Innovative Technology
Summary Report

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Urethane Foam Void Filling

Deactivation and Decommissioning Focus Area

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INNOVATIVE TECHNOLOGY
Summary Report

Urethane Foam Void Filling

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Deactivation and Decommissioning
Focus Area

Demonstrated at
Fernald Environmental Management Project
Fernald, Ohio

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Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under "Publications."

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SECTION 1

SUMMARY

Introduction

The United States Department of Energy (DOE) continually seeks safer and more cost-effective remediation technologies for use in the decontamination and decommissioning (D&D) of nuclear facilities. To this end, the Deactivation and Decommissioning Focus Area (DDFA) of the DOE's Office of Science and Technology sponsors Large-Scale Demonstration Projects (LSDP) at which developers and vendors of improved or innovative technologies showcase products that are potentially beneficial to the DOE's projects, and to others in the D&D community. Benefits sought include decreased health and safety risks to personnel and the environment, increased productivity, decreased costs and shortened schedules.

Under the D&D Implementation Plan of the DOE's Fernald Environmental Management Project (FEMP), non-recyclable process components and debris that are removed from buildings undergoing D&D are disposed of in an on-site disposal facility (OSDF). Critical to the design and operation of the FEMP's OSDF are provisions to protect against subsidence of the OSDF's cap. Subsidence of the cap could occur if void spaces within the OSDF were to collapse under the overburden of debris and the OSDF cap. Subsidence may create depressions in the OSDF's cap in which rainwater could collect and eventually seep into the OSDF. To minimize voids in the FEMP's OSDF, large metallic components are cut into smaller segments that can be arranged more compactly when placed in the OSDF. Component segmentation using an oxy-acetylene torch was the baseline approach used by the FEMP's D&D contractor on Plant 1, B&W Services, Inc., for the dismantlement and size-reduction of large metal components. Although this technology has performed satisfactorily, it is time-consuming, labor-intensive and costly. Use of the oxy-acetylene torch exposes workers to health and safety hazards including the risk of burns, carbon monoxide, and airborne contamination from combustion of residual lead-based paints and other contaminants on the surface of the components being segmented. In addition, solvents used to remove paint from the components before segmenting them emit flammable, noxious fumes.

This demonstration investigated the feasibility of placing large vessels intact in the OSDF without segmenting them. To prevent the walls of the vessels from collapsing under the overburden or from degradation, an innovative approach was employed which involved filling the voids in the vessels with a fluid material that hardened on standing. The hardened filling would support the walls of the vessels, and prevent them from collapsing. This report compares the cost and performance of the baseline segmentation technology and the innovative void filling technology using expanded polyurethane foam.

Technology Summary

Baseline Technology

In situ component segmentation is a fully developed process that is widely used throughout the DOE Complex for preparing D&D debris for disposal. The technology used for segmenting components is an oxy-acetylene cutting torch. To reduce airborne contamination and the risk of fire, paint solvents are used to remove combustible paint from the sections of components that are to be cut with the torch. Components are then cut into segments according to the FEMP's OSDF waste acceptance criteria (WAC, see Appendix C) that stipulate the maximum dimensions of debris that can be disposed of in the OSDF to prevent excessive void volumes.

Innovative Technology

Void filling using expanded polyurethane foam is a fully developed and commercially available technology. Current applications include thermal insulation of roofs and walls, filling of flotation chambers in boats, and in the manufacture of lightweight furniture.

How it works

The polyurethane foam used in the demonstration was produced by mixing two liquid chemicals, polymeric diphenylmethane diisocyanate (MDI) and polyol blend. The product is a liquid foam mixture that expands and hardens on standing. Figure 1 shows the mixing control unit that pumps the chemicals from containers, and delivers them in very precise proportions via separate hoses to a mixing gun.

Figure 1. The mixing control unit regulates and pumps chemicals to the mixing gun.

The chemicals combine in the mixing gun to form a liquid foam mixture that is immediately injected into the vessel being filled (see Figure 2). The foam is injected into the vessel in layers, and each layer is allowed to expand fully, cool and harden (about five minutes) before the next is added. This ensures proper expansion and curing of the foam, and prevents it from collapsing under its own weight before hardening. The hardened foam supports the walls of the vessel and prevents them from collapsing.

As an alternative to component segmentation, void filling of intact components has the potential to reduce significantly the time taken to prepare D&D debris for disposal in an OSDF, and accelerate overall D&D schedules. It would also reduce the airborne contamination, worker health and safety risks, and personal protective equipment (PPE) requirements associated with using a cutting torch. If these objectives are met, the void filling technology could result in substantial savings for D&D projects. The major drawback of this technology is the additional space required for disposal of intact components in the OSDF. Alternatives for minimizing this drawback are discussed at the end of this summary.

Production of polyurethane foam to meet prescribed specifications requires knowledge of the equipment used, and involves handling hazardous chemicals. Only trained, experienced personnel should be used in the process. Urethane Foam Specialists of Newcomerstown, Ohio were contracted to provide trained technicians, equipment and the chemicals required to produce the foam used for the demonstration.

Figure 2. The mixing gun combines the chemicals and injects the liquid foam into the vessel.

Demonstration Summary

The component segmentation and void filling technologies were demonstrated at the FEMP's Buildings 1A and 30B from May 16, 1996 through February 4, 1997. The actual time required to conduct the demonstration of both technologies was approximately 3 days. Baseline data were collect in May and June of 1996, however, the tanks needed for the void-filling exercise could only be removed from Building 1A as and when the dismantlement schedule permitted. Hence, the demonstration took nine months to be completed.

The purpose of the demonstration was to assess void filling of intact components as a viable alternative to component segmentation, for preparing D&D debris for disposal in the FEMP's OSDF.

Ideally, components should be void-filled after placing them in the OSDF. At the time of the demonstration, the FEMP's OSDF was not able to accept debris for disposal. Components removed from Building 1A had to be placed in a temporary work area where they were void filled, and then transported to a holding site pending final disposition. The cost of labor and transportation to move filled components from the work area for final disposition could be significant depending on the density of the void fill medium, and the weight that it adds to the components. The density of the void-fill medium was therefore an important consideration. It was imperative that the selected void fill medium be light enough that filled vessels could later be transported without the need for special equipment, and also be strong enough to withstand the compressive load in an OSDF. The engineering team contracted to design the FEMP's OSDF established a minimum compressive strength of 10 pounds per square inch for debris stored in OSDF. One of the candidate media selected for the void filling demonstration was expanded polyurethane foam. The main advantages of using this medium are that it is lightweight and can be synthesized to meet the minimum compressive strength requirement. An alternative medium that was also selected for demonstration at the FEMP is low-density cellular concrete (LDCC) which is described in Section 4 of this report.

The key objectives of the demonstration were:

- to determine whether expanded polyurethane foam could be synthesized to meet the minimum compressive strength required for debris disposal in the FEMP's OSDF, and;

- to assess the operational and economic feasibility of void-filling intact components with expanded polyurethane foam to prepare them for disposal in the FEMP's OSDF, versus the current baseline procedure of segmenting components using an oxy-acetylene torch.

Key Results

The key results of the FEMP demonstration were:

- The urethane foam void-filling technology is a practicable and effective means of eliminating void spaces from vessels that are to be disposed of intact. However, as demonstrated at the FEMP LSDP, this technology is not as productive or as cost-effective as segmenting vessels using an oxy-acetylene torch. Table 1 summarizes the key cost and performance factors that were measured during the demonstration.

- The vessels that were used for the demonstration had very few internal obstructions. Vessels containing obstructions such as heat exchangers, multiple chambers, baffles or tubing would have required a greater effort to segment and, in such instances, void filling would likely be more productive and more cost-effective.

- The oxy-acetylene torch does not readily cut thorough rusted steel or cast iron. Thus, it may be more productive to void fill vessels that are rust encrusted or constructed of cast iron.

- During segmentation, residual contaminants on the inner surfaces of vessels normally become airborne. Void filling these vessels would fix the contaminants to the inner surfaces and prevent them from becoming airborne. Void filling would be a safer alternative to segmentation for preparing radioactively contaminated vessels for disposal.

Table 1. Summary of key performance factors

	Segmenting using an Oxy-acetylene Torch (Baseline)	Void-Filling with Expanded Polyurethane Foam (Innovative)
Demonstration scale	694 ft^3	114 ft^3
Volume of vessels after treatment	22 ft^3	114 ft^3
Productivity	6.3 ft^3/h	3.5 ft^3/h
Variable Unit Cost for Performing D&D Work *	$22.21 / ft^3	$52.07 / ft^3 **
Fixed Cost	$0	$2,929
Total (variable + fixed) Unit Cost (based on demonstration scale)	$22.21 / ft^3	$77.76 / ft^3
Break-even Point	Not applicable.	

* Includes amortized capital cost of equipment
** Includes the rental cost of the foam equipment.

Productivity

- Using expanded polyurethane foam, it was possible to fill voids in components at a rate of approximately 125 cubic feet per hour. However, when all the steps involved in preparing the components for placement in the OSDF (see Table 2 in Section 2) are taken into consideration, the overall productivity rate is only 3.5 cubic feet per hour.

- Using component segmentation, it was possible to size-reduce empty vessels at a rate of 6.3 cubic feet of void spaces per hour.

- Void filling offers no advantage over segmentation in terms of accelerating D&D schedules. It was expected that void filling would permit faster removal of components from buildings allowing other D&D work to continue. However, if components to be segmented were removed from buildings before segmentation, the effect on the D&D schedule would have been the same as with void filling, but the higher productivity of segmentation would actually be more advantageous.

Cost of Performing D&D Work

- The variable unit cost of void filling components is more than twice that of segmenting with an oxyacetylene torch (see Table 1). In addition, the rental cost of the foam equipment is much higher than the amortized capital cost of the oxy-acetylene torch.

- Mobilization and demobilization costs for the void filling technology were also higher due to the cost of transporting the large pieces of foam-making equipment on and off site. Similar costs for the oxy-acetylene torch were negligible.

- Void filling does not reduce the volume of the vessels treated. Segmentation reduced the volume of the vessels by a factor of 32 significantly reducing waste disposal costs.

Performance

- Expanded polyurethane foam can be formulated to meet or exceed the minimum compressive strength of 10 pounds per square inch required to ensure stability of debris disposed of in the OSDF. The foam used for the demonstration averaged about 21 pounds per square inch with a density of about 2.1 pounds per cubic foot.

- The equipment used to produce the foam functioned well throughout the demonstration and the problems encountered were minor and quickly resolved. Only trained, experienced personnel should operate the foam generator because the density and compressive strength of the foam vary considerably depending on the temperature, flow rate and ratio of the chemicals used.

Personal Protective Equipment

- Segmentation required a higher level of PPE due to the increased risk of fire and burn injury to personnel. However, PPE cost per unit of D&D work completed was actually lower for segmentation due to this technology's higher productivity (see Appendix D).

Health and Safety

- Extreme care is needed when handling the chemicals used in generating the polyurethane foam. They are hazardous, however, once fully reacted the resulting foam is non-hazardous.

- Segmentation using the oxy-acetylene torch presents risks of explosion, fire and bodily harm. It also produces significant airborne contaminants such as carbon monoxide and lead.

- Lead-based paint is stripped from only those sections of components that are to be cut with the oxyacetylene torch. The remaining paint on the surfaces of void-filled or segmented components is not removed before disposal of the components and could leach into the soil if water permeates the OSDF cap.

- When vessels are void filled, the foam acts as a fixative for contaminants on the inner surfaces and reduces the risk of leaching.

Airborne Contamination

- Void filling produced considerably less airborne contamination than segmentation. Void filling generated minimal traces of toxic MDI vapor. The oxy-acetylene torch produced toxic carbon monoxide and elevated levels of airborne lead due to the combustion of residual lead-based paint and other contaminants on the surfaces of the components. Paint solvents used in the segmentation process are flammable and produce noxious vapors.

Portability

- The equipment and drums of chemicals used to produce polyurethane foam are large and heavy, and not easily transported unless mounted on a truck as in the case of the FEMP demonstration.

Permits, Licenses and Regulatory Considerations

No special permits or licenses were required to operate the foam void filling equipment at the FEMP since it was owned and operated by the contractor, Urethane Foam Specialists. An open flame permit was required to operate the oxy-acetylene torch.

The demonstrations involved the handling of hazardous chemicals and contaminated debris, and the use of power tools and machinery. Technical support in the areas of radiation protection, health and safety, and regulatory compliance was provided by Fluor Daniel Fernald (FDF).

Technology Limitations and Needs for Future Development

Void filling is not a feasible option when components are simply too large or too heavy to be removed from buildings intact. At the FEMP site, intact removal is limited to components that are less than 15 feet in diameter and 25 feet long, and weigh less than 10 tons. Almost all of the vessels at Plant 1 can be removed intact.

For the FEMP demonstration, components had to be void filled in a temporary work area and moved to a holding site pending final disposal. The density and added weight of the selected void filling medium were therefore major concerns. In applications where components can be disposed of directly in the OSDF before void filling, the density of the medium would not be as critical, and alternative media such as cement, contaminated soil, and other D&D debris could be used. The revised procedure would involve:

- placing all components to be void filled directly in the OSDF;
- filling large voids with smaller components, waste material, contaminated soil, and other D&D debris;
- performing a mass filling of any remaining voids with an appropriate void fill medium.

This revised procedure may increase the productivity and reduce the cost of void filling, and make it a more viable alternative to segmentation.

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Web Site

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SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process Definition

The void filling technology selected for demonstration at the FEMP entails filling hollow spaces within D&D debris with a fluid material that hardens on standing. This technology was investigated as a means of eliminating void spaces within debris placed in an OSDF that could collapse over time and lead to subsidence of the OSDF's cap. The current baseline approach for minimizing voids within debris is component segmentation using an oxy-acetylene torch. During segmentation, components are cut into smaller segments that can be arranged more compactly in the OSDF, thereby minimizing voids.

A key consideration in selecting a void fill medium is its compressive strength. Candidate media selected for the FEMP's OSDF should be capable of supporting the walls of void filled vessels and other debris and prevent them from collapsing either under the compressive load of the overburden in the OSDF or if they degrade over time. Expanded polyurethane foam is a lightweight candidate medium that can be synthesized to meet or exceed the minimum compressive strength of 10 pounds per square inch recommended by the engineering team that designed the FEMP's OSDF. A lightweight fill medium was desirable because at the time of the demonstration the FEMP's OSDF was not yet ready to accept debris for disposal, and the vessels had to be filled in one location and then transported to a holding site for later disposal. A dense fill medium would have made the vessels excessively heavy, and more difficult and costly to transport for disposal.

Figure 3 illustrates the process of void filling with expanded polyurethane foam.

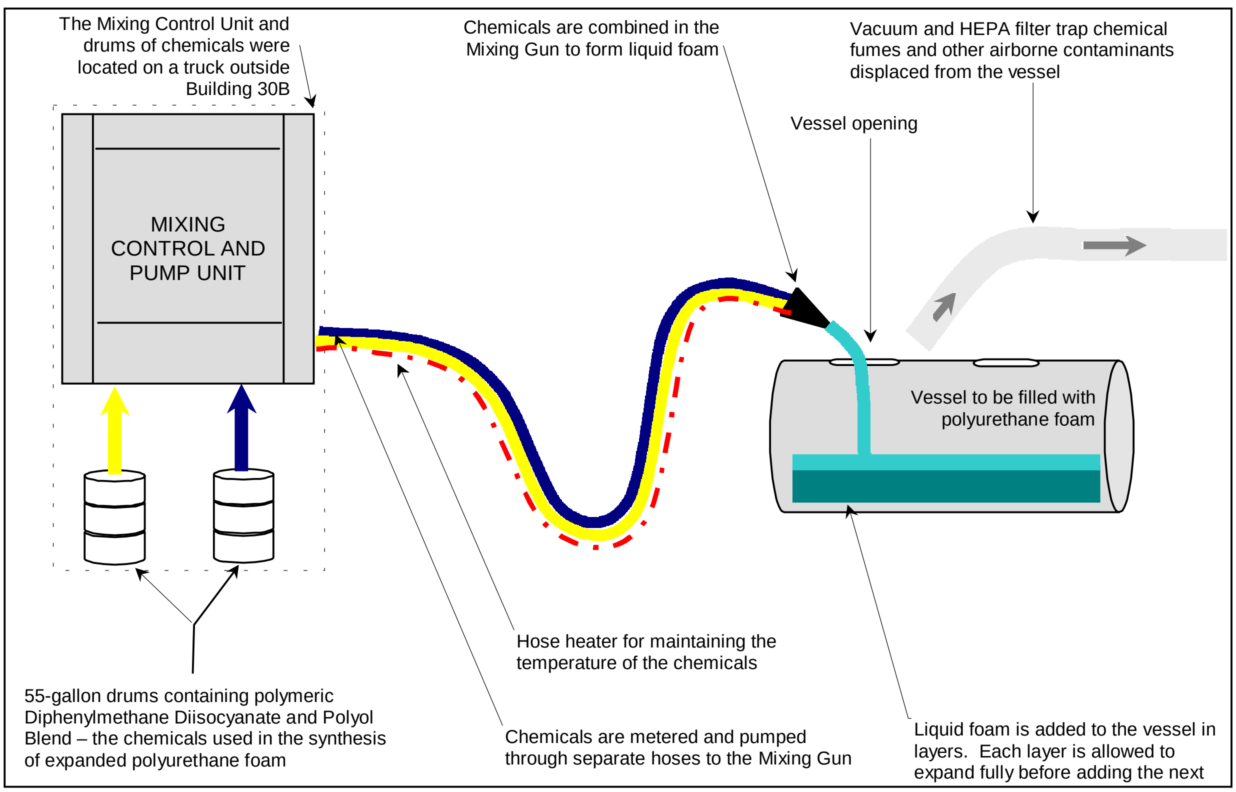

Figure 3. Schematic of the expanded polyurethane foam void filling process.

The equipment used to generate the polyurethane foam for the demonstration was contracted from Urethane Foam Specialists who also provided trained technicians to perform the void filling exercise, as well as the chemical components used to synthesize the foam.

System Operation

Polyurethane foam is produced by mixing two liquid chemicals, polymeric diphenylmethane diisocyanate (MDI) and polyol blend. MDI is toxic and presents a health hazard, but when mixed with the polyol blend, the resulting polyurethane foam is non-toxic. During the production, the two chemicals are kept separate and only mixed to form the liquid foam just before it is injected into the vessel. Regulating the temperature and/or the ratio of the chemicals controls the rate at which the liquid expands and hardens. These parameters also determine the compressive strength of the foam after it hardens, therefore knowledge of the process parameters and equipment is essential.

To prevent debris compaction and collapse of the OSDF, the void fill medium should have a minimum compressive strength of 10 psi. The compressive strength of the foam supplied by Urethane Foam Specialists typically has a variance of plus or minus 10 percent. A target value of 15 psi was selected for the demonstration to ensure that the 10 psi minimum was met.

Process Overview

Table 2 outlines the steps involved in segmenting and void filling vessels at the FEMP.

Table 2. Overview of segmentation and void filling processes

Segmentation	Void Filling
• Strip paint from all areas to be cut with the torch. • Secure segments to be cut with rigging if necessary. • Cut segments and remove them. • Wash and dry segments. • Dispose of segments.	• Strip paint from sections of vessels that must be cut to remove them from their housing. • Secure vessels to be removed with rigging if necessary. • Cut vessels free of their housing. • Move vessel by forklift to work area. • Wash and dry vessels. • Mobilize foam equipment. Pre-heat chemicals. Test foam samples for compressive strength. • Fill vessels with foam in layers. Allow each layer to expand, cool and harden. • Allow foam to set for 8 hours. • Demobilize foam equipment. • Dispose of vessels.

Void Filling Procedure

Vessels to be void filled were removed intact from Building 1A and placed in a temporary work area in Building 30B. The vessels were washed to remove surface contaminants, and allowed to dry completely before void filling. They were then laid horizontally with their largest openings facing upwards, and all other openings were sealed with duct tape to prevent the void fill medium from escaping.

The mixing control unit used was a Dussmere H2 proportioning pump, and the mixing gun was a Gusmer AR-250 foam gun. The mixing unit pumped the chemicals from drums in precise, predetermined proportions, via separate hoses to the mixing gun where they were combined to form liquid polyurethane, which was immediately injected, into the vessel being filled. The MDI was pumped at a pressure of 800-1,000 psi, and the polyol blend was pumped at 950-1,150 psi. A hose heater that ran alongside the hoses heated the chemicals on their way to the mixing gun to about 105°F. Once ejected from the mixing gun, the liquid began to expand and harden. With the chemicals heated to 105°F, the foam began to gel in about 1 minute, and was tack-free in about 2 minutes. The foam was added in layers about 8 inches deep and each layer was allowed to expand fully (to about 12 inches), harden and cool before adding the next layer (about 10 minutes). This ensured proper expansion and curing of the foam, and prevented collapse of the foam under its own weight if too much liquid foam were added at once. Three layers were necessary to fill the demonstration tanks that were approximately 3 feet in depth.

Table 3 summarizes the operational parameters and conditions of the void filling demonstration.

Table 3. Operational parameters and conditions of the void-filling demonstration

Working Conditions	
Work area location	Building 30B of Plant 1 at the FEMP site.
Work area access	Accessible by forklift via roll-up doors to facilitate placement and removal of large intact components.
Work area description	The floor of the work area was lined with poly sheeting to contain chemical or liquid foam spills. The vessels to be filled were placed by forklift on wooden pallets on the floor of the work area.
Work area hazards	Hazardous chemicals delivered under high-pressure. Tripping hazard from hoses. Minimal level of airborne polymeric diphenylmethane diisocyanate. Heavy machinery and equipment.
Equipment configuration	The mixing control unit and chemicals were mounted on a truck immediately outside Building 30B. The foam-producing chemicals were pumped to the void-filling work area via high-pressure hoses.
Labor, Support Personnel, Specialized Skills, Training	
Work crew	Three-person work crew required to: 1) operate the mixing control unit 2) perform the void filling 3) position ventilation hose
Additional demonstration support personnel	Full-time data taker Part-time Forklift Operator Radiation Technician Health and Safety Officer
Specialized skills	Technicians experienced in using the foam equipment were contracted from Urethane Foam Specialists.
Training	Work crew members were briefed on health and safety issues related to the work site, including material safety data sheet (MSDS) procedures for handling the chemicals used. Workers provided by Urethane Foam Specialists each required 48 hours of site specific training to become certified to enter the exclusion zone at the FEMP.
Waste Management	
Primary waste generated	Void-filled intact components. Foam samples used for compressive strength tests.
Secondary waste generated	Disposable PPEs Poly sheeting used for lining the work area. Protective wrapping for hoses. HEPA filter and vacuum hose.
Waste containment and disposal	Secondary waste was packaged in 55-gallon plastic bags for disposal.

Equipment Specifications, Operational Parameters and Portability					
Dimensions/weight		**Height**	**Width**	**Depth**	**Weight**
	Mixing control unit	47 in.	40 in.	22 in.	425 lb.
	Recommended maximum length of hose = 260 ft.				
Portability	The mixing control unit and chemicals are normally mounted on a truck and transported to project sites. The high-pressure hoses and the mixing gun can deliver the liquid foam mixture up to 260 feet from the truck.				
Materials Used					
Work area preparation	Poly sheeting and duct tape for lining the work area.				
Personal protective equipment (see Appendix D)	Cotton coveralls, hood and booties Rubber boots Rubber shoe cover Nytrile gloves and liners Impermeable Saranex disposable suit Nytrile gauntlets Respirator (half-face, charcoal filter air purifying)				
Air filtration	Vacuum hose and HEPA filter				
Chemicals for generating foam	55 gallon drum of polymeric diphenylmethane diisocyanate 55 gallon drum of polyol blend				
Utilities/Energy Requirements					
Equipment	Mixing control unit requires 220 volt, 100-ampere supply.				
Work Area	Six 110 volt, 1,500 watt space heaters were used to maintain a minimum work area ambient temperature of 40^{o}F to avoid freezing of the chemicals.				

Assessment of Technology Operation

Operational Strengths of the Void Filling Technology

Void filling with expanded polyurethane foam is a relatively safe process and the equipment is easily operated by trained personnel.

Throughout the demonstration, the void filling equipment performed without any significant problems, and those that arose were minor and quickly resolved.

The equipment and chemicals were mounted on a truck and easily transported to the work site.

Operational Weaknesses of the Void Filling Technology

When filling the vessels, the foam must be added in layers and each layer must be allowed sufficient time to cool, expand fully and harden. This could result in significant idle time for the workers. During the FEMP demonstration, idle time was avoided by processing two vessels at the same time. Layers of foam were added while alternating between the two vessels, i.e. while one layer was hardening in one vessel, another layer was added to the other vessel. Higher productivity would likely be achieved by filling more than two vessels at a time.

Other Considerations

At the time of the demonstration, the FEMP's OSDF had not yet been completed and vessels had to be void filled in a temporary work area and then transported to a holding area for later disposal. Placing vessels directly into the OSDF and then filling them would expedite the process. In doing so, the weight of the fill medium would not be an issue and less expensive fill media could be used.

SECTION 3

PERFORMANCE

Demonstration Plan

Demonstration Objectives

The purpose of the demonstration was to assess void filling with expanded polyurethane foam as an alternative to the baseline component segmentation for preparing D&D debris for disposal. This investigation assessed void filling based on its performance, relative to the segmentation technology, in achieving the following demonstration objectives:

- increased productivity;
- reduced cost;
- reduced levels of airborne contamination;
- reduced PPE requirements;
- improved worker safety;
- potential for reducing overall D&D schedules.

In addition, a minimum compressive strength of 10 psi for the polyurethane foam must be achieved for it to be acceptable as a candidate void-filling medium.

Demonstration Site Description

The void filling technology was demonstrated in Building 30B of Plant 1 at the FEMP site. The components to be void filled were removed intact from Building 1A and transported by forklift to Building 30B. The work area was lined with poly sheeting to contain spillage of chemicals and the liquid foam. Portable heaters were used to maintain a minimum ambient temperature of 40^{o}F in the work area. The foam generating equipment was located on a truck immediately outside Building 30B.

The component segmentation technology was demonstrated in Building 1A of Plant 1. The components were segmented in place using the oxy-acetylene torch. Ladders and a manlift provided access to the components, and rigging was installed to lower the segments as they were cut away.

Demonstration Boundaries

The void filling technology was demonstrated in February 1997. At the time of the demonstration, the FEMP's OSDF was not yet ready to accept debris for disposal. Components had to be placed in a temporary work area to be void filled, and then transported to a holding area before disposal in the OSDF. A more economical approach would have been to place the components directly into the OSDF before filling them, however, this could not be done due to the unavailability of the OSDF.

Treatment Performance

The segmentation technology was demonstrated on four cylindrical vessels/tanks with a combined total internal volume of 694 cubic feet. The void filling demonstration used two vessels with a combined total internal volume of 114 cubic feet (see Table 6). The vessels to be void filled had internal baffle plates that provided an opportunity to assess the technology's ability to fill between and around obstructions.

Assessment of expanded polyurethane foam as a fill medium

The foam produced for the demonstration has a compressive strength variance of plus or minus 10 percent. To ensure that the foam would meet the prescribed compressive strength of 10 psi, the foam supplier was instructed to target a minimum compressive strength of 15 psi. Foam samples tested during the demonstration continually met or exceeded this specification, except for the first samples that were used to calibrate and set up the equipment. Table 4 summarizes the test results.

Table 4: Results of the compressive strength tests performed on polyurethane foam samples taken during the demonstration

	Compressive Strength in psi and Core Density in lb/ft^3 (in parentheses)			
Sample Set Number	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
#1	7.4 (2.0)	9.5 (2.1)	17.1 (2.1)	14.1 (1.9)
#2	20.7 (2.2)	20.8 (2.2)	22.7 (2.1)	24.7 (1.9)
#3	18.4 (2.2)	18.5 (2.2)	19.5 (2.1)	24.0 (1.9)
#4	18.4 (2.1)	18.1 (2.2)	22.9 (2.1)	28.2 (1.9)

Performance relative to demonstration objectives

Table 5 summarizes the overall performance results of the void filling and component segmentation technologies for each of the demonstration objectives listed above.

Table 5. Performance comparison between component segmenting and void filling technologies

Performance Factor	Component Segmenting	Void Filling with Polyurethane Foam
Productivity	6.3 ft^3/h	3.5 ft^3/h
Cost of performing D&D work	\$22.21 / ft^3	\$52.07 / ft^3
Airborne contamination	▪ Carbon monoxide ▪ Paint remover vapors ▪ Carbon soot ▪ Airborne lead and uranium (up to 420 % of Derived Air Concentration (DAC)); average 140 % of DAC.	▪ Traces of foam production chemicals (less than 2 ppm MDI) ▪ Traces of airborne uranium-238 (less than 1.4 % of DAC).
	Note: Ambient airborne uranium within building 30B is typically less than 2% of DAC which translates to 4x10^{-13} microcuries per cubic centimeter (µCi/cm^3).	
PPE requirements	\$14.96 / h of D&D work performed or \$7.07 / ft^3 of void eliminated.	\$6.94 / h of D&D work performed or \$8.32 / ft^3 of void filled.
	The oxy-acetylene torch required more restrictive PPE hence higher cost per hour. However, its higher productivity resulted in lower cost per unit of work.	
Worker safety	Risks from open flame, higher airborne contamination, combustible paint remover, and risk of falling.	Risks from handling hazardous chemicals under pressure, and using heavy machinery to transport large components.
Overall D&D schedule	Components were segmented in the building. This precluded other D&D work from taking place in the same area at the same time. Similar to void filling, schedules could potentially be accelerated if the components were first removed intact for buildings, and then segmented.	Components were removed more quickly from the building permitting other D&D work to proceed which could accelerate D&D schedules.

Productivity rates achieved during the demonstration

Table 6 summarizes the productivity rates achieved by the component segmenting and void filling technologies. The productivity rates are based on the total process time taken to prepare the debris for disposal (see Table 2), and not simply the speed at which the torch cuts, or the rate at which foam can be pumped into the vessels.

Table 6. Productivity data for component segmenting versus void filling

Component Segmenting *		**Void Filling**	
Component	**Volume (ft^3)**	**Component**	**Volume (ft^3)**
Setting tank	404	Vacuum tank	57
Overflow tank	198	Vacuum tank	57
Water tank	75		
Filter	17		
Total Volume	**694**	**Total Volume**	**114**
Total Processing Time (3 person work crew)	**328 man hours 109 work hours**	**Total Processing Time (3 person work crew)**	**97 man hours 32 work hours**
Productivity	**6.3 ft^3 / h**	**Productivity**	**3.5 ft^3 / h**
Estimated Process time for 1,000 ft^3 of debris	**16 days**	**Estimated Process time for 1,000 ft^3 of debris**	**29 days**

* All tanks were constructed of 3/8-inch carbon steel.

The actual filling of the vessels with foam took about one hour and at a fill rate of approximately 125 cubic feet per hour. However, when all steps required to prepare debris for disposal were taken into consideration, the productivity was 3.5 cubic feet per hour. The productivity achieved by the segmentation process was 6.3 cubic feet per hour.

Airborne Contaminants

Segmentation resulted in considerably higher levels of airborne contamination than void filling (see Table 5). When cutting with the torch, uranium contamination embedded in the surface of the components, and residual lead-based paint were vaporized and became airborne. The void filling technology generated only trace amounts of MDI (one of the chemicals used in the production of polyurethane foam). Very low levels of uranium were also recorded but this was most likely due to the ambient uranium levels within Building 30B and not a result of the void-filling demonstration.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Technology Applicability

Void filling with polyurethane foam is a fully developed and commercially available technology. Current uses include thermal insulation of roofs and walls, filling of flotation chambers in boats, and in the manufacture of lightweight furniture.

Void filling with polyurethane foam is an effective means of eliminating voids in large components that are to be placed intact in an OSDF. However, based on the FEMP demonstration, void filling is more costly and less productive than the baseline segmentation technology.

Competing Technologies

Other technologies that may be considered for preparing D&D debris for disposal are:

Segmentation using an oxy-gasoline torch

The oxy-gasoline torch was demonstrated as a part of the FEMP LSDP. It is similar in operation to the oxy-acetylene torch but uses gasoline instead of acetylene as the fuel. During the cutting process, the oxy-gasoline torch oxidizes the steel 100 percent to a granular slag that is readily blown from the cut allowing the flame to penetrate deeper into the cut. As a result, the oxy-gasoline torch is able to cut thick metal faster and cleaner than the oxy-acetylene torch. At metal thicknesses above four inches, the oxy-gasoline torch is about three times as fast as the oxy-acetylene torch. Other benefits of the oxy-gasoline torch include:

- lower airborne contamination
- lower fuel cost
- reduced risk of explosion (liquid gasoline cannot burn or explode on impact; acetylene can)
- no risk of backflash up the fuel line.

The oxy-gasoline torch is manufactured by Petrogen International, Ltd. of Richmond, California; telephone (510) 648-4785.

Void filling using low-density cellular concrete

This technology was also demonstrated as part of the FEMP LSDP. The process is similar to void filling with expanded polyurethane foam except that the medium employed is low-density cellular concrete (LDCC). LDCC is produced by combining a low-density geo-foam with concrete. The product is a lightweight concrete/foam matrix with density as low as 35 pounds per cubic foot compared to 150 pounds per cubic foot for a typical concrete mixture. The productivity achieved using this technology at the FEMP LSDP was 9.8 cubic feet per hour, higher than that achieved by either void filling with polyurethane foam (3.5 cubic feet per hour) or segmentation with an oxy-acetylene torch (6.3 cubic feet per hour). The cost of void filling with LDCC is slightly higher than segmenting with an oxy-acetylene torch, and the cost of the equipment is significantly higher. Consequently, void filling with LDCC offers no cost advantage over the baseline segmentation with an oxy-acetylene torch, even with its higher productivity rate.

Patents/Commercialization/Sponsor

This demonstration involved the use of a fully developed technology. Void filling with polyurethane foam is not a patented process, however, some of the chemicals used in the process (such as accelerators and catalysts) are proprietary blends developed by producers of the foam and may require permission for use.

SECTION 5

COST

Introduction

This analysis compares the cost of preparing large D&D components for disposal either by segmenting them with an oxy-acetylene torch, or by void-filling the intact components with polyurethane foam. The purpose of the cost analysis is to present validated demonstration data that were collected during the LSDP, in a manner that will enable D&D decision-makers to select the preferred technology for their specific applications. It strives to develop realistic estimates that are representative of work performed within the DOE Complex, however, the reader should be aware that it is only a limited representation because it uses only data that were observed during the limited duration of the demonstration, and is based on prevailing conditions at the FEMP. Some of the observed costs have been eliminated or adjusted to make the estimates more realistic. These adjustments have been made only when they do not distort the fundamental elements of the observed data (i.e., they do not change productivity rates, quantities, work elements, etc.), or when activities are atypical of normal D&D work. Additional cost information and demonstration data are contained in the *Detailed Technology Report for the Urethane Foam Void Filling Technology*, FEMP, 1997 which is available on request from the FEMP.

Methodology

Cost and performance data were collected for each technology during the demonstration. The following cost elements were identified in advance of the demonstration, and data were collected to support a cost analysis based on these elements:

- **Mobilization:** includes the cost of transporting equipment to the demonstration site, training the crew members to use the equipment, providing crew members (including vendor-provided personnel) with FEMP site-specific training, constructing temporary work areas, and installing temporary utilities.

- **D&D Work:** includes the cost of labor, utilities consumed, supplies, and the rental or amortized cost of using the equipment during the demonstration. The rental cost of the foam equipment includes the chemicals used in synthesizing the foam.

- **Waste Disposal:** is the cost of disposing of the primary waste products of the demonstration such as the segmented components, the void-filled tanks, and the foam samples from the compressive strength tests (see Table 7 for resulting waste volumes).

- **Demobilization:** includes removal of support equipment such as riggings and manlifts, disconnection of temporary utilities, dismantlement of temporary work areas (including associated secondary waste disposal), and equipment decontamination and removal from the site.

- **Personal Protective Equipment**: includes the cost of all protective clothing, respirators, etc., worn by crew members during the demonstration.

Measurement of D&D Work

The objective of the segmentation and void-filling exercises was to eliminate void spaces from D&D debris before their disposal. The productivity of the technologies was therefore determined based on how quickly they could achieve this objective. In the case of void filling, productivity was a direct measurement of the volume of void spaces filled over a period. The productivity of the segmentation technology was the rate at which void spaces were eliminated by segmenting the components, i.e. the difference in the estimated volume of the debris before and after segmentation.

Measurement of Costs

The fixed cost elements (i.e. those independent of the quantity of D&D work, such as equipment mobilization and demobilization – see Appendix D) were calculated as lump sums. The variable cost elements (i.e. those dependent on the quantity of D&D work, such as labor costs) were calculated as costs per cubic foot of void eliminated from the vessels.

For the oxy-acetylene torch which was owned by the D&D contractor, equipment costs were based on ownership. Hourly equipment rates were calculated based on the procedure outlined in EP 1110-1-8, *Construction Equipment Ownership and Operating Expense Schedule, Region II*, US Army Corps of Engineers, September 1997. Hourly rates were calculated using the capital cost of the torch ($299), a discount rate of 5.6%, an estimated equipment life of 10,000 operating hours as advised by the vendor, and an estimated annual usage of 1,040 hours.

The equipment and foam used for the void filling demonstration were supplied by the vendor under a service contract that covered the cost of the chemicals and rental of the foam generating equipment. The vendor estimated that if the equipment were purchased it would cost approximately $20,000 and have an estimated lifetime of 22,000 operating hours.

Costs for materials and supplies used during the technology demonstrations were estimated by the FEMP IC Team. Costs for the disposal of waste in the FEMP OSDF that is under construction were estimated by FDF.

Where work activities were performed by the D&D contractor, labor rates used were those in effect at the FEMP at the time of the demonstration. Contractor indirect costs were omitted from the analysis since overhead rates can vary greatly among contractors and locations. Site-specific costs such as engineering, quality assurance, administrative costs and taxes were also omitted from the analysis. Where appropriate, D&D decision-makers may modify the FEMP base unit costs determined by this analysis to include their respective site-specific indirect costs.

PPE costs are duration dependent. Four changes of PPE clothing were required for each crew member per day. Reusable PPE items were estimated to have a life expectancy of 200 hours. Disposable PPE items were assumed to have a life expectancy of 10 hours - the length of the daily shift. The cost of laundering reusable PPE clothing items is included in the analysis (see Appendix D).

Cost Analysis

Table 7 summarizes the costs associated with the segmentation and void filling technologies. Details of these costs are presented in Appendix D.

Note, the capital cost of using the oxy-acetylene torch for the duration of the demonstration is negligible (approximately $0.03 per hour) and were excluded from the analysis.

The unit costs for elements that are dependent on the quantity of work performed are based on the cost of performing one unit of work, i.e. the cost of eliminating one cubic foot of void space from empty/unsegmented vessels. For example, Table 7 shows that the segmentation technology eliminated 694 cubic feet of void spaces and resulted in 22 cubic feet of waste (segmented vessels). The total disposal cost for 22 cubic feet of segmented vessels, at $8 per cubic foot is $176. Therefore the unit cost for eliminating one cubic foot of void space is $176 ÷ 694 = $0.25 per cubic foot.

Table 7. Costs of using the void filling and component segmentation technologies

	Segmenting			Void Filling		
Cost Elements	**Fixed Costs [1]**	**Variable Costs [2]**	**Unit Costs [3]**	**Fixed Costs [1]**	**Variable Costs [2]**	**Unit Costs [3]**
Mobilization [1]	$0	-	-	$2,390	-	-
D&D Work [2]	-	$10,331	$14.89 / ft^3	-	$3,356	$29.44 / ft^3
Waste Disposal [2]	-	$176	$0.25 / ft^3	-	$1,631	$14.31 / ft^3
PPE [2]	-	$4,907	$7.07 / ft^3	-	$949	$8.32 / ft^3
Demobilization [1]	$0	-	-	$539	-	-
Total	**$0**	**$15,414**	**$22.21 / ft^3**	**$2,929**	**$5,936**	**$52.07 / ft^3**

	Segmenting	Void Filling
Quantity of D&D Work	694 ft^3	114 ft^3
Resulting primary waste volume	Segmented vessels 22 ft^3 Other -	Unsegmented vessels 114 ft^3 Foam samples (trash) 58.4 ft^3
FEMP OSDF Waste disposal rates	Segmented vessels $ 8.00/ft^3 Unsegmented vessels $12.10/$ft^3$ Trash $ 4.30/ft^3	

1. These costs are independent of the quantity of D&D work performed and therefore not included in unit costs.
2. These costs are dependent of the quantity of D&D work performed.
3. Based on the cost of eliminating one cubic foot of void space.

Fixed Costs

No costs were incurred for mobilizing the segmenting equipment because it was already being used at the site as the baseline technology. Even if this were not the case, mobilization costs such as equipment transportation and training would have been negligible because the equipment is easily transported and requires minimal training. On the other hand, mobilization costs for the void filling technology were significant because large pieces of equipment had to be transported to the work site, a temporary work area had to be constructed, and workers had to be given FEMP site-specific training before they could enter the exclusion zone. By the same token, there were no costs incurred in demobilizing the segmentation technology, but significant costs were incurred in dismantling and disposing of the temporary work area, and transporting the void filling equipment from the work site back to the vendor. Neither technology required any significant decontamination. Note, fixed costs are not included in the unit costs of operating each technology (see Table 7).

Variable Costs

The unit cost of performing D&D work was higher for void filling due to the several labor-intensive and time-consuming activities (see Table 2) involved in the process that reduced productivity and increased costs.

The unit cost of waste disposal was significantly lower for segmentation because this technology actually reduces the volume of the vessels by a factor of almost 32, whereas void filling does not reduce the volume of the vessels. In other words, for a given amount of D&D work, void filling produces 32 times as much waste volume as segmentation. In addition, the cost of disposing of waste in the FEMP OSDF is about 50% higher for large unsegmented vessels/components due to the additional work required to handle these large items, and to backfill them after they are placed in the OSDF.

Segmentation required a higher level of PPE that is more expensive per work shift than that required for void filling (see Appendix D). However, overall PPE costs per unit of D&D work performed was actually lower for segmentation because its productivity rate is almost twice that of void filling and required about half the time and half the number of work shifts to complete a given amount of D&D work.

Cost Variable Conditions

The DOE complex presents a wide range of D&D work conditions. The baseline and innovative technology estimates presented in the analysis are based on a specific set of conditions and work practices found at Fernald Plant No. 1. Table 8 presents some of the FEMP-specific factors that have a direct bearing on the costs of segmentation and void filling. This information is intended to help the technology user to identify work differences that can result in cost differences.

Table 8: Summary of cost variable conditions

Cost Factor/Variable	Segmentation	Void Filling
Scope of Work		
Quantity D&D work	694 cu ft	114 cu ft
Debris treated	Tanks constructed of 3/8-inch carbon steel.	Tanks constructed of 3/8-inch carbon steel.
Work Area		
Outside temperature(^{o}F)	< 32	< 32
Ambient temperature (^{o}F)	40	40
Work area access	The components were segmented in place, lowered using chain rigging, and removed with a forklift.	The work area was accessible by forklift for moving the large vessels in and out of the area.
Demonstration Plan		
Work process		A low-density medium was used because the components had to be void filled in a temporary work area and then transported for disposal. Void filling directly in an OSDF would improve productivity and reduce costs. In addition, a less expensive fill medium could be used.
Other		
Capital cost of equipment	$299	$20,000
Estimated cost of labor	$30/h	$30/h

SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

The regulatory/permitting issues related to the operation of the Foam Void Filling Technology at the FEMP Building 30B site are governed by the following safety and health regulations.

- **Occupational Safety and Health Administration (OSHA) 29 CFR 1926**

- 1926.300 to 1926.307	Tools – Hand and Power
- 1926.400 to 1926.449	Electrical – Definitions
- 1926.28	Personal Protective Equipment
- 1926.52	Occupational Noise Exposure
- 1926.102	Eye and Face Protection
- 1926.103	Respiratory Protection

- **Occupational Safety and Health Administration (OSHA) 29 CFR 1910**

- 1910.211 to 1910.219	Machinery and Machine Guarding
- 1910.241 to 1910.244	Hand and Portable Powered Tools and Other Hand-Held Equipment
- 1910.301 to 1910.399	Electrical Definitions
- 1910.95	Occupational Noise Exposure
- 1910.132	General Requirements (Personal Protective Equipment)
- 1910.133	Eye and Face Protection
- 1910.134	Respiratory Protection

Safety, Risks, Benefits, and Community Reaction

Component segmentation and void filling involve similar activities, such as cutting metal with a torch, using rigging and a forklift to handle heavy components, and working on platforms and ladders above ground. Thus, both technologies have similar safety concerns, however, the risk to D&D workers is probably greater when segmenting due to the risk of burn, fire and explosion while using the torch for extended periods. Segmentation also generated considerably more airborne contamination.

A safety assessment performed on the void filling technology found that it involved, “Standard industrial or construction hazards” which is the least critical hazard category.

Due to concerns raised by local stakeholders and regulatory agencies, the FEMP has decided not to place the majority of oversized material generated during D&D into the OSDF. These concerns stem from the perception that these large components may have an adverse effect on the engineered cap and liner system, and thus the long-term stability, of the OSDF. In addition, while expanded polyurethane foam has proven to be an effective fill medium, further investigation is required to determine its long-term stability in an OSDF, and whether it will retain its compressive strength over the years.

SECTION 7

LESSONS LEARNED

Implementation Considerations

This void filling demonstration was conducted under the constraint that components would have to be void filled in a temporary work area outside the OSDF. The cost effectiveness and productivity of the technology could be improved if the empty components were placed directly into the OSDF and then filled. In addition, if the components were filled after placement in the OSDF, there would be no need to minimize the density of the void filling medium, and lower cost foam, grout or other fill media could be used, provided they meet the compressive strength requirement for the FEMP's OSDF.

Even if cost savings had been achieved with this technology, it is unlikely that it would have been implemented at the FEMP site due to concerns raised by the Fernald stakeholders after the technology had been selected and demonstrated at the FEMP. Their main concern centered on placement of large objects in the OSDF and whether the spaces around these objects could be adequately compacted with soil to prevent future settling and subsidence of the engineered OSDF cap. Also of concern was the long-term effect that large heavy objects might have on the integrity and protectiveness of the impermeable OSDF lining.

Technology Limitations and Needs for Future Development

The void filling technology using expanded polyurethane foam performed without any significant technical or mechanical problems during the demonstration and there appears to be no need for future development.

Technology Selection Considerations

Void filling is not a feasible option when components are simply too large or too heavy to be removed from buildings intact.

Void-filling components directly in an OSDF could make this technology more cost-effective and more productive than segmentation, and possibly lead to savings in other areas such as D&D schedule acceleration. Another advantage of using polyurethane foam to void-fill vessels either before or after placing them in the OSDF is that the lightweight medium facilitates re-positioning of the vessels within the OSDF.

APPENDIX A

REFERENCES

B&W Services, Inc., *Environmental Safety and Health Plan*, B&W Services, Inc., Lynchburg, Virginia.

Fluor Daniel Fernald, *Detailed Technology Report for the Urethane Foam Filling Technology, Large Scale Technology Demonstration Project*, U.S. Department of Energy's Fernald Environmental Management Project, Cincinnati, Ohio, September 1997.

Fluor Daniel Fernald, *Detailed Technology Report for the Low-Density Cellular Concrete Void Filling Technology*, *Large Scale Technology Demonstration Project,* U.S. Department of Energy's Fernald Environmental Management Project, Cincinnati, Ohio, September 1997.

U.S. Army Corps of Engineers (USACE), *Hazardous, Toxic, and Radioactive Waste Remedial Action Work Breakdown Structure and Data Dictionary*, USACE, 1996.

U.S. Army Corps of Engineers (USACE), *Construction Equipment Ownership and Operating Expense Schedule*, Washington D.C., August 1995.

U.S. Army Corps of Engineers (USACE), *Productivity Study for Hazardous, Toxic, and Radioactive Waste Remedial Action Projects*, USACE, October 1994.

APPENDIX B

ACRONYMS AND ABBREVIATIONS

Acronym/Abbreviation	Description
CFR	Code of Federal Regulations
DAC	Derived Air Concentration
D&D	Decontamination and Decommissioning
DB	Decibels
DDFA	Deactivation and Decommissioning Focus Area
DOE	Department of Energy
ESH	Environment, Safety and Health
^{o}F	Degrees Fahrenheit
FDF	Fluor Daniel Fernald
FETC	Federal Energy Technology Center
FEMP	Fernald Environmental Management Project
FIU	Florida International University
ft^2	Square feet
ft^2/min	Square feet per minute
ft^3	Cubic feet
Gpm	Gallons per minute
H&S	Health and safety
HEPA filter	High efficiency particulate air filter
HCET	Hemispheric Center for Environmental Technology (at Florida International University)
Hr	Hour
HTRW	Hazardous, toxic, radioactive waste
IH	Industrial hygiene
In	Inch
Lb	Pound
LDCC	Low Density Cellular Concrete
LF	Linear feet (foot)
LLW	Low-level waste
LSDP	Large-scale demonstration project
µCi/cm^3	Microcuries per cubic centimeter
OEM	Office of Environmental Management (of the DOE)
OSHA	Occupational Safety and Health Administration
OSDF	On-site disposal facility
OST	Office of Science and Technology
PPE	Personal protective equipment
Ppm	Parts per million
Psi	Pounds per square inch
USACE	United States Army Corps of Engineers
WAC	Waste Acceptance Criteria

APPENDIX C

WASTE ACCEPTANCE CRITERIA FOR PLACEMENT OF DEBRIS IN THE FEMP'S ON-SITE DISPOSAL FACILITY

Debris Category	**Maximum Dimensions**			**Other**
	Length (ft)	**Width (ft)**	**Height (ft)**	
General criteria for all categories of debris	10	10	1.5	Maximum height = 1.5 ft. including projections. No dimension greater than 10 ft. including projections. No void spaces greater than 1 ft^3.
Accessible metals	10	4	1.5	
Inaccessible metals	10	4	1.5	
Painted light gauge metals	10	4	1.5	
Concrete	6	4	1.5	
Non-regulated asbestos containing material	8	4	1.5	Bundled stacks.
Regulated asbestos containing material	10	4	1.5	Maximum volume per piece = 27 ft^3. Pipes with diameter of 12 in. or more must be segmented so that no piece is greater than 12 in. in height.
Miscellaneous materials	8	4	1.5	All miscellaneous materials must be compacted.

APPENDIX D

SUMMARY OF COST ELEMENTS

Table D.1. Details of major cost elements

Fixed Costs

Description	Quantity	Unit	Man hrs	Labor	Equipment	Materials	Other	Total
Segmentation	694	ft^3						
Mobilization			0	$0	$0	$0	$0	$ 0
Demobilization			0	$0	$0	$0	$0	$ 0
Total	**694**	ft^3	**0**	**$ 0**	**$ 0**	**$ 0**	**$ 0**	**$ 0**
Void Filling	114	ft^3						
Mobilization			16	$480	$13	$22	$1,875	$2,390
Demobilization			18	$525	$14	$0	$0	$ 539
Total	**114**	ft^3	**34**	**$1,005**	**$ 27**	**$ 22**	**$1,875**	**$2,929**

Variable Costs

Description	Quantity	Unit	Man hrs	Labor	Equipment	Materials	Other	Total	Unit Cost
Segmentation	694	ft^3							
D&D Work			328	$9,931	$0	$400	$0	$10,331	**$ 14.89**
Disposal			0	$0	$0	$0	$176	$ 176	**$ 0.25**
PPE			0	$0	$0	$0	$4,907	$4,907	**$ 7.07**
Total	**694**	ft^3	**328**	**$9,931**	**$ 0**	**$ 400**	**$5,083**	**$15,414**	**$ 22.21**
Void Filling	114	ft^3							
D&D Work			63	$2,039	$77	$1,140	$100	$3,356	**$ 29.44**
Disposal			0	$0	$0	$0	$1,631	$1,631	**$ 14.31**
PPE			0	$0	$0	$0	$949	$ 949	**$ 8.32**
Total	**114**	ft^3	**63**	**$2,039**	**$ 77**	**$1,140**	**$2,680**	**$5,936**	**$ 52.07**

Total Costs

Description	Quantity	Unit	Man hrs	Labor	Equipment	Materials	Other	Total	Unit Cost
Segmentation	694	ft^3							
Mobilization			0	$0	$0	$0	$0	$ 0	**$ 0.00**
D&D Work			328	$9,931	$0	$400	$0	$10,331	**$ 14.89**
Disposal			0	$0	$0	$0	$176	$ 176	**$ 0.25**
Demobilization			0	$0	$0	$0	$0	$ 0	**$ 0.00**
PPE			0	$0	$0	$0	$4,907	$4,907	**$ 7.07**
Total	**694**	ft^3	**328**	**$9,931**	**$ 0**	**$ 400**	**$5,083**	$15,414	**$ 22.21**
Void Filling	114	ft^3							
Mobilization			16	$480	$13	$22	$1,875	$2,390	**$ 21**
D&D Work			63	$2,039	$77	$1,140	$100	$3,356	**$ 29.44**
Disposal			0	$0	$0	$0	$1,631	$1,631	**$ 14.31**
Demobilization			18	$525	$14	$0	$0	$ 539	**$ 4.73**
PPE			0	$0	$0	$0	$949	$ 949	**$ 8.32**
Total	**114**	ft^3	**97**	**$3,044**	**$ 104**	**$1,162**	**$4,555**	$8,865	**$ 77.76**

Table D.2. Personal Protective Equipment Costs and Requirements per Crew Member

Cost Assumptions:

Daily Shift Length:	10 hours	hrs
Useful Life of Reusable PPE Items:	200 hours	hrs

Reusable PPE - Daily Requirements[1]

			Segmentation using an Oxy-acetylene Torch (Baseline)		Void Filling with Polyurethane Foam (Innovative)	
Item	**Unit Cost**	**Unit**	**Quantity**	**Total Cost**	**Quantity**	**Total Cost**
Cotton coveralls (yellow)	$5.90	ea.	4	$23.60	4	$23.60
Cotton hoods (yellow)	1.16	ea.	4	4.64	4	4.64
Cotton shoe covers (yellow)	1.84	Pair	4	7.36	4	7.36
Leather welding apron	20.00	ea.	1	20.00	0	0.00
Leather welding gloves	7.00	Pair	1	7.00	0	0.00
Full-face respirators	174.00	ea.	4	696.00	0	0.00
Reusable PPE laundry costs[2]	1.39	Load	1	1.39	1	1.39
Hourly Reusable PPE Cost				**$ 3.80**		**$ 0.18**

Disposable PPE - Daily Requirements[3]

			Segmentation using an Oxy-acetylene Torch (Baseline)		Void Filling with Polyurethane Foam (Innovative)	
Item	**Unit Cost**	**Unit**	**Quantity**	**Total Cost**	**Quantity**	**Total Cost**
Tyvek suits	$4.09	ea.	0	$0.00	4	$16.36
Saranex suits	23.77	ea.	0	0.00	0	0.00
Mar-mac fire-resistant coveralls	3.36	ea.	4	13.44	0	0.00
Cotton glove liners	0.28	Pair	4	1.12	4	1.12
Cotton work gloves	0.54	Pair	0	0.00	0	0.00
Nytrile gloves	0.24	Pair	4	0.96	4	0.96
Rubber shoe covers	12.28	Pair	4	49.12	4	49.12
Rubber boots	29.30	Pair	0	0.00	0	0.00
Ear plugs	0.12	Pair	0	0.00	0	0.00
Ear protectors	18.72	ea.	0	0.00	0	0.00
Respirator cartridges	11.74	Pair	4	46.96	0	0.0
Hourly Disposable PPE Cost				**$11.16**		**$6.76**
TOTAL HOURLY PPE COST				**$ 14.96**		**$ 6.94**

[1]Requires four changes per worker each day. Expected life = 200 hours.

[2]One day's reusable PPE for one crew member is one laundry load. Cost per laundry load is $1.39. Data provided by Fluor Daniel Fernald.

[3]Requires four changes per worker each day. Expected life = 10 hours (the length of one shift).