

## **Technical Assistance to Ohio Closure Site**

### **Technologies to Address Leachate from the On-Site Disposal Facility at Fernald Environmental Management Project, Ohio**



**SCFA Technical Assistance Request #143**

**Fernald, OH**

**August 6-7, 2002**

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## **EXECUTIVE SUMMARY**

### **Technical Assistance Process**

On August 6-7, 2002, a Technical Assistance Team (“Team”) from the U.S. Department of Energy (DOE) Subsurface Contaminants Focus Area (SCFA) met with Fernald Environmental Management Project (FEMP) personnel in Ohio to assess approaches to remediating uranium-contaminated leachate from the On-Site Disposal Facility (OSDF). The Team was composed of technical experts from national labs, technology centers, and industry and was assembled in response to a request from the FEMP Aquifer Restoration Project.

Dave Brettschneider of Fluor Fernald, Inc., requested that a Team of experts be convened to review technologies for the removal of uranium in both brine ion exchange regeneration solution from the Advanced Wastewater Treatment facility and in the leachate from the OSDF. The Team was asked to identify one or more technologies for bench-scale testing as a cost effective alternative to remove uranium so that the brine regeneration solution from the Advanced Waste Water Treatment facility and the leachate from the OSDF can be discharged without further treatment. The Team was also requested to prepare a recommended development and demonstration plan for the alternative technologies. Finally, the Team was asked to make recommendations on the optimal technical solution for field implementation. The Site’s expected outcomes for this effort are schedule acceleration, cost reduction, and better long-term stewardship implementation.

To facilitate consideration of the most appropriate technologies, the Team was divided into two groups to consider the brine and the leachate separately, since they represent different sources with different constraints on solutions, e.g., short-term versus very long-term and concentrated versus dilute contaminant matrices. This report focuses on the technologies that are most appropriate for the leachate from the OSDF. Upon arriving at FEMP, project personnel asked the Team to concentrate its efforts on evaluating potential technologies and strategies to reduce uranium concentration in the leachate.

The two-day meeting began on Tuesday, August 6, 2002, with a tour of the OSDF leachate collection and leak detection system (LCS/LDS). Next, the Team met with the OSDF-LCS/LDS operators to discuss the data collected from Cell 1 (completed), baseline technologies, design constraints, regulatory issues, public acceptability, etc. The Team then identified critical issues and brainstormed potential innovative and cost effective solutions, evaluated alternatives, and developed a technology matrix to compare the technologies being considered. On Wednesday, August 7, the Team further refined the technology matrix and prioritized the remediation technologies that were most applicable to the leachate treatment. The meeting concluded with a closeout session at which the Team briefed FEMP personnel with a draft summary of the report and invited feedback for improving the final product.

## Background

The OSDF was designed to contain debris and contaminated soil from the decommissioning and decontamination activities at Fernald. The waste acceptance criteria allow a variety of materials to be put into the facility but the principle contaminant of concern is uranium. The OSDF was built on the east side of FEMP because the thickness of the gray clay layer that overlies the Great Miami Aquifer would provide the most protection to the aquifer in this part of the Site. Construction of the first of seven cells began in December 1997. The cells will cover an area 800 feet east to west and 4300 feet north to south with a maximum height of 65 feet. The cells are expected to contain 2.5 million cubic yards of impacted material. It is expected that approximately 80 percent of the material will be impacted soil and the remaining 20 percent will consist of building demolition rubble, fly ash, lime sludge, and small amounts of miscellaneous materials. The first cell was permanently capped in December 2001 and Cells 2 and 3 are being actively filled, with capping expected during the next couple of years. Each cell has a redundant leachate collection system and a leak detection system. Each cell currently has a valve control house that collects leachate and pumps it to the Advanced Waste Water Treatment facility. The most significant contaminant of concern expected and observed to date in the leachate is uranium. Other contaminants (i.e., boron, TOC and TOX) have been observed in the leachate, but are not expected to be significant.

## Critical Issues

1. Protection of the Great Miami Aquifer.
2. The Site needs a leachate treatment alternative to the Advanced Waste Water Treatment Facility in place by the end of FY 2007, the Site's closure deadline.
3. Discharge to the Miami River must not exceed 30 parts per billion (ppb) of uranium on an average monthly basis (600 pounds annually).
4. The solution design must handle a wide range of volumes, stabilizing around an estimated 1000 gallons/month/cell just after closure (much higher during completion and initial operation of each cell). Initial volumes are to be processed through the Advanced Waste Water Treatment Facility until its closure.
5. The Site would like a technically mature solution. If materials are required, the Site wants them to be available commercially in the quantities needed.
6. The Site also considers that the passiveness of the technology to be used is important, since it would bound any potential treatment technology. The site defines 'passive technology' as one that primarily utilizes gravity flow of the leachate and has minimal requirements for electrical energy, other utilities, and maintenance, e.g., only annual or semi-annual maintenance.
7. The regulators and the site may also be concerned with poking a hole in the caps for leachate recirculation. One of the selling points for the cell was that once capped it would dry up, and the integrity of cell would be 'guaranteed'.
8. Public sensitivity – Although generally in alignment with the regulators, the public could potentially be concerned with sending surface water to wetlands. In general, the public is concerned with exposure scenarios, despite completion of remediation.

## **Unresolved Issues**

1. The Site should determine how much leachate flow is expected from the completed cells. This number seems to vary greatly and has a high level of uncertainty, but will be critical for design criteria for any leachate treatment system.
2. There is uncertainty about how the concentration of the contaminants is expected to change through time. However, based on sampling results from Cells 1, 2, and 3, the uranium concentration in the leachate is anticipated to be less than 150 ug/L.

## **Remediation Technology Matrix**

A complete array of physical, chemical, and biological remediation technologies was considered in a matrix evaluation (see Appendix D). Each of these technologies was compared and ranked using the following criteria: effectiveness, ability to obtain permits, ability to implement, health and safety issues, cost, public acceptability, acceptability to the Site, long-term liability, technical maturity, and secondary waste generation. The recommended technologies considered in decreasing rank order were: leachate recirculation, 3M filtration, Self-Assembled Monolayers on Mesoporous Silica (SAMMS) filtration, phosphate, zero-valent iron, reverse osmosis, ion exchange resin (the Site's baseline technology), and thermal evaporation. Hot air drying of the waste mass, constructed wetlands, in situ biostabilization, and ex situ bioreactor were considered but not recommended. Chemical oxidation and reduction, electro-chemical treatment, and natural attenuation were also discussed but not deemed effective for dilute media or leachate treatment and are not believed to be commercially available.

## **Recommendations**

1. The Site should consider recirculation of the leachate, at least for the cells that have not yet been completed. Leachate recirculation would eliminate the need for leachate treatment and would keep all the uranium in the cells. This would also enable the addition of amendments to further stabilize the uranium in the cells. The cost would be the least of any technology considered and could be easily incorporated into the existing landfill cell design. Using this technology will require a design change, but the life cycle cost reduction, lack of secondary waste, and improved health and safety for workers and the public should give this technology high priority. In combination with waste mass amendments, this strategy could eliminate or greatly reduce contaminants in the leachate and the need for any treatment in a fairly short period of time. The leachate collected from all cells could be disposed of in only one or two cells, possibly the last ones constructed. Although adding amendments to all currently uncompleted cells would be desirable, such addition would be particularly recommended for those cells chosen to receive the returned leachate.

2. The Site should also consider the possibility of using a flow-through gravity filtration system to treat the leachate. Using gravity feed to pass the leachate through a filtration/removal system for uranium would minimize cost and maintenance. By adding stabilization amendments to the waste mass, the amount and length of time that the leachate needs to be treated would be greatly reduced. This filtration system could also be used with a recirculation system for the initial higher flow rates and then phased to complete recirculation.
3. The Site should seriously consider amendments to the waste mass to improve stabilization of the uranium in the waste mass for the remaining cells (too late for Cell #1). Phosphate, zero-valent iron, and electron donors for biostimulation could be added to the waste mass prior to final capping or as the waste mass is placed in the cell. The Team does not believe these amendments will affect the cell integrity and should decrease the leaching of uranium. This would reduce cost, the amount of leachate that needs to be treated, and the length of time that the leachate would need to be treated.
4. Whatever leachate treatment strategy is selected, the Site should consider discharging all remaining effluent to constructed wetlands. This would serve as a tertiary treatment for the leachate and be part of the modified end state for FEMP.

## 1.0 ON-SITE DISPOSAL FACILITY BACKGROUND



*Aerial view of the OSDF.*

The On-Site Disposal Facility (OSDF) is located on the eastern side of the Fernald Environmental Management Project (FEMP). Including liner and cover, the OSDF has a depth of 65 feet. It is estimated that approximately 2.5 million cubic yards will be deposited in the facility, 80 percent of which will be impacted soil and 20 percent will be concrete, debris, asbestos, building materials, and various other materials. Within the cells, waste is organized into alternating lifts of soil and debris, with horizontal segregation of the debris according to type (i.e., grouping asbestos material together). Below the cover system and waste mass in each cell, there is a multi-layer liner system, a

leachate collection system (LCS), leak detection system (LDS), and a compacted clay liner.

Seven cells are planned, although only three are currently active. Cell 1 has been filled and capped; Cells 2 and 3 are in the process of being filled. Cell 2 is almost full and will be capped soon. Leachate volumes from Cell 1 have decreased, but have been higher than expected, possibly because infiltrating precipitation from the currently uncapped Cell 2 enters the south side of Cell 1.

Each cell has an associated valve house, through which leachate flows and is monitored.



*Tank for the Leak Detection System in Valve House 1.*

All valve houses are connected and drain by gravity to a pump house. From the pump house, the leachate is transferred to the Advanced Waste Water Treatment facility, where the leachate mixes with other effluents, is treated and discharged to the Miami River. The Site is looking for a passive or low-maintenance treatment method that could replace the current role of the

Advanced Waste Water Treatment facility, which will only be operated until the end of FY 2007. While in previous years the Site has only

discharged 200-300 pounds of uranium to the river annually, this year (2002) it will approach the Record of Decision (ROD) annual limit of 600 pounds, due largely to pumping much higher volumes of groundwater in an effort to accelerate the cleanup of the aquifer. (Comprehensive Stewardship Plan FEMP, 2001).

There are 18 possible constituents that are routinely monitored for in the leachate, but so far only 4 constituents have been detected frequently enough to perform statistical analyses in Cells 1-3: uranium, boron, total organic carbon, and total organic halogens. Of these, the only contaminant of concern is uranium. (Note: The other contaminants could become concerns, depending upon their concentrations in the future.)

The Site is being remediated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) remediation. While no Resource Conservation and Recovery Act (RCRA) permit is required, the OSDF has been designed to meet the Applicable, Relevant, and Appropriate Requirements of RCRA Subtitle C. The OSDF is located within a Corrective Action Management Unit (Comprehensive Stewardship Plan FEMP, 2001).

## **2.0 ISSUES ANALYSIS**

A number of critical and unresolved issues emerged during the briefings and discussions.

### **3.1 Critical Issues**

The Team defined critical issues as factors that influence and bound the final remedial decision.

1. Protection of the Great Miami Aquifer. The Site is located on a layer of glacial overburden, consisting of clay and silt interspersed with sand and gravel, overlying the Great Miami Aquifer, which is exposed in Paddys Run (a creek that flows into the Miami River, about 1.5 miles south of the Site) and one of the Site's storm sewer outfall ditches, along the western boundary.
2. The Site needs a leachate treatment alternative prior to the closure of the Advanced Waste Water Treatment facility by the end of FY 2007, the closure deadline for the Site.
3. Discharge to the Miami River must not exceed 30 parts per billion (ppb) of uranium on a monthly average (600 pounds annually). Further, a discharge pathway must be defined in the solution, as it is possible for leachate to be discharged directly in the Miami River, if contaminants of concern are at appropriate concentrations, or in the wetland areas along Paddys Run.
4. The solution design must handle a wide range of leachate volumes, estimated to stabilize around 1,000 gallons/month/cell shortly after closure of the last cell. Anticipated volumes for leachate from the cells are difficult to estimate; a Site Project Team member offered 1,000 gal/month/cell as a high-end estimate, noting that volumes will be much higher during completion and initial operation of each cell. Currently 6 cells are planned, but a seventh will likely be added, making the total leachate volume for treatment design in the range of 6-7,000 gallons/month initially; then the volume is anticipated to decline gradually into numbers approaching the post closure design flow rates.

5. Technically mature solution – As Fernald is scheduled to close by 2007, the Site would like a technically mature solution. If materials are required, the Site wants them to be available commercially in the quantities needed.
6. The Site also considers that the passiveness of the technology to be used is important, since it would bound any potential treatment technology. The site defines ‘passive technology’ as one that primarily utilizes gravity flow of the leachate, has minimal requirements for electrical energy, other utilities, and maintenance, e.g., only annual or semi-annual maintenance.
7. The regulators and the site may also be concerned with poking a hole in the caps for leachate recirculation. One of the selling points for the cell was that once capped it would dry up, and the integrity of the cell would be “guaranteed.”
8. Public sensitivity – Although generally in alignment with the regulators, the public could potentially be concerned with sending surface water to wetlands. In general, the public is concerned with exposure scenarios, despite completion of remediation.

## **2.2 Unresolved Issues**

The Team identified the following unresolved issues:

1. The Site should determine how much leachate flow is expected from the completed cells. This number seems to vary greatly and has a high level of uncertainty, but will be critical for design criteria for any leachate treatment system. (Note: The site has stated that the leachate flow volume is indeterminate at this time. The design estimate of the post-closure LCS flow rate is much less than what is being observed in Cell 1, which was closed in 2001. Cell 1 LCS volume for July 2002 was 3540 gallons, down from 5050 gallons in May 2002 and 6300 gallons in November 2001.)
2. The expected variation in concentrations of the contaminants through time is uncertain. However, they will likely stay within a range that can be estimated, e.g., based on sampling results from Cells 1, 2, and 3, the uranium concentration in the leachate is anticipated to be less than 150 ug/L.

## **3.0 REMEDIATION TECHNOLOGIES EVALUATION**

The Team evaluated several remedial technologies to treat the leachate from the OSDF. Appendix D lists the strategies in prioritized order. Below is a discussion of the technologies, grouped by remedial strategy: physical, chemical, or biological.

In addition, as an overarching treatment to be used in combination with the technologies described below, the Team discussed the possibility of amending the waste material to reduce the amount of uranium in the leachate. Several soil amendments that are commercially available have demonstrated success at reducing the leachability of uranium from soil. Soil amendments adsorb uranium to reactive surfaces, chemically react with soluble uranium creating relatively insoluble minerals (e.g., uranium-phosphate compounds), or create reducing conditions that encourage microbial populations that will directly or indirectly reduce soluble uranium to form less soluble compounds. Stabilization and treatment amendments include ZVI, apatite, other phosphate stabilizers (Ecobond© and others), electron donors, including Hydrogen

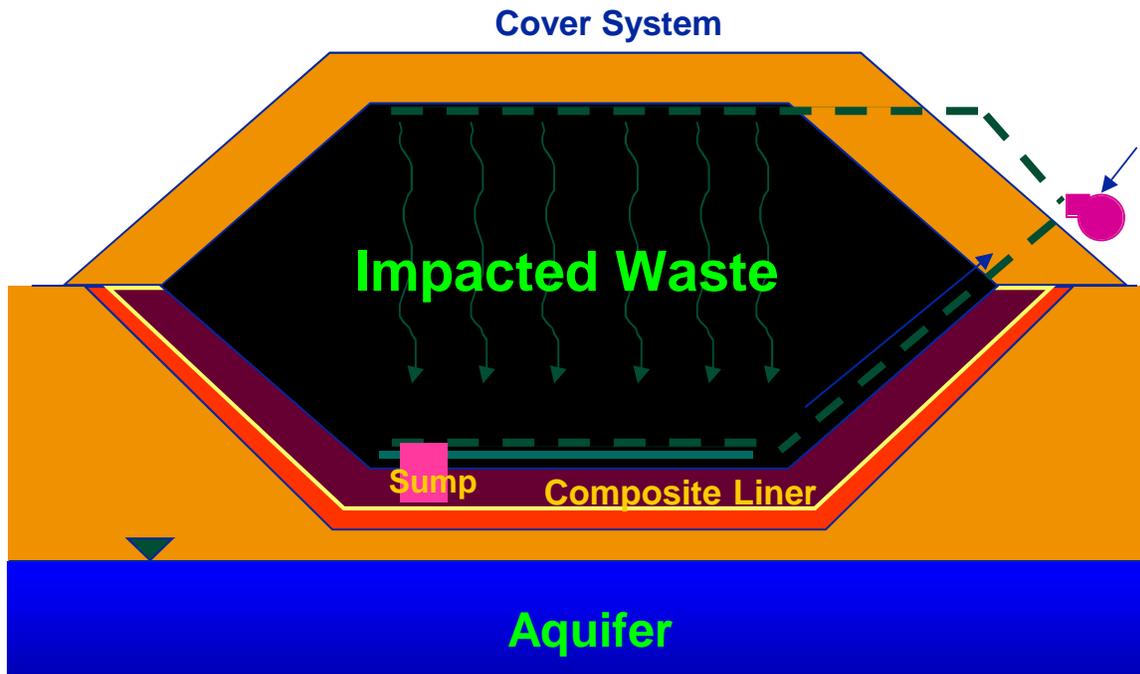
Release Compound (HRC© from Regenesis, i.e., polylactate) and other lactate compounds (NorthWind).

### 3.1 Physical Strategies

Physical strategies evaluated were: leachate recirculation with air injection, reverse osmosis, thermal evaporation (in-drum), and hot air drying. Technologies are discussed in priority order. All are recommended except hot air drying.

#### 3.1.1 Leachate Recirculation (with air injection as an option)

In leachate recirculation, the leachate is reinjected back into the cell, eliminating any discharge. In part, this is based on the fact that drainage into the leachate collection system will decline even as the leachate water is returned to the top of the cell. Possible mechanisms for supporting such a decline include loss of water vapor from the cell and consumption in in-situ chemical reactions, including formation of hydrous metal oxides from corrosion of steel and other structural metals, as well as metals from processing operations. Such processes might also lead to more reducing (or at least less oxidizing) conditions, which would tend to reduce uranium mobility. Another option would be to inject air, which could help accelerate the above hydrolysis reactions. However, as long as air injection is done, it will help maintain oxidizing conditions. The distribution of water in the waste mass of landfills is always very heterogeneous, so that even with water accumulating at the bottom, there are many areas within the landfill that are quite dry. Leachate recirculation will evenly distribute this moisture over the entire refuse mass, thereby greatly increasing the moisture that the waste mass is retaining. These types of phenomena have been extensively studied in municipal solid waste landfills for a number of years (Reinhard and Townsend, 1998).



*Leachate recirculation*

One potential downside of leachate recirculation is that drainage into the leachate collection system might fail to decline. Currently, no detailed models of the hydraulic and chemical conditions in these cells exist, even for the baseline case. Before leachate recirculation is attempted, a quantitative numerical model should be developed to allow predictions of baseline and modified designs. The Help model used to estimate the LCS/LDS flow rates for the cell design was inadequate for this type of need. This modeling should focus on liquid and gas phase transport, the relevant chemical processes, and include at least a two-dimensional representation of the model systems. Modeling the gas phase transport and the chemical reactions will enable determinations of long-term stability of the metal components, abiotic and biotic degradation of hazardous organics, and rates of reactions for more accurate predictions of leachate quality and quantity for the contaminants of concern. The cost of developing, calibrating, and validating such a model, as well as related schedule impacts, needs to be considered.

Another potential downside is that if this strategy were to be applied to Cell 1, the cap in Cell 1 would have to be penetrated to return the leachate to the cell. Breaching the bottom of the cap apron might also be required to facilitate the egress of injected air, though this may not be necessary if the current design allows venting. These points of penetration would have to be carefully engineered to prevent possible points of entry for water (apart from the returned leachate). Also, any significant pressurization of the inside of the cell by air injection should be avoided. Methods to seal points of penetration should be developed. Penetration of the cap could be accomplished in a manner similar to the penetration that is already being done for leachate collection.

Concentrating the leachate prior to reinjection could also facilitate the dewatering of the cells. This could be accomplished through methods such as evaporative concentration or reverse osmosis. The only advantage this might have is in eliminating the need to dispose of an additional waste stream since the concentrated material would be added back to the cell.

Another potential problem is the effect of air injection on the concentration of uranium in the leachate, as it may promote the oxidation of uranium to uranium (VI), which tends to be soluble. However, air injection may also promote the oxidation of organics, including complexing ligands whose presence would tend to increase uranium solubility. Also, the oxidation of steel to form hydrous ferric oxides provides additional substrate for uranium sorption. Generally, the air injection should have a beneficial effect since it can easily be incorporated into the leachate collection system with some general-purpose blowers (Reinhard and Townsend, 1998; Oldenburg, 2001).

Overall, the effectiveness of recirculating the leachate could be high, as there would be no discharge. A revised Record of Decision would be required. Although F039 waste would be created, it would be returned to the cell. In terms of technical maturity, this technique is not how Subtitle C remediations have been done in the past, although the technological pieces are simple and known from other applications. The recommended computer model for the hydrology and chemistry inside the cell represents a leap forward in the present type of application, but similar models have been constructed for other applications. Examples would include Yucca Mountain thermohydrology and reactive transport models (e.g., Doughty and Bodvarsson, 1996; Sonnenthal et al., 1997; Hardin et

al., 1998), though something less sophisticated (and that runs on a personal computer) would be more appropriate in the present case. The reactive transport code developed for Yucca Mountain, TOUGH2, has recently been modified for use in modeling landfill bioreactors that use leachate recirculation and air injection, T2LBM (Oldenburg, 2001).

Leachate recirculation is an established and proven technology for municipal solid waste (Subtitle D) landfills. It has been used for decades to increase the stabilization rate of the landfill, improve leachate quality and decrease leachate treatment costs (Reinhart and Townsend, 1998; Senior, 1995). Though municipal solid waste has a much higher organic carbon content, the fundamental concepts can be applied in a similar fashion to the OSDF to reduce or eliminate the need for leachate treatment, especially as the leachate volume produced from the OSDF declines over time. This approach is likely to be considered highly desirable by the public since uranium exposure and transport out of the waste mass are minimized. As long as cap integrity is protected, the regulators are likely to approve this strategy.

The costs involve a simple irrigation system pump to trickle the leachate back into the waste mass just below the cap. The existing leachate collection system could be easily and cheaply modified at the time the cap is installed by installing the irrigation system on top of the waste mass and below the cap. Another option that could also be considered is the use of just the last one or two cells to contain the leachate from all the cells. (Note: This option has a drawback in that the thickness of the glacial clay decreases toward the south - recirculating all the leachate in the last cell or two might not be recommended.) This option could be viable if the amount of leachate from the cells is quite low, but would require modeling verification. This option would also further minimize the installation costs. Typically these types of leachate recirculation systems have been installed for less than \$10,000 in municipal landfills this size. Maintenance and monitoring are minimal and could be easily incorporated into the leachate collection system monitoring that will already be required.

For the air injection option, the major capital cost will be the blowers. Blowers used for landfill injection typically generate 250 sqfm at a 6-inch backpressure and cost <\$2,000 (e.g., Sweetwater, Inc.). Each cell may require only 1, or at most 3, of these blowers and could be installed in the existing valve house with the power that is already present. These blowers have been used in landfill operations reliably for several years of continuous operation.

### ***3.1.2 Reverse Osmosis***

Reverse osmosis is a membrane separation process that effectively removes ions from water by allowing water to diffuse through the membrane under high pressure while the membrane rejects the ions. The process works by applying the appropriate pressure to the system to overcome the osmotic pressure and drive the water from the dissolved solids side of the membrane to the pure-water side. This process would be successful in removing the uranium in the leachate at the FEMP. In addition to the uranium removal, reverse osmosis would also successfully remove other constituents present in the leachate. Reverse osmosis systems are used in drinking water treatment, desalination, ultra pure water production, and industrial process water production (Mallevalle, et al.,

1996). As a result of this maturity in the technology, permitting and implementation at the FEMP are considered to be feasible.

Reverse osmosis is mature and scales well to meet any flow rate. Cost would be medium due to membrane replacement and concentrate handling. The uranium-containing concentrate and other waste streams make the long-term liability and secondary waste streams high. The health and safety risks are considered medium due to the waste streams. Acceptability to the public and the Site are considered high due to the effective removal of all species. Overall, the Team recommends reverse osmosis as a better strategy than the baseline, but other technologies may be more suitable. The principal attributes that make reverse osmosis better than the baseline are the large number of applications and vendors, lower cost, smaller foot print, smaller secondary waste disposal (no resin to dispose of as mixed waste), and lower maintenance that these types of systems typically have.

### ***3.1.3 Thermal Evaporation (in-drum)***

Thermal evaporation could be deployed either in-drum or as a comparable unit process. With in-drum evaporation, the leachate is evaporated to a solid in drums heated with electrical heaters. The solidified waste is then shipped to an appropriate disposal facility. This would have a relatively high cost of operation due to increased energy usage and operation requirements for workers. It is also possible that any organic constituents could volatilize, presenting a concern with air emissions. Application would be relatively simple, by placing an in-drum evaporation unit in each of the valve houses or a larger unit located after the last cell's valve house. However, this option would not be truly feasible until the initial volume surge had passed. Depending on experience developed as the newer cells are closed and capped, this approach might be appropriately phased in as the wastewater treatment facility is deactivated.

### ***3.1.4 Hot Air Drying***

Hot air drying involves pumping hot air through the cell to remove water. In theory, if the cap performs well, the LCS discharge should be reduced. Evaluation of this approach would require the development of a thermohydrologic computer model of the cell, tracking both the liquid and vapor phase of water. Such a model would require calibration and validation.

This technology also requires penetrating the cell cap, and therefore shares similarities, both positive and negative, with the leachate recirculation/air injection approach. An additional point of concern is that the mechanical properties of the cell or any of its key components might be compromised by too much heating or drying. Related testing and/or modeling would be required to show that such compromise could be avoided. Significant amounts of energy would be required to heat and inject the air.

The effectiveness and acceptability of this method could be high, as discharge would be virtually nonexistent (though that is not guaranteed). Coupling hot air drying with another method would enhance acceptability, although it should be noted that this approach has not been attempted at this scale. The Team does not recommend hot air

drying as a remediation technology for the leachate from the OSDF, due to concerns about the long-term cell stability.

## **3.2 Chemical Strategies**

Chemical treatment strategies evaluated were: 3M uranium selective separation cartridges, self-assembled monolayers on mesoporous silica (SAMMS) ion exchange, zero-valent iron and apatite in passive reactive systems, and the baseline technology of ion exchange. Technologies are discussed in priority order. Chemical oxidation and reduction and electrochemical remediation technologies were also considered, but not recommended due to lack of commercial availability, and poor performance when handling dilute waste streams like the OSDF leachate.

### ***3.2.1 3M Uranium Selective Separation Technology***

The 3M Uranium Selective Separation Cartridge (SSC) is an adsorbent depth cartridge in which small, active particles are closely packed, but uniformly dispersed, in a fibrous membrane. These cartridges offer selective removal of uranium from aqueous waste streams in a durable, easy-to-use cartridge system. 3M's adsorbent material was successfully tested last summer on uranium-contaminated groundwater from the Great Miami Aquifer beneath the FEMP. As a result of that test, the SSCs were considered a viable technology to treat OSDF leachate. Concurrent Technologies Corporation is currently conducting a treatability study using the uranium SSC for treating OSDF leachate. The 3M technology would be comparable to reverse osmosis to implement in terms of mobilization and capital costs, but would require less maintenance and energy and have an even smaller foot print.

Because of the successful demonstration on Fernald groundwater, 3M uranium SSCs are believed to have a high potential for providing long-term treatment of OSDF leachate. The technology will be easy to implement, most likely being situated in-line to passively treat leachate via gravity drainage, though pumping through the cartridge may be necessary if a significant backpressure develops. However, the overall effectiveness of such a technology approach is deemed medium to high (as opposed to the apparent possibility of a "high" rating) because, as a filtration technology, the SSCs will result in effluent water that will require monitoring and management. The Team rated the technology favorably in the areas of ability to permit, ability to implement, acceptability to the public and the Site, and technical maturity. The technology rated "medium" in areas relating to long-term liability because as a filtration technology, routine sampling will be required to ensure that breakthrough does not occur, and a uranium-contaminated waste (the spent cartridge) will require handling, shipping and disposal.

### ***3.2.2 Ion Exchange – SAMMS***

Self-assembled monolayers on mesoporous silica (SAMMS) is a high efficiency, high capacity material developed with an actinide-specific coating designed to remove actinides from solutions. The material has a large surface area, typically on the order of 1000 m<sup>2</sup>/g, with distribution coefficients for uranium as high as 160,000. The kinetics is fast, with 99 percent removal in one minute. With the alumino-silicate backbone, the

material does not suffer attrition like resin-based ion exchange media and survives regeneration well (Fryxell, et al., 2001).

One major drawback is a lack of commercial quantities of the material, although these should be available by the end of the FY02. The available monolayers have been shown to be highly selective for the contaminants tested, but the material has not been demonstrated in a full-scale application, making the technical maturity low.

It is believed that if this technology were available, its ability to be implemented and permitted would be good since it is similar to the baseline ion exchange process. For the same reason, acceptability to the public and the Site are expected to be high. Health and safety issues would be medium, given that the material would need to be handled for disposal. However, the residuals would be low in volume due to the surface area and loading capacity of the material, making the secondary waste medium. Due to the nature of the residuals, the long-term liability may be medium with the cost low to medium.

### ***3.2.3 Zero-Valent Iron and Apatite in Passive Reactive Systems***

Zero-valent iron and apatite have each been demonstrated to effectively remove uranium from contaminated groundwater (for zero-valent iron, see Gu et al., 1998; for apatite, see Bostick et al., 2000). In general, zero-valent iron removes uranium by redox-driven precipitation and sorption to the iron; apatite treatment results in the formation of low solubility uranium-phosphate minerals.

The system envisioned for treating OSDF leachate is based on the design of the Rocky Flats Mound Plume treatment system. The Rocky Flats system utilizes a passive treatment approach whereby gravity drainage drives the flow of water through two treatment cells set up in parallel. Permit issues are not believed to be significant and annual costs are expected to be low to medium, as the system would only require periodic monitoring. Waste disposal will be a periodic, but predictable event; however, handling, shipping and disposal are issues that will need to be considered. An additional concern is the development of biofilms, which have been observed in association with zero-valent iron reactive barriers, but the effect on treatment has, so far, been found to be negligible. Biofilm development will be a concern if the treatment approach results in surface disposal of the effluent.

The potential effectiveness of the approach for apatite is deemed medium because apatite has not been used specifically for this type of application. Zero-valent iron has been demonstrated as effective when treating uranium in similarly designed systems. However, since the technology solution results in an effluent stream requiring monitoring and generally, some form of management, the overall effectiveness of this sort of approach is considered medium to high.

### ***3.2.4 Ion Exchange (baseline)***

Ion exchange technology is currently the baseline solution for uranium removal at the FEMP. Commercial grade ion exchange media are used to remove the uranium from groundwater pump and treat waste streams and leachate from the OSDF. The current system uses DOWEX 21K 16-30-mesh resin to remove the uranium. Dowex 21K is a

strong base anion type resin with a quaternary amine functional group manufactured by Dow Chemical Company. The system is effective and is already implemented and permitted. Thus, the technology is mature, with high public and Site acceptance.

Regeneration of the resin results in the uranium being concentrated in the regeneration brine, which causes some problems, and, as a result, the secondary waste is high. Given the probable low post-closure volumes/concentrations to treat, the resin would last a long time before becoming spent or before breakthrough of an unacceptably high effluent concentration. The FEMP would probably just dispose of spent resin and replace it with new rather than regenerating the resin. Disposal of the spent resin would be a significant cost since it likely to be considered mixed waste due the high concentrations of hazardous organics and metals that accumulate in the resin beds. The long-term liability and health and safety are considered medium due to the waste streams generated by the technology. Maintenance and operations result in a medium cost classification.

### ***3.2.5 Chemical Oxidation/Reduction and Electrochemical Remediation Technologies***

The technical assistance Team was unable to identify any commercially available treatment technologies in these categories that would be appropriate for the treatment of the leachate. There are probably several precipitation type agents, but none were identified as having been demonstrated as effective at less than 30 ppb. Electrochemical remediation technologies have been reported as effective in Europe, but no data were available to support these technologies. The dilute nature of the leachate would also make the practical application difficult and costly relative to other potential solutions.

## **3.3 Biological Strategies**

Biological strategies involve the adsorption, bioaccumulation and concentration, or reduction/oxidation of contaminants into other compounds that are less soluble, less toxic and less reactive. Because of their low maturity for these types of applications and because of their potential for being much higher cost than most of the other technologies considered, none of the biological strategies are recommended as stand-alone solutions. However, the constructed wetlands and the in situ biostabilization approaches could be incorporated into a treatment train with other strategies being considered and simultaneously reduce cost and provide a better long-term solution for the final disposition of the leachate.

### ***3.3.1 Constructed Wetlands***

The wetlands approach involves discharging the collected leachate from the OSDF to a constructed wetland. This is a relatively passive approach. No or minimal discharge to the Miami River is expected. The uranium in the leachate would be deposited in wetland sediments or absorbed into the vegetation. This may be one of the major drawbacks of this option. If the wetland dries up, the sediments may become airborne and be released from the FEMP. The uranium may also be spread to the public by waterfowl landing in the wetland, feeding on the vegetation, leaving the wetland, and depositing their wastes at other locations. The wetlands may also offer attractive nuisance opportunities for unapproved visitors looking for a place to swim or fish. To prevent this, it would be necessary to maintain secure fences and property boundaries.

The cost of construction for the wetland may be higher than the expected capital cost of other treatment technologies. However, once constructed, the wetlands should have a lower cost of operation than most other approaches. Constructed wetlands alone as an approach may not be well-received by the public and regulators due to the perception that the uranium will directly enter the groundwater or that other dispersal to the environment may take place. It may be possible to use the uranium surface water limit of 530 ppb for acceptance and justification for use of this type of system.

Constructed wetlands are a mature technology for tertiary and even secondary treatment of municipal and industrial effluents and have been tested on a small scale for effluents with actinides; however, the technical assistance Team was not aware of any long-term or large-scale applications that would provide the necessary data to verify the efficacy and overall risk (Banaszak et al., 1999).

The Site has indicated interest in incorporating wetlands into a remediation strategy as a modified end state. After undergoing treatment, leachate could be discharged to constructed wetlands that would provide tertiary treatment, e.g., the leachate could be passed through an apatite or zero-valent iron bed or combination of both before going to the wetland. This approach would provide better control of contaminants that might be in the leachate and minimize and potential contamination and increased environmental risk posed by the wetlands.

### ***3.3.2 In Situ Biostabilization – Active and Passive***

Anaerobic bioremediation is a proven technology in which anaerobic microorganisms degrade organic compounds by the mechanism of reductive metabolism. It has also been demonstrated that a number of metals can also be transformed into less soluble forms by the same mechanism, e.g., chromium, uranium (Banaszak et al., 1999). This type of microbial activity requires strongly anaerobic conditions and the presence of anaerobic microorganisms possessing reductive capability. In cases where natural conditions do not support active anaerobic reduction, biostimulation (addition of carbon sources to produce anaerobic conditions) is commonly deployed to achieve in situ anaerobic biodegradation of organics and biotransformation of metals and radionuclides. Water and macronutrient additions (primarily nitrogen and phosphorous) may also be required. Active biostimulation of the waste mass in the cells would require a leachate recirculation system that would allow addition of organics and macronutrients.

The effectiveness of biostabilization strategies for uranium have an uncertainty as to their long-term stability and their effectiveness under normal environmental conditions, though laboratory studies show great promise. Hydrogen Release Compound (HRC) has already been injected into a uranium-contaminated aquifer at the Ashtabula Site (SCFA Technical Assistance Request #141). HRC was a good choice as an electron donor for biostimulation of indigenous microbes. HRC is a polylactate compound that slowly releases lactate when mixed with water. The released lactic acid stimulates both aerobic and anaerobic microbes by providing a carbon and energy source. Anaerobic microbes ferment the lactic acid into pyruvic acid and then to acetic acid, releasing 2 moles of molecular hydrogen per mole of lactate. Investigations conducted by Regenesys, Ltd., showed that the slow release characteristics of HRC cause reducing conditions to be

maintained for a long time (up to 18 months) with a single HRC application. Compounds like HRC could also be applied passively. In this case, the electron donor would be added to the waste mass before the completion of the cap. This could create reducing conditions that would immobilize the uranium and reduce its leaching. The uranium would remain immobile as long as reducing conditions were maintained, which could be a very long time if the cell remained impermeable to sources of oxidizing conditions.

It is probable that a biotreatability study would be required for biostabilization of soils at Fernald. This study would demonstrate feasibility and provide an opportunity to optimize the bioprocess for Fernald soils. However, this would increase the cost and time required for regulatory approval.

### **3.3.3 *Ex Situ Bioreactor***

Bioreduction and precipitation or direct biomass adsorption of heavy metals and uranium is a proven technology that has had numerous commercial applications. The algae *Chlorella* has been used to directly adsorb metals, including actinides, in effluents from industrial processes. It has also been demonstrated that the uranium can be removed from aqueous streams by bioprecipitation of phosphate solids (Banaszak et al., 1999). Still others have shown that fluidized bed bioreactor systems can be used to remove nitrates and other organic contaminants and co-precipitate uranium when other metal species are present, e.g., aluminum.

This strategy could potentially treat the leachate to the necessary uranium concentrations; however, the costs of construction and operation and maintenance of one or more large bioreactors would be much greater than almost any of the other strategies considered. The advantage would be that any additional organic that might appear in the leachate would also be destroyed in the bioreactor. The secondary waste stream, which would include precipitate and contaminated biomass, would be much more difficult to handle than the other waste streams. The operation would require careful monitoring and has the potential for catastrophic upset if unusual influents reached the bioreactor or there were power outages, etc. The Team did not recommend this strategy as a stand-alone treatment or even as a secondary treatment when combined with in situ stabilization.

## **3.4 In Situ Stabilization Strategies**

Stabilization technologies are part of the broad category of soil treatment technologies termed "solidification/stabilization." Solidification generally refers to processes that encapsulate the waste material in a high integrity monolithic solid (e.g., cementation, polymer encapsulation), thereby reducing or minimizing contaminant solubility, mobility, and toxicity. Stabilization processes generally employ chemical reactions to convert or change the molecular characteristics of the contaminants, thereby making the waste constituents less leachable (soluble), mobile, or toxic. Similar to solidification, some stabilization technologies result in a solidified or semi-solidified product. Further, most solidification and stabilization technologies can be implemented both in situ as well as ex situ. Solidification technologies were not considered because of the need for compaction of the waste material in the disposal cell.

Stabilization amendments such as apatite, proprietary phosphate products such as EcoBond™, biostimulators (as discussed in 3.3.2), and zero-valent iron have been shown to be effective at reducing the leachability of uranium from contaminated soil. The various treatments react with the uranium in soil pore water, producing mineral precipitates with very low solubility products. These mineral phases then adsorb on the soil matrix, thereby removing them from the leaching transport pathway.

Stabilization amendments may be applied both in situ and ex situ. In the case of apatite, phosphate bonding agents and zero-valent iron, the simplest application would be to amend the waste soil ex situ prior to dispersal in the cell. The general action of dumping, spreading and grading would result in sufficient mixing to ensure proper treatment. Most stabilization amendments provide treatment at ambient soil moisture levels, and, in the case of the OSDF, the additional water applied for dust control will ensure complete contact of uranium with the treatment media. The large amount of iron debris being added to the cells could in fact already be contributing to the zero-valent iron type of reactions that are bonding the uranium to the waste mass soil.

All of the remediation strategies considered for the leachate would benefit from in situ stabilization since the amount of uranium could be significantly reduced in the leachate, thus reducing the amount of treatment necessary and potentially reducing the time until the waste mass is stable and no longer leaching uranium.

#### **4.0 SUMMARY AND CONCLUSIONS**

During the closeout session, members of the Team conveyed to the Site how impressed they were at the thoroughness of the Site's investigation and consideration of cost options for remediation. The following overall recommendations were agreed upon:

1. The Site should consider recirculation of the leachate, at least for the cells that have not yet been completed. Leachate recirculation would eliminate the need for leachate treatment and would keep all the uranium in the cell. This would also enable the addition of amendments to further stabilize the uranium in the cell. The cost would be the least of any technology considered and could be easily incorporated into the existing landfill cell design. Using this technology would require a design change, but the life cycle cost reduction, lack of secondary waste, and improved health and safety for workers and the public should give this technology high priority. In combination with waste mass stabilization amendments, this strategy could eliminate or greatly reduce contaminants in the leachate and the need for any treatment in a fairly short period of time.
2. The Site should also consider the possibility of using a flow-through gravity filtration system to treat the leachate. Using gravity feed to pass the leachate through a filtration/removal system for uranium would minimize cost and maintenance. By adding stabilization amendments to the waste mass, the amount and length of time that the leachate needs to be treated would be greatly reduced. This filtration system could also be used with a recirculation system for the initial higher flow rates and then phased to complete recirculation.
3. The Site should seriously consider amendments to the waste mass to improve stabilization of the uranium. Phosphate, zero-valent iron, and electron donors for biostimulation could be added to the waste mass prior to final capping or as the waste

mass is placed in the cell. The Team does not believe these amendments will affect the cell integrity and should decrease the leaching of uranium. This would reduce cost, the amount of leachate that needs to be treated, and the length of time that the leachate would need to be treated.

4. Whatever leachate treatment strategy is selected, the Site should consider discharging outfall to constructed wetlands. This would serve as a tertiary treatment for the leachate and be part of the modified end state for the FEMP.

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**APPENDIX A PARTICIPANTS AND CONTACT INFORMATION**

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Fernald Environmental Management Project, Ohio  
August 6-7, 2002**

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\*Although not in attendance at the meeting, Malcolm Siegel provided an external review of the report; the technical assistance Team expresses its gratitude for this service.

**APPENDIX B**

**TECHNICAL ASSISTANCE TEAM EXPERTISE**

**THOMAS A. ANDERSON**

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***Education:***

M.S. in Environmental Science/Engineering, Colorado School of Mines  
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***Areas of Expertise:***

Mr. Anderson has over 12 years of experience in technical and field project management roles in the environmental science and engineering arena. He has a diverse background including project development and work plan preparation, fieldwork, data analysis and final report writing. He has developed and carried out work plans for soil, surface water and groundwater investigations at Superfund sites; RCRA mandated surface impoundment closures; and for leaking underground storage tank sites. His field experience includes: soil gas sampling; borehole logging; monitoring well installation and development; soil, groundwater, and surface water sampling; aquifer parameter testing using slug tests, pump tests, and packer tests. He has experience evaluation treatment alternatives for groundwater and soil remediation, calculating risk-based clean-up goals, estimating the fate and transport of contaminants in the subsurface, and using probabilistic methods for exposure and risk assessments, including the use of geostatistical methods for estimating contaminant distribution.

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***Education:***

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B.S. in Chemistry, South Dakota School of Mines and Technology

***Areas of Expertise:***

David L. Eaton is a regulatory specialist for the Transuranic & Mixed Waste Focus Area. He is responsible for providing regulatory support to research and development activities that support the DOE complex's need for mixed waste treatment technologies. His primary responsibility is to remove or resolve regulatory barriers to the implementation of appropriate treatment technologies. These activities include helping technology developers understand development requirements driven by both current and developing regulations in addition to complying with current waste management regulations. Mr.

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Eaton also coordinates several workgroups comprised of DOE, DOE contractors, EPA, and State regulatory personnel in their efforts to work together to ensure that treatment options are available and permitted for meeting DOE's treatment needs. Mr. Eaton has spent the last 28 years resolving environmental and regulatory issues. Prior to joining INEEL, he worked in the phosphate fertilizer industry, as well as in EPA and State government.

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Ms. Eddy-Dilek is a research scientist in the Environmental Restoration Technology Section at the Savannah River Technology Center, the research and development laboratory supporting SRS. Her responsibilities have included many aspects of applied research related to characterization of hazardous waste sites and monitoring and performance assessment of remedial technologies. This work has a strong geotechnical, geological, and geohydrologic basis. For the last four years, she has been the lead investigator for the DOE's cone penetrometer sensor testing and evaluation program and has been actively involved in the development, evaluation, and application of new sensors and approaches for site characterization and monitoring. During 1998-1999, she led the site characterization efforts for the Interagency DNAPL Consortium Program at the Cape Canaveral Air Station, Florida, a joint EPA-NASA-DoD-DOE program for evaluation of innovative technologies for DNAPL remediation.

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***Education:***

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***Areas of Expertise:***

Dr. Hazen's area of specialty is environmental microbiology, especially as it relates to bioremediation. His current research is focused on aerobic bioremediation of landfills, PAH contaminated soil, solvent contaminated soil and groundwater, and actinide biogeochemistry. Since early 1998, Dr. Hazen has been Head of the Microbial Ecology and Environmental Engineering Department and Lead Scientist for the Environmental Remediation Technology Program in the LBNL Earth Sciences Division. Since September 1999 he has also been head of the Center for Environmental Biotechnology. He is a fellow of the American Academy of Microbiology and has authored more than 151 scientific publications, not including more than 390 abstracts and chapters in several books. He has also given more than 670 scientific presentations, 75% of them invited. Dr. Hazen received the 1995 R&D 100 Award, 1996 R&D 100 Award, and the 1996 Federal Laboratory Consortium Excellence in Technology Transfer for bioremediation technologies. He has patents on 5 bioremediation processes that are being used in 15 states; these technologies have been licensed to more than 30 companies. Dr. Hazen has acted as an expert reviewer for 25 different scientific journals and 14 federal research granting agencies. He has supervised and consulted on the implementation of bioremediation at more than 50 sites in several countries. He is currently the LBNL representative to the DOE EM50 Strategic Lab Council, the DOE Natural and Accelerated Bioremediation Research Program Field Research Center, the EM50 Subsurface Contaminant Focus Area Lead Lab POC, and the EM50 lead for LBNL. He was recently appointed to the United Nations Global Water Quality Task Force, one of only two US scientists.

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M.S. in Mathematics, Montana State University  
B.S. in Applied Mathematics, Montana College of Mineral Science and Technology

***Areas of Expertise:***

Dr. Wend is a registered Professional Engineer in the field of Environmental Engineering. His doctoral research investigated biofouling reduction in membrane water treatment processes and his areas of expertise include biofilms, water treatment, water chemistry, membrane desalination, process engineering, and modeling. As an Environmental Engineer, he is knowledgeable in the areas of wastewater treatment, water chemistry, groundwater hydrology, contaminant hydrogeology, hazardous and solid waste management, air pollution control, microbial processes, and water microbiology.

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At Pacific Northwest National Laboratory, he has been the principal investigator for the preparation, testing, and delivery of an actinide specific self-assembled monolayer on mesoporous silica (SAMMS) material to ANL. He has also worked on disposal treatment requirements for spent silver mordenite; provided biofilm expertise for the development of acoustic microscope in biofilm systems; developed preliminary design, cost, and water quality information for membrane wastewater reuse in Mexico City, Mexico; and conducted a risk uncertainty and analysis for the Hanford Tank Program.

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**THOMAS J. WOLERY**

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***Education:***

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***Areas of Expertise:***

Dr. Wolery is the principal developer of the software package EQ3/6, an internationally recognized code package for thermodynamic and kinetic modeling of rock/water interactions. Dr. Wolery has conducted or participated in various modeling studies for the Salt Repository Project, WIPP, and Yucca Mountain Project addressing rock/water interaction, aqueous speciation, and radionuclide solubilities. He is currently the Chemical Environment Modeling & Analysis Lead in the Waste Package Department of the Yucca Mountain Project. He has particular interests in the fundamental theory and application of solution thermodynamics in both aqueous solutions and solid solutions. He is the author of more than three dozen scientific papers and reports on topics including radioactive waste disposal, environmental contamination and remediation, global geochemical cycles, thermodynamics, chemical kinetics, and electrolyte theory.

**APPENDIX C**

**TECHNICAL ASSISTANCE REQUEST**

**Request for an OST Technical Solution**

**Project Title: Solution for Fernald Treatment of Uranium in Brine Ion Exchange Regeneration Fluid and in the Leachate from the On-Site Disposal Facility**

**Section 1 – Required Signatures**

\_\_\_\_\_  
Site Contact or Operable Unit Manager

\_\_\_\_\_  
OST/HQ Program Manager

\_\_\_\_\_  
Site Manager

\_\_\_\_\_  
OST/HQ Office Director

**Section 2 – Point of Contact Information (Contractor Program Manager)**

Name of Requestor: **Dave Brettschneider**

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**Section 2 – Project Information**

Project Title and Location: **Fernald Advanced Waste Water Treatment Project and On-Site Disposal Facility**

Description of Requested Technical Solution: **Convene a Technical Assistance Team of experts to review technologies for the removal of uranium in both brine ion exchange regeneration solution from the Advanced Wastewater Treatment Facility (AWWT) and in the leachate from the Fernald On Site Disposal Facility (OSDF). The team will identify one or more technologies for bench-scale testing as a cost effective alternative to remove uranium so that the brine regeneration solution from the AWWT and the leachate from the OSDF can be discharged without further treatment. The team will prepare a recommended development and demonstration plan for the alternative technologies. Finally, the team will make recommendations for the optimum Technical Solution for Fernald’s problem of field implementation.**

Qualification and Expertise of Person(s) needed to provide the Technical Solution: **The person or persons should have a background in aqueous uranium chemistry, uranium treatment technology, and must understand treatment field operations and closure site schedule needs.**

Type of Deliverable Requested: **Technical Solution Recommendation Report and supporting documentation.**

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Type of Deliverable Requested: **Technical Solution Recommendation Report and supporting documentation.**

Benefits and/or Objectives of Technical Solution: **Schedule acceleration, cost reduction, and long-term stewardship implementation.**

TA Uranium removal comparisons

**APPENDIX D TECHNOLOGY REMEDIATION MATRIX**

Fernald Leachate Treatment

Note: Recommended remediation technologies are listed in priority order.

Remediation Technology	Remediation Strategy	Effectiveness	Permitability	Implementability	Health and Safety Risks	Annual Cost	Public Acceptability	Site Acceptability	Long-Term Liability	Technical Maturity	Secondary Waste	Overall
<b>Leachate Recirculation (with air injection as an option)</b>	Physical	High, since treatment goal is 30 ppb. Not as good for the initial high volume flow.	Medium to High. Requires modifying the ROD, but Site has good relationship with regulators.	Medium with current design; air would not be difficult. Would require changing design.	Low, since contained and there is a cap. No transporting, handling, workers, etc.	Low on annual basis. Potentially only have to monitor the LDS.	Very high because stops discharges to Miami River.	Medium	Low because monitoring and outyear costs not as significant.	Medium – High. New application of commercial technology.	None	Viable
<b>3M Uranium Selective Separation Technology</b>	Chemical	Medium to High	High	High	Medium	Low to Medium; only cost is monitoring for breakthrough	High	High	Medium because of residuals.	High	Medium; higher loading capacity.	Viable
<b>SAMMS (Self Assembled Monolayer on Mesoporous Silica)</b>	Chemical	Medium to High	High	High	Medium	Low to Medium. Only cost is monitoring for breakthrough	High	High	Medium because of residuals.	Low; not commercially available, EMSP report has shown for U	Medium; higher loading capacity.	Viable, pending commercial availability. Higher project risk.
<b>Apatite in passive reaction systems</b>	Chemical	Medium; has not been implemented in this situation	High	Medium	Medium	Low to Medium	Medium	Medium	Medium	High; apatite has been used for U-absorption; widely available as a material	Medium	Viable

Remediation Technology	Remediation Strategy	Effectiveness	Permitability	Implementability	Health and Safety Risks	Annual Cost	Public Acceptability	Site Acceptability	Long-Term Liability	Technical Maturity	Secondary Waste	Overall
<b>Zero-valent Iron in passive reaction systems</b>	Chemical	Medium to High	Medium to High; permeable reactive barriers are widely accepted. Possible problems with TOC, and pH getting too low for NPDES outfall.	Medium to High; easy to implement, but high risk of failure if it dries out... redundancy in design could help here	Medium	Low to Medium; will have to sample, as with resins. Cost to get rid of Fe	Medium	Medium	Medium; monitoring needed	High	Medium	Viable
<b>Reverse Osmosis</b>	Physical	High; good for U. Also work for TOC and TOH.	High	High	High; some handling involved, high pressures.	Medium	Medium to High	High	High because of maintenance and monitoring needed, shipping excess U.	High	High	Viable
<b>Ion Exchange Resin (Baseline)</b>	Chemical	Medium to High	High	High	High; requires regeneration	Medium; high cost of disposing g resins	High (baseline)	High	Medium because of residuals.	High	High	Baseline
<b>Thermal Evaporation (in-drum)</b>	Physical	High; effective for low volumes, but waste of energy for higher.	Medium because of presence of VOCs.	High	Medium	Low; residuals and handling.	Medium	Medium	Medium because of residuals.	High	High	Viable
<b>Remediation Technologies <u>Not Recommended</u></b>												
<b>Hot Air Drying</b>	Physical	High. Effective for low volumes.	Low	Medium	Medium	Medium; will require lot of energy.	High; nothing leaves the site.	Low; better if coupled with another solution.	Medium	Low to Medium. No fatal flaws, but never done at	None	Not recommended. Concern with long-term effect

Remediation Technology	Remediation Strategy	Effectiveness	Permitability	Implementability	Health and Safety Risks	Annual Cost	Public Acceptability	Site Acceptability	Long-Term Liability	Technical Maturity	Secondary Waste	Overall
										this scale.		on cell stability.
<b>Constructed Wetlands</b>	Biological	Low to Medium; reaction rates slow in winter	Low; Migration out of system possible; biomagnification	High	High	Low to medium, higher capital	Low	Medium	High	High	High	Not recommended
<b>In Situ Biostabilization – active and passive</b>	Biological	Medium; feasible, would need recirculation system.	Low; has not been used for U (still experimental)	Medium; must penetrate cap for active; passive easier	Low	Medium for active  Low for passive	High	Low for active  Medium for passive	Medium for active  Low for passive but don't know about reoxidation – depends on water, TOC	Low	None	Not recommended; too many uncertainties
<b>Ex Situ Bioreactor</b>	Biological	Medium	Low to medium; not much data	High	Medium to High since pumping and treating, have to deal with biofilm	Medium to High for maintaining such a large system to remove low conc. Lot of maintenance, add nutrients	Medium	Medium	High; many initial capital costs	Medium	High	Not recommended

Cost, estimated annually: Low = Less than \$1 million; Medium = \$1-\$5 million; High = Greater than \$5 million

Note: The technical assistance Team considered chemical oxidation or reduction and electrochemical treatment as remediation strategies, but was not aware of any commercially available technologies for such a dilute leachate. Monitored Natural Attenuation was also considered, but would be labor intensive and only viable as a supplement to recirculation.