions debris requirements at 40 CFR 268.45. This memorandum:

- clarifies the types of hazardous mercury-containing wastes that are eligible for management under the debris treatment standards, including whether containerized mercury is excluded as debris;
- provides information on the improved capabilities of mercury "retorters" to accept and recover mercury from debris-like waste; and
- describes how to meet the performance standards for the hazardous debris treatment technologies.

The topics that are discussed in this memorandum have been raised to the Agency as areas for clarification or have arisen from advancements in research and technology developments. However, we are aware that the information that we are providing will not answer all of the questions that you may encounter as you consider the appropriateness of technologies for site-specific conditions.

Background

Treatment Standards for Non-Debris Hazardous Wastes. For D009 wastes (wastes that meet the toxicity characteristic for mercury) that are not classified as debris and are not wastewaters or mixed (radioactive and hazardous) wastes, the RCRA land disposal restrictions (LDRs) set four treatment standards (see 40 CFR 268.40). These wastes are in either the "low mercury subcategory" (i.e., containing less than 260 mg/kg total mercury), or the "high mercury-inorganic subcategory" (i.e., containing more than 260 mg/kg total mercury). The treatment standard for low mercury wastes requires that leachate from treatment residuals, using the Toxicity Characteristic Leaching Procedure (TCLP), have a mercury concentration of less than 0.025 mg/L (or 0.20 mg/L for residues from retorting). Treatment by stabilization can be used to achieve this standard. The treatment standard for "high mercury inorganic category" wastes, which contain more than 260 mg/kg total mercury, is mercury recovery ("RMERC") in a thermal processing unit that volatilizes and subsequently condenses the mercury. These units are commonly referred to as "retorters," and the recovery process as "retorting." (40 CFR, 268.42, Table 1).

Treatment Standards for Hazardous Debris Wastes. The treatment requirements for hazardous debris, which were promulgated in 1992, are based on performance standards and specified technologies that reflect the technical challenges of treating debris-like objects and cleaning up remediation sites (see 40 CFR 268.45). These requirements allow use of specified technologies as an alternative to meeting the standards for non-debris hazardous wastes (40 CFR 268.45(a)) that are otherwise required; in this memo, we refer to these treatment standards as the alternative debris standards. The treatment technologies that generally apply to mercury-containing debris are microencapsulation and macroencapsulation[1]. These technology options do not distinguish between debris containing high and low levels of mercury. EPA's guidance on how to best achieve the performance requirements for these technology options is described below.

It is important to remember that if the alternative debris standards are not used as the basis of compliance for the land disposal restrictions, the mercury-containing hazardous debris are subject to the non-debris standards, which include retorting for high-mercury wastes. The non-debris standards will also apply if the alternative debris standards cannot be adequately met.

What are Debris/Hazardous Debris?

Definition of Debris. Debris is defined at 40 CFR 268.2 (g) as a "solid material exceeding a 60 mm particle size that is intended for disposal and that is: A manufactured object; or plant or animal matter; or natural geologic material." The next section describes the exceptions to this definition.

Definition of Hazardous Debris. Under 40 CFR 268.2(h), *hazardous debris* means debris that contains a listed hazardous waste or exhibits a characteristic of hazardous waste. Deliberately mixing prohibited waste with debris to change the treatment classification from waste to hazardous debris is not allowed under the dilution prohibition in 40 CFR 268.3.

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[1]Although "source separation" is not identified as a specific technology under the debris treatment standards, for waste streams with readily identifiable mercury sources, it is a preferred method of removing liquid mercury from hazardous debris waste streams, or of removing the mercury characteristic from the hazardous debris. (See further discussion of this technology later in the memorandum.)

What Is Not Hazardous Debris?

Exclusions from the Debris Definition. The debris regulations specifically exclude certain materials from the definition of "debris." One exception under the 40 CFR 268.2(g) debris definition of great pertinence to mercury-containing wastes is for "intact containers of hazardous waste that are not ruptured and that retain at least 75% of their original volume." The preamble to the Debris Rule discusses this exclusion in detail (see 57 FR 37225, August 18, 1992: "Intact Containers Are Not Debris").

EPA has long interpreted certain manufactured objects that hold liquids, including mercury-containing pumps[2] and batteries, to be "containers." Under 40 CFR 260.10, containers are defined as "any portable device in which a material is stored, transported, treated, disposed of, or otherwise handled." Under this definition, mercury-containing items such as thermometers, pumps, manometers, thermostats, jars of elemental mercury, batteries, dental amalgam collection devices, and ampules are containers. These items, therefore, do not fall under the debris definition and are subject to the non-debris mercury treatment standards.[3]

In situations where intact containers are mixed with true debris (i.e., materials classified as debris under the debris rule) and the mixture is RCRA hazardous, the intact containers would have to be removed and managed separately. EPA also recognizes that certain states have passed regulations that prohibit disposal and require mercury recovery from mercury-containing devices.

Size Limitations. The debris standards require that debris contain materials 60 mm or greater in size. Many mercury-containing devices, such as automotive switches, are substantially smaller than 60 mm and would not be eligible for treatment under the debris treatment standard because of their size. It is important to note, however, that many switches would not likely be eligible as debris because they are intact containers, as discussed above.

What Hazardous Debris is Exempt from RCRA Subtitle C?

We are aware that there is some confusion about the regulatory status of certain hazardous debris that is currently exempted from RCRA Subtitle C. At the federal level, there are two main exemptions from the RCRA hazardous waste regulations that pertain to hazardous debris-like mercury-containing wastes. The first is for mercury wastes from households, such as

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[2] Note that the debris rule preamble describes circumstances where pumps can be debris (57 FR 37225 and 37229). Pumps containing enclosed mercury, however, function as containers and would not be eligible as debris if the criteria for the intact container exclusion are met.

[3] States may have designated certain mercury-containing items such as thermostats as "universal wastes" under state regulations. Such designations allow for streamlined collection requirements, but do not exempt such wastes from the hazardous waste treatment requirements.

thermostats and thermometers, which are exempted from the RCRA hazardous waste regulations under the household waste exclusion (see 40 CFR 261.4(b)(1)). The second exemption is for hazardous wastes that are generated by conditionally exempt small quantity generators (CESQGs; see 40 CFR 261.5). CESQGs are defined as those generators that generate less than 100 kg of hazardous waste per calendar month or less than 1 kg of acutely hazardous waste per calendar month. CESQG requirements also limit the facility's waste accumulation to less than 1,000 kg of hazardous waste, 1 kg of acute hazardous waste, or 100 kg of any residue from the cleanup of a spill of acute hazardous waste at any time.[4] As an example, under federal regulations, a small dental office collecting mercury amalgam scrap that exhibits the hazardous characteristic for mercury would be a CESQG if it did not exceed the hazardous waste limits noted above. EPA strongly recommends that households and CESQGs make every effort to preserve the integrity of mercury-containing devices and that such devices are collected and recycled.

It is important to note that certain states have passed laws or regulations requiring that collected mercury-containing household wastes or mercury-containing CESQG wastes be subject to specific treatment and management standards, such as retorting. In addition, nearly half of the states have not adopted the less stringent CESQG requirements, and generators of mercury-containing hazardous waste in such states are subject to the small (or large) quantity generator requirements, or to other more stringent state requirements. Therefore, you should consult your state agency(s) to determine whether more stringent state requirements are applicable.

Treatment Technologies for Mercury-Containing Debris

Table 1 of 40 CFR 268.45 (the debris regulation), Alternative Treatment Standards for Hazardous Debris, contains technology descriptions, performance and/or design and operating standards for each technology, and restrictions on contaminants for specific technologies. Table 1 categorizes technologies into three technology groups--extraction (physical and chemical), destruction (biological and chemical), and immobilization (macroencapsulation, microencapsulation, and sealing).[5] In our experience, the treatment technologies listed in Table I

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[4] Note that most mercury wastes will not be "acutely hazardous," and the larger generation and accumulation amounts would apply for purposes of this exemption. See 40 CFR 261.30(b).

[5]Destruction technologies are not applicable to metal contaminants. We are not aware of chemical extraction technologies that could be applied to remove mercury from debris. Physical extraction technologies listed under the debris standard, including abrasion, grinding, spalling, or vibratory finishing, might be capable of removing mercury contamination from certain contaminated surfaces; we are not, however, aware of any examples where these technologies have been used for this purpose. We anticipate that physical extraction technologies would present potential cross-media contamination, especially volatilization of mercury into the

that are applicable to mercury-containing debris are microencapsulation and macroencapsulation. However, source separation and retorting can also be effective technologies for mercury-contaminated debris.

The following section describes each of these technologies and EPA's guidance on how to best achieve the performance standard for microencapsulation and macroencapsulation. This guidance reflects the technical challenges associated with treating mercury, which can be difficult to stabilize and has the potential to become volatile at ambient conditions.

Retorting. Mercury retorters are capable of accepting many mercury-containing materials, including mercury-containing debris, with certain limitations and exceptions. The websites of existing vendors list a variety of retortable materials that could be potentially associated with debris, including cleanup materials, building materials and many mercury-added products such as those referenced earlier in this memorandum. In addition, vendors can manage different forms of mercury salts and compounds. Since the hazardous debris rule was promulgated in 1992, vendors have increased their capability to handle larger objects in their retorters. Vendors typically manage drums of waste, but can, in some instances, handle even larger objects, such as roll-off containers of wastes. In general, we encourage you to contact the vendors to determine if there are any size, concentration, or contaminant restrictions that would require pre-treatment or special management considerations, or that would prevent the waste from undergoing retorting.

RCRA regulations for mercury retorting are found at 40 CFR 266.100(d), which conditionally exempts certain metal recovery units from regulation under RCRA Subtitle C. To retain this conditional exemption, retorters must comply with waste limitations regarding organic matter content and heating value. Specifically, under 40 CFR 266.100(d)(2), a retorter cannot accept wastes exceeding 500 ppm by weight of Appendix VIII organics, as fired, and cannot accept wastes exceeding a heating value of 5000 BTU/lb or more. Please see 40 CFR 266.100(d) for more details on these provisions. To ensure that air emissions from mercury retorters are controlled adequately, the Agency also specified, as part of the Best Demonstrated Available Technology (BDAT) determination under the RCRA land disposal restrictions regulations, that the retorting unit either: (a) be subject to the mercury National Emission Standards for Hazardous Air Pollutants (NESHAP); (b) be subject to a Best Available Control Technology (BACT) or Lowest Achievable Emission Rate (LAER) standard for mercury imposed pursuant to a Prevention of Significant Deterioration (PSD) permit; or (c) that it be subject to a state permit that establishes emission limitations (within the meaning of section 302 of the Clean Air Act (CAA)) for mercury (see 40 CFR 268.42 Table 1 (RMERC), and http://www.epa.gov/air/caa/caa302.txt). This standard is enforceable under RCRA pursuant to the authority in section 3008(a). There are no Maximum Achievable Control Technology (MACT) standards for mercury retorters set under

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atmosphere, that could make the technology unacceptably risky to the environment. Permitting authorities should ensure that this potential for risk is minimized. In addition, the removed mercury, associated media, and extraction materials that fail the Toxicity Characteristic for mercury would be subject to the RCRA hazardous waste requirements for non-debris wastes.

the CAA at this time. See 55 FR 22569-22570 (the June 1, 1990 Land Disposal Restrictions Third Third Rule) for more details on the RCRA requirements for retorters. For more information on the CAA requirements cited here, see http://www.epa.gov/ttn/catc/rblc/htm/rbxplain.html and http://www.epa.gov/ttn/nsr/psd_abs.html.

Source Separation. For mercury-containing debris exhibiting the D009 characteristic for mercury, we use the term "source separation" to refer to the process of removing mercury-contaminated material from the bulk of the debris. For example, mercury-contaminated piping or broken gauges could be removed and managed under the non-debris treatment standards for hazardous wastes. Although source separation is not listed as a specific technology under the debris standards on Table 1, in many circumstances, it will be the preferred approach to remove mercury-containing devices or other items with readily identifiable mercury from the debris, and may even result in removing the mercury characteristic from the debris.[6] Moreover, as noted earlier, where intact containers containing hazardous waste are mixed with true debris, the intact containers (such as mercury-added products) must be removed and managed separately as non-debris hazardous waste.

Microencapsulation. This technology involves mixing wastes with reagents and stabilization materials to produce a more stable waste form. The Table 1 performance standard for microencapsulation is that "the leachability of the hazardous contaminants must be reduced." EPA recently published the results of treatment research conducted on non-debris mercury wastes and pure elemental mercury to assess whether the current retorting standard could be supplemented with an alternative disposal standard (Notice of Data Availability (NODA), 68 FR 4481, January 29, 2003). The results of this study are applicable to mercury-containing debris. In the study, treated wastes were subjected to a range of highly buffered pH liquids and were sampled to determine the amount of mercury in the subsequent leachate. We concluded that the waste forms that we examined were not sufficiently stable across the range of expected Subtitle C landfill conditions for the Agency to propose an alternative treatment standard for all hazardous non-debris mercury wastes. The Agency also concluded, however, that, on a site-specific basis, taking into consideration actual disposal conditions, mercury wastes could be potentially treated via microencapsulation and disposed of in a protective manner.

EPA's treatment research provides information on specific factors that may be considered when evaluating microencapsulation for treatment and disposal of mercury-containing hazardous debris. These factors assist you in determining whether or not the performance standard for

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[6]As is the case for all characteristic wastes, removing the characteristic will not necessarily result in achieving compliance with the land disposal restriction treatment standards for that waste. Please also note, under 40 CFR 268.45(c), hazardous debris contaminated with a listed waste that is treated by an immobilization technology specified in Table I must be managed in a subtitle C facility.

microencapsulation–"leachability of the hazardous contaminants must be reduced"–is being met.[7] For example, the results of the treatability studies discussed above demonstrate that each treatment technology exhibits its own pattern of mercury leaching from the treated waste forms across a range of plausible pH conditions. The research also found a significant increase in leachability of one treated waste form as leachate salinity was increased (only one treated waste form was tested with increasing salinity). When assessing the appropriateness of microencapsulation for mercury-containing debris, the primary factors to keep in mind include the chemical composition of the leachates to which the stabilized waste will be exposed, including pH and major anions, cations and organic compounds. It is also important to consider what additional measures, if any (e.g., macroencapsulation), will be put in place to prevent leachate from mobilizing the hazardous constituents. Please note, as well, that free liquids are prohibited from land disposal in microencapsulated debris (see discussion in the debris rule preamble at 57 FR 37235 and RCRA regulations at 40 CFR 264.314 and 265.314).

Macroencapsulation. This technology uses surface coatings or jackets to substantially reduce surface exposure to potential leaching media. The performance standard listed in Table 1 for this technology is that the "encapsulating material must completely encapsulate debris and be resistant to degradation by the debris and its contaminants and materials into which it may come into contact after placement (leachate, other waste microbes)." Methods for ensuring that the encapsulating material completely encapsulates the waste are specific to the technology used. For example, leak-tightness or pressure testing of High Density Polyethylene (HDPE) pipes or containers has been approved for testing of treated debris. Visual inspection may be appropriate for verifying that sprayed-on or applied coatings have complete integrity, without cracks, voids or protruding waste to ensure that the hazardous debris is completely encapsulated. The performance standard also requires that the encapsulating material be resistant to degradation by the debris itself and the case-specific disposal environment. Information on the durability of potential encapsulating materials when exposed to multiple organic compounds can be found on the internet from many vendors of HDPE/Low Density Polyethylene (LDPE) products. For example, LDPE has general resistance to chemicals, although it is slowly attacked by strong oxidizing agents, and some solvents will cause softening or swelling. HDPE generally has higher chemical resistance than LDPE, but it too can be affected by solvents. In general, if significant organics are present in the waste or in the disposal environment leachate, plastic encapsulating materials should not be used as the primary basis of meeting the debris treatment standard, or should be carefully researched. It may be necessary to conduct case-specific testing, if you cannot find information in the literature on materials that would pertain to specific disposal conditions.

Another measure of the ability of a macroencapsulation technology to substantially reduce

[7] Note that HSWA 3004(m) requires EPA to "promulgate regulations specifying those levels or methods of treatment, if any, which substantially diminish the toxicity of the waste or substantially reduce the likelihood of migration of hazardous constituents from the waste so that short-term and long-term threats to human health and the environment are minimized."

surface exposure to potential leaching media is the structural integrity of the waste form produced by the technology. This factor is especially significant for mercury-bearing wastes, as mercury is volatile at disposal temperatures, and if present in liquid form, is directly mobile. Because of the mobility of mercury as a gas and liquid, macroencapsulation may be an inappropriate technology for hazardous debris containing readily removable liquid mercury.[8] An assessment of structural integrity will depend upon the specifics of the encapsulating technology and the case-specific disposal environment. Note that the disposal environment may include significant short-term stresses from management in the disposal cell, including driving of heavy equipment over disposed wastes. Disposed waste forms also will be subjected to burial stresses, which can result in compression and long-term creep; these stresses can be significant, especially if load-bearing will be accommodated at pressure points. Some vendors of macroencapsulation technologies can provide information, based on testing or modeling, of the ability of their technology to withstand burial pressures, drops onto soft or hard material (e.g., concrete), internal pressures caused by the wastes, puncture (such as to simulate forklift puncture), and vibration (to simulate transportation). In addition, some waste forms, such as those involving plastics, will lose strength after burial and exposure to the temperature, pressure and chemical conditions in the disposal cell. As discussed above, information on the durability of potential encapsulating materials when exposed to organic compounds and to temperature can be found on the internet from many vendors of HDPE/LDPE products.

Questions?

Any questions on management of mercury-containing debris should be directed to Laurie Solomon on my staff at (703) 308-8443.

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[8] Some states consider land disposal of macroencapsulated waste containing liquid mercury as prohibited disposal of containerized liquids. You should consult with your state agency(s) to determine whether they take such a position.