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Alternate Retrieval A-105 Application Assessment Report

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Executive Summary

This report summarizes the historical development of the Confined Sluicing End Effector (CSEE) technology as well scarification technology. We also summarize the systems integration and deployment of that technology in the Gunite and Associated Tanks (GAAT) at the Oak Ridge Reservation where the retrieval system successfully removed the remaining sludge and heel in the eight tanks for tank closure and disposition. We also summarize the lessons learned from the deployment at Oak Ridge.

Simulant development and testing have been key activities for any waste retrieval effort as many of the physical properties of the waste are unknown; therefore, this report discusses a bounding series of simulants that helps to reduce uncertainty for operations. These simulants have been developed for potential Hanford waste retrieval deployment.

The potential key attributes for retrieval, based upon information provided by Washington River Protection Services (WRPS), of single-shell tank A-105 are discussed along with the potential application of CSEE technology to the challenges presented by the unique nature of A-105. These unique features include a major tear in the bottom of the tank, which necessitates technologies other than past practice sluicing to be deployed to prevent further intrusion of waste into the vadose zone. In addition, significant in-tank hardware makes A-105 particular challenging. However, there appear to be a number of parameters that should be investigated through additional testing or review of prior testing that may demonstrate the applicability of the CSEE technology to A-105. Testing of the Waste Retrieval End Effector (WREE), which was based on the original CSEE design, to demonstrate the ability to remove sludge and hardpan from Tank 241-C-106 will be reviewed to determine relevance to the Tank A-105 retrieval. The test report is included in the Appendix of this document to provide additional information about the WREE performance with respect to several simulant materials. There may be new requirements for the deployment system that accesses the tank with the CSEE because the tank bottom may not be flat, requiring the ability to maneuver the CSEE to maintain the appropriate stand-off distance from the CSEE and the tank bottom.

Finally, we provide a set of recommendations, a set of task descriptions, and a range of estimated costs for a demonstration of the technology by the end of FY17. These tasks are summarized as:

- Complete system-level functional requirements
- Procure or access the capacity to perform
- Generate simulant development and simulant testing
- Develop CSEE functionality
- Develop demonstration plan
- Perform demonstration
- Analyze and document testing results
- Perform project management and engineering

Acronyms and Abbreviations

ACTR	Acquire Commercial Technology for Retrieval
CSEE	Confined Sluicing End Effector
DOE	U.S. Department of Energy
DOF	degrees-of-freedom
DSR	decontamination spray ring
GAAT	Gunite and Associated Tanks
gpm	gallons per minute
GSEE	Gunite Scarifying End Effector
GUI	graphical user interface
HMA	hose management arm
HTB	Hydraulic Test Bed
HTI	Hanford Tanks Initiative
MET	Mast evaluation table
MLDUA	Modified Light Duty Utility Arm
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
ROV	Remotely Operated Vehicle
SREE	Sludge Retrieval End-Effector
WD&C	Waste Dislodging and Conveyance System
WREE	Waste Retrieval End Effector

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1.0 Introduction

This report provides a history of the development of one family of technologies, commonly called Confined Sluicing or Scarification, for use in underground nuclear waste tanks for the U.S. Department of Energy (DOE) Complex. In addition, this report summarizes the development of what is commonly called the Confined Sluicing End Effector (CSEE) that was successfully deployed as part of a waste retrieval system to remove the waste from the eight Gunite and Associated Tanks (GAAT) at the Oak Ridge Reservation in the late 1990s and early 2000s. However, the motivation for this report is to also provide an initial consideration of the use of this alternative type of technology for the potential retrieval of waste from Hanford Tank A-105, which has a large tear in the bottom of the tank due to operations in the tank many years ago. Finally, we provide a list of primary tasks and challenges that must be addressed that will be necessary to complete a functional demonstration of confined sluicing technology within one year.

1.1 History and Development of Confined Sluicing

The use of waterjet-based technologies for waste retrieval operations at Hanford and other DOE sites is common. Waterjet-based technologies are commonly used in industrial tank cleaning operations for above- and below-ground tanks, especially in the petrochemical sector. Typically, sluicing technologies have been successfully deployed in sound underground tanks, especially for removing soft sludges and for assistance in dissolution of saltcake-based waste forms. These systems consist of long jet sluicers, which typically operate at 100-300 gallons per minute (gpm) and have coherent jets that can reach across 75-80 feet and can typically rotate to reach all locations in the tank. They are assisted by large fixed pumps to remove the resulting slurry from the tanks for transfer to another tank or other processes. However, in many underground storage tanks, there are concerns about actual or potential leaking tanks that require other technologies that result in the close coupled introduction and removal of water/slurry.

It is important to provide a definition of Confined Sluicing and Scarification in a historical context. The overarching technologies that were developed for use in underground storage tanks are considered to be high-pressure waterjet systems. We define high-pressure waterjets as those systems that use water pressures ranging from 2,000 psi up to 50,000 psi. Industry further designates the term ultra-high-pressure waterjets for pressures approximately 30,000 psi and higher. Waterjetting applications for underground storage tanks typically range from 2-4 gpm per waterjet, which is an order of magnitude less water flow than with sluicing technologies. It is also important to note that the effective range of the energy for the dislodging or mobilization of waste from a high-pressure waterjet is only a few inches and is one of several critical design parameters that should be considered. Confined Sluicing can be loosely defined as a system that uses medium-pressure waterjets in the range of 5,000 to 10,000 psi and is closely coupled with a removal system that can consist of a separate educator jet pump system or a pneumatic conveyance system. We define scarification as a system that uses high-pressure waterjets ranging from 30,000 psi to 50,000 psi to dislodge/mobilize the waste and is closely coupled, typically with a pneumatic conveyance system. We should also note that both of these technologies that were developed for underground storage tank retrieval could conceivably be hybridized for potential consideration.

The design concept for the CSEE originated at the Rock Mechanics & Explosives Research Center at the Missouri University of Science and Technology (MUST). It was an outgrowth of conceptual development work (Summers et al. 1994) for a proposed Hanford-scale end effector, based loosely on commercial waterjet scarifier devices. This work at MUST began as an investigation of a means for dislodging and conveying waste currently stored in underground storage tanks. A series of experiments were carried out to evaluate the potential of a medium-pressure, medium-flow-rate cutting system as a means of dislodging the waste. Waterjets at a pressure of 10,000 psi were found to effectively cut the material that has been chosen to simulate the waste within the storage tanks. It was determined that an inlet flow volume of approximately 30 gpm is sufficient to excavate 30 gpm of waste from a tank. To transport the resulting slurry from the tank, a modified jet pump was developed and demonstrated its capability of conveying fluid and waste particles, up to one inch in diameter, to a height of more than 60 feet. Note that most pumps or eductor systems that are used in Hanford tanks have 3/8-inch mesh “rock stopper” screens at the inlet. Consideration for particle size greater than 3/8 inch is probably not practical. Experiments were conducted to examine different configurations to achieve the production levels required for waste removal and to clean the walls of residual material. Cleaning the tank surface using an inclined angle of impact was found to be more effective than using a perpendicular angle of impact to provide a safeguard against driving the water through any cracks in the containment. It was demonstrated that, with carefully selected mining strategies, jet geometries, and operating pressure, excavation can take place with almost total immediate extraction of the water and debris from the cutting process. The results under controlled test conditions using a test apparatus unconstrained by deployment considerations qualitatively demonstrated the potential of a medium-pressure waterjet system for achieving the required results for underground storage tank waste retrieval.

1.2 Technology Application at the Oak Ridge Gunite and Associated Tanks

The development and subsequent design of the Confined Sluicing technology, leading to the CSEE, for GAAT deployment was based upon a number of specific requirements at Oak Ridge. First, the GAAT Treatability Study assumed that the CSEE technology would need to be operated by the Modified Light Duty Utility Arm (MLDUA), which was a robotic arm that was designed to perform inspection, sampling, and in the case at Oak Ridge, retrieval operations. In addition, the CSEE needed to be operated by the Houdini remote crawler, which necessitated a small robotic arm to be integrated with the crawler to wield the system. Oak Ridge, through a series of systems requirement definition meetings, determined that they would use a waterjet pump eductor to remove the waste from the tank. The development of the CSEE for GAAT was conducted in three basic steps and was based upon prior work that had been done by the Pacific Northwest National Laboratory, the University of Missouri at Rolla (now MUST), and Waterjet Technologies Inc. (WTI—formerly known as Quest Integrated in Seattle, WA and no longer in business). MUST was responsible for parametric studies to define waterjet rotational rates, translational rates, and waterjet angle with respect to the system inlet. WTI was responsible for the CSEE design and construction. Pacific Northwest National Laboratory (PNNL) was the integrator and also completed performance testing, which included force/torque measurements, so-called mining strategies in different simulants, retrieval rates, and water balance. Upon completion of performance testing, the CSEE was transferred to the GAAT project where it went through a series of systems integration and readiness testing prior to being used in the GAAT.

The CSEE and the associated systems were mobilized on a platform over the first tank for retrieval, and then the entire system was moved from one platform to the next for retrieval of each of the subsequent GATTs. The entire effort and the lessons learned have been documented (Lewis et al. 2001).

1.3 The Role of Simulants

The use of simulants is important for waste retrieval technology development for a wide variety of reasons. Ideally, the physical properties of the waste should be well understood, including shear strength, compressive strength, cohesiveness, and other properties. If those properties are well known and based upon sampling and testing of real waste, then a simulant that closely mimics the key physical properties can be developed and used for testing. However, as in the case with all underground storage wastes, the sampling and testing of real waste materials may be prohibitively expensive or technically difficult. Therefore, to reduce the risk of ineffective retrieval performance, a series of simulants needs to be developed that are likely to be bounding of what may be encountered in the tank. While this is not an ideal situation, this approach has been used in the past (Powell 1997; Powell 1996). The other challenge with the development and use of simulants is a practical one. Simulants for bench-scale testing are used in small quantities; however, in full-scale tests, the volume of simulant required is quite large, and cost has to play a key role in the materials that are chosen for simulants. Equally, the ability to easily dispose of spent simulant material is a necessity.

1.3.1 History of Physical Simulants at Hanford

Approximately 56 million gallons of radioactive waste are currently stored in underground storage tanks at the Hanford Site in southeastern Washington State. The waste was generated by decades of nuclear materials processing, primarily for defense purposes. The rheological and mechanical properties of the tank wastes vary considerably, depending on the waste chemistry and tank conditions (e.g., humidity and temperature). Some waste consists of viscous liquids; some is sticky, paste-like sludge; and some is hard saltcake.

Much of this waste must be retrieved from the tanks and processed to create immobilized wasteforms suitable for long-term storage. Methods for removing waste from the tanks have been identified and developed to generate baseline schedule and cost estimates for waste retrieval. The current baseline waste-retrieval approach is to use sluice jets for single-shell tanks (SSTs) and mixer pumps for double-shell tanks. There remains a group of SSTs that may not be amenable to sluicing. This group includes those tanks containing difficult-to-retrieve wastes and those that cannot be sluiced because of known or suspected leaks.

The Acquire Commercial Technology for Retrieval (ACTR) effort was initiated in 1996 to help augment or replace the baseline waste retrieval methods. Communications with a variety of vendors identified improved waste-retrieval methods that could be implemented at Hanford with little or no additional development. After reviewing the vendor methods submitted, the most applicable and promising, commercially available retrieval methods were evaluated using a combination of testing and system-level cost estimation.

Waste simulants needed to support the testing of candidate retrieval technologies were developed and used in ACTR testing. The current progress toward this goal is documented in this report. Test materials were designed to be similar to bound tank waste in certain key respects and are described herein.

One of the principal goals of ACTR was to compare various commercially available retrieval methods with the baseline Hanford waste-retrieval methods (e.g., sluicing for SSTs). Those technologies that represent improvements over the baseline methods were recommended for further consideration. To help perform this assessment, tests of each proposed method were conducted in which the methods were applied to a variety of simulated waste materials.

Of course, it would be ideal if these test materials were identical, in all relevant aspects, to the actual tank waste. This is not possible at this time for several reasons. First, there is not adequate characterization of the physical properties of Hanford tank waste for accurate waste simulants to be designed. Second, the physical and chemical properties that determine process performance are not known for all of the commercially available retrieval methods. Third, even if the key waste properties were known and the magnitudes of those properties had been measured on waste samples, it is probable that matching all of the relevant properties exactly would require the use of hazardous materials. Because retrieval methods need to be tested at a fairly large scale, the expense of working with and subsequently disposing such hazardous materials could easily consume the majority of the testing budget (and may prevent testing altogether).

The simulants developed by the ACTR program were designed to model four different types of tank waste. Simulant recipes were given for wet sludge, hardpan/dried sludge, hard saltcake, and soft saltcake. The specified simulants are made from relatively inexpensive, non-hazardous materials that present no unusual disposal problems. Note that tank A-105 does not currently contain wet sludge or salt cake tank but rather hard sludge. The discussion below is intended to illuminate the process of simulant development from a historical perspective.

A comparison of the expected waste properties with the recommended simulant properties shows that, in many cases, the simulant properties are in the range expected for the waste. In other cases, there are not sufficient waste characterization data to make a meaningful comparison. Some of the key points of the simulant vs. waste comparisons are summarized below.

The shear strength of the wet sludge simulant (66% kaolin clay in water) falls within the range expected for wet tank sludge. Furthermore, the simulant density is representative of that measured for samples taken from the waste tanks. Particle size analyses of both sludge samples and the simulant show similar average sizes and distributions. The qualitative descriptions of sludge samples also are consistent with the behavior of the 66% kaolin clay sludge simulant (e.g., “The solids were sticky…”).

No quantitative physical property characterization data are available for samples of hardpan or dried tank sludge. There are, however, indirect indications of some of the hardpan strength properties. For example, previous sluicing campaigns were incapable of dislodging the hardpan wastes, and samples of the hardpan are said to have the consistency of “blackboard chalk.” Based on this information, an estimated range for hardpan mechanical strength was developed. The recommended simulants fall within this range. It is expected that the hardpan/dried sludge simulant strengths will need to be refined, once the needed physical property characterization data are available.

The recommended hardpan/dried sludge simulants are not appreciably soluble. It is known that the retrieval of at least some of the hardpan wastes is improved when a low-ionic-strength sluice fluid is used. This implies that dissolution is a potential retrieval mechanism for some hardpan wastes. It is not expected, however, that all dried sludge will be appreciably soluble. The recommended hardpan dried sludge simulants (kaolin/plaster) do not presume waste solubility, so the performance of dissolution-based waste-retrieval processes against these simulants is likely to be worse than would be expected if the processes were applied to actual waste. For dried sludge that is soluble, using chemical dissolution to weaken the sludge before conducting waste retrieval using medium-pressure waterjets may be advantageous. Also, the sludge in Tank A-105 has been found to be hard dry grout-like material that is likely immune to low-pressure water jets.

Mechanical strength measurements made using chemically based hard saltcake simulants were used as the basis for selecting the target compressive strength of the hard saltcake simulants. At the time that the saltcake simulant recipes were developed (1996), no such measurements had been made using actual saltcake samples, but the selected target strengths are consistent with qualitative descriptions of the hard saltcake strength. Similarly, the target strengths of the soft saltcake simulants are consistent with the “soft snow cone” descriptions given for samples of soft saltcake.

Dissolution rate data indicate that the K-Mag hard saltcake simulants dissolve more slowly than the rate expected for the actual hard saltcake. For this reason, the hard saltcake simulants (K-Mag) might not be appropriate for testing dissolution-based retrieval methods. Predicted hard saltcake-retrieval rates for dissolution-based retrieval methods, based on the testing of K-Mag simulants, will likely be much lower than the actual rates. The porosity of the soft saltcake simulants (rock salt/plaster) is much higher than that expected for hard saltcake, so the soft saltcake simulants are probably not useful for predicting the dissolution rates of hard saltcake. The development of appropriately soluble hard-waste simulants is a continuing effort.

The rock salt/plaster simulants for soft saltcake appear to approximate the dissolution characteristics of soft saltcake reasonably. Uncertainties in the saltcake porosity and morphology prevent accurate, quantitative comparisons of simulant and saltcake dissolution rates, but dissolution rate testing for various salts supports the validity of the rock salt/plaster simulants.

1.3.2 Performance-Based Simulants

Future test work with waterjet-based retrieval would benefit from the use of performance-based simulants tailored to the phenomenon associated with waterjet mobilization, erosion, and retrieval (e.g., entrainment) of tank waste. This is in comparison to circa 1990 testing that relied on simulates developed based on predicted material properties. Meacham et al. 2012, Wells et al. 2011, and Lee et al. 2012 are examples of performance-based simulants. Performance-based simulants become very useful in addressing the uncertainties of waste properties and provide future retrieval projects with data that can be used in comparison and contrast to actual waste retrieval operations.

1.4 Systems-level Approach

The ability to achieve the goals of any waste retrieval campaign is highly dependent upon a systems-level approach. The topic of this report is specific to CSEE technology; however, the CSEE is only the “tip of the iceberg.” A number of systems are necessary to enable the success of the CSEE. Simple categorical areas include how to access the tank (i.e., riser size), how to enter the tank (via a remote arm, a remote vehicle, or another subsystem [as in the GAAT work] that deploys the CSEE for use by the arm and the remote vehicle in tank, how the waste is mobilized and removed locally, then how waste is removed from the tank, and how the waste is transferred to its next destination. Each of these subsystems has a myriad of requirements that must be met in order for the system to successfully operate in the waste tank. . An introduction to a typical remote systems consideration has been documented (Bailey et al. 2009).

2.0 Historical Applications of Confined Sluicing at Oak Ridge Reservation and other DOE Facilities

2.1 Oak Ridge Reservation GAAT Retrieval

2.1.1 System Overview

The Oak Ridge Reservation's GAAT are a group of eight underground gunite storage tanks built in the 1940s having capacities of either 161 m^3 (42,500 gallons) or 643 m^3 (170,000 gallons). Some of these tanks had some of the waste removed in the 1980s using standard hydraulic sluicing that left behind a hard waste deposit in the heel of these tanks up to a depth of 0.9 m (3 ft) and associated radiation levels up to 200 R/hr. In the late 1990s, the remaining waste on the tank bottoms was removed from these tanks using remote retrieval technologies using medium-pressure sluicing/scarifying techniques and integrated into the Waste Dislodging and Conveyance System (WD&C). This system was deployed into the GAAT for retrieval operations using a long-reach manipulator known as the MLDUA or a remotely operated vehicle system called the Houdini. The discussion below is limited to GAAT retrieval operations that used a medium-pressure CSEE for the GAAT tank heel retrieval. Our discussion of the Gunite Scarifying End Effector (GSEE), adapted from the CSEE, is limited as its primary function was to clean/scarify the GAAT walls (removing up to 0.1 inch depth of wall material) after waste retrieval operations were completed (PNNL and DOE/EM 2001).

The CSEE with its more confined medium-pressure water jet spray(s) was developed as an option to the past practice sluicing (the baseline technology at the time for tank waste retrieval that used large nozzle jets that covered up to the full tank waste volume).

Advantages of the CSEE over past practice sluicing includes:

- Short standoff distance resulting in greater control of sluicing operations
- Less water usage to remove the waste
- Waste heels that resist mobilization by long-range sluicing jets have a high potential to be removed

Disadvantages of the Oak Ridge National Laboratory (ORNL) GAAT CSEE design for consideration in waste retrieval operations include:

- Small amounts of water must be added to the tanks to operate the CSEE
- Operating the CSEE on an arm or a remotely operated vehicle is expensive and requires specialized training

This technology has the potential for use at other DOE sites for tank waste retrieval and tank cleaning. Depending on the specific requirements for tank waste retrieval operations, the ORNL GAAT-style CSEE may be modified to address special needs (e.g., larger size for larger tank volumes, use of larger access ports, minimization of water use, jet stream modifications including size, number, location, angle, pressure, etc.).

2.1.2 Description of the System

For the ORNL GAAT tank retrieval, the WD&C components included:

- The CSEE, which helped break up the sludge waste
- The water power eductor (jet pump), which was used to remove waste from the tanks
- A waste transfer hose
- the Hose Management Arm (HMA), which supported the hoses connecting the CSEE and the jet pump
- The flow control equipment box and confinement box, which contained the control hardware for the WD&CS and waste slurry sampling
- The decontamination spray ring (DSR) used for decontamination
- The graphical user interface (GUI)

The CSEE is deployed by either robotic arm (MLDUA) or robotic crawler (Houdini). In-tank and out-of-tank CSEE GAAT retrieval support systems at ORNL are shown in Figure 2.1 and Figure 2.2. A detailed description of the ORNL GAAT systems (including the CSEE and GSEE) and ORNL retrieval operations are detailed in GAAT Lessons Learned (ORNL 2003a and ORNL 2003b).

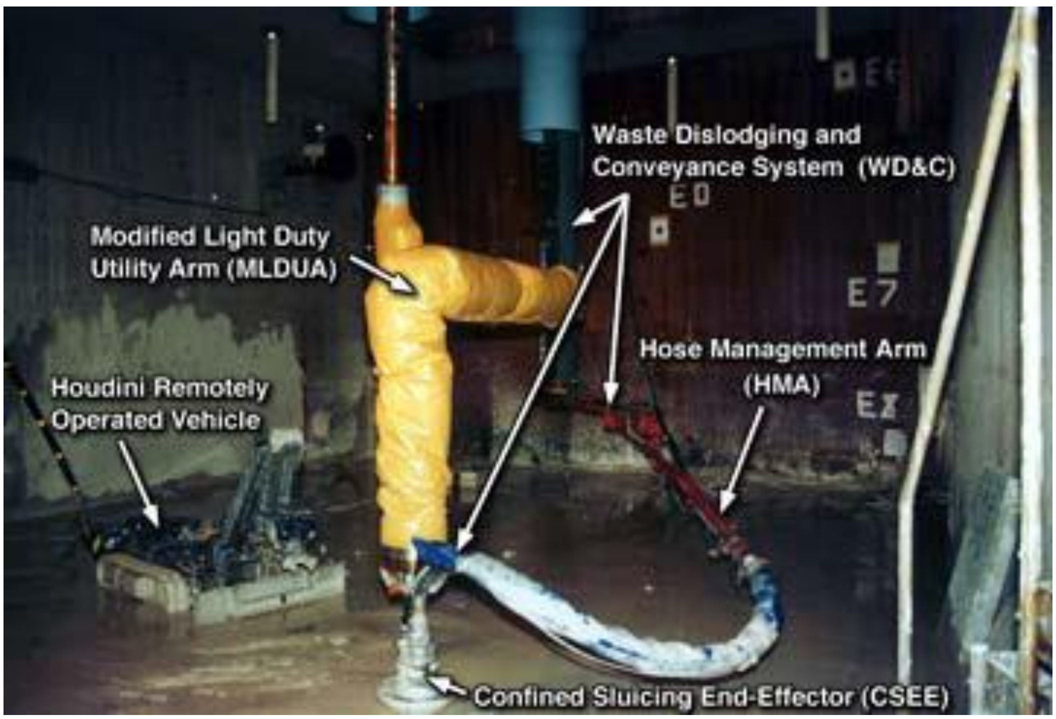

Figure 2.1. ORNL GAAT Retrieval In-tank WD&C System with CSEE

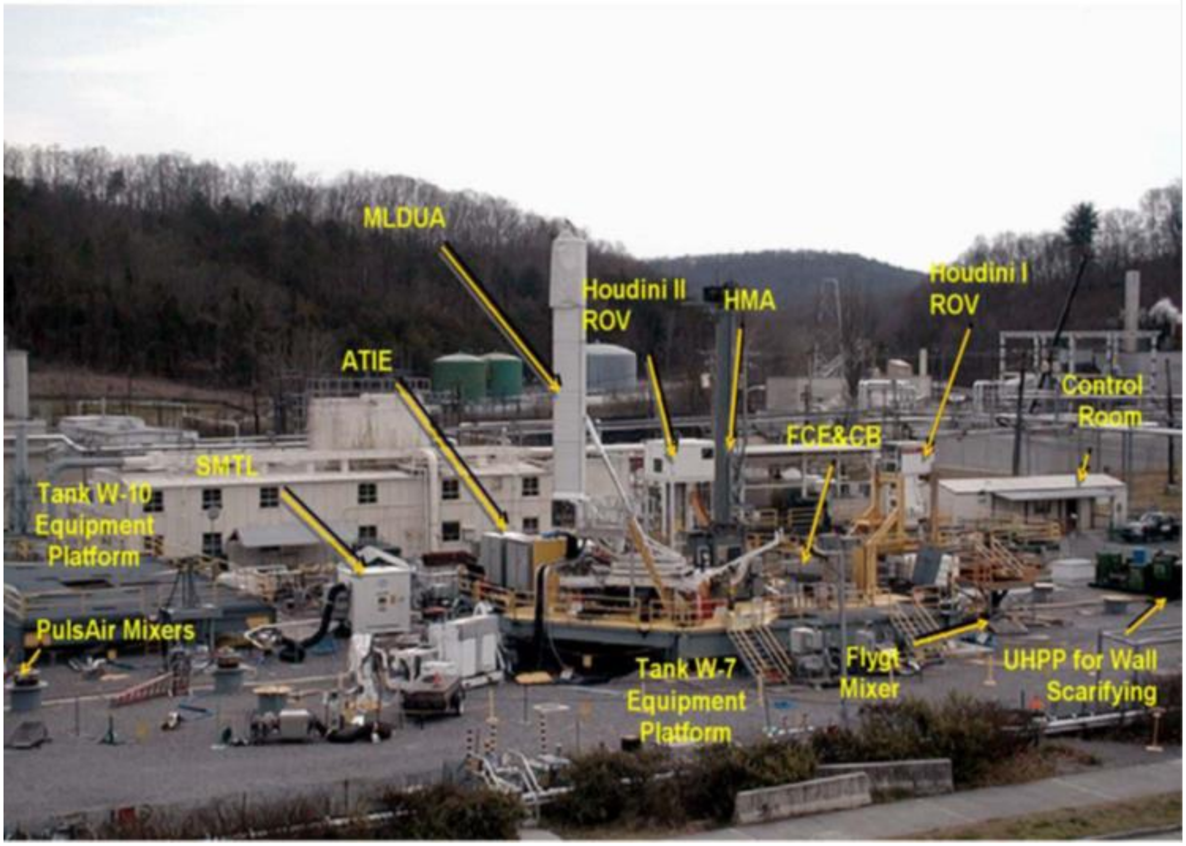

Figure 2.2. ORNL GAAT Retrieval Out-of-tank Support Systems including Deployment Systems

A high-level description of the CSEE is found in (DOE/EM 2001). Summary details of the CSEE, its associated WD&C key components, and its associated deployment options are described below.

2.1.2.1 Confined Sluicing End Effector

System Attributes: Rotating water-jet cutter and retrieval head used to dislodge and mobilize sludge and (some) solid waste. Cutting jets operate from 200 psi up to 7000 psi (system components and construction rated to 10,000 psi—administratively limited to 7000 psi) and can be rotated at 0-600 rpm to break up the sludge and create a slurry. Waste is removed from the tank through the opening in the base of the CSEE by the jet pump (see below) which is mounted in the HMA mast (developed by PNNL and MUST). The CSEE devices are shown in Figure 2.3 and 3.4.

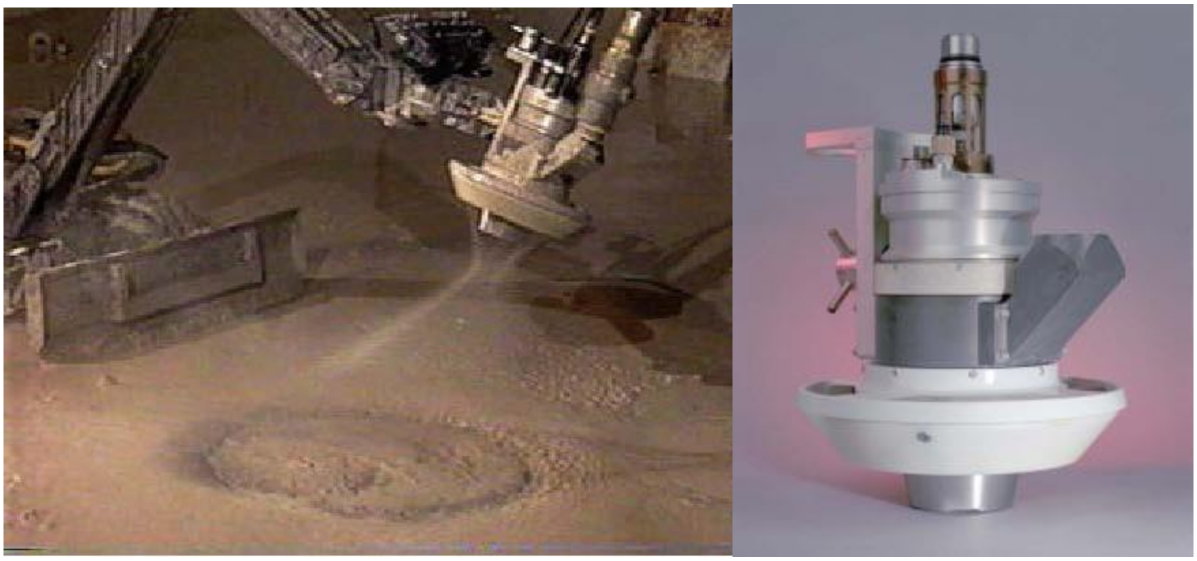

Figure 2.3. CSEE Device and Operation View of the CSEE held by Houdini I and Showing the Rotating Cutting Jets Used to Mobilize Waste Material from the GAATs

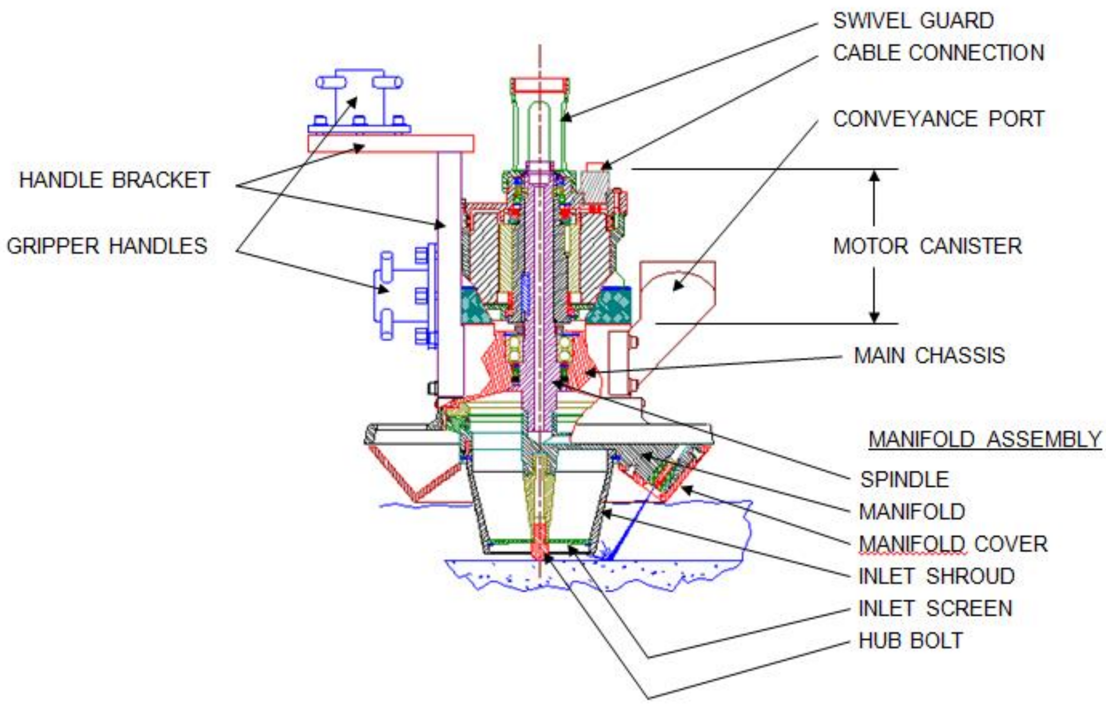

Figure 2.4. CSEE Schematic Cross Section Showing Components

Waste Form: The CSEE is primarily designed for the retrieval of soft and/or hard sludges. It can also be used without cutting jets to remove excess supernatant. It was used in GAAT with some success to scarify tank walls; however, the narrow focus of water jets (~2-in. diameter) and stand-off distance limit its efficiency as a wall scarifying tool. It was also used with limited success to dislodge some solid waste deposits in the tanks. Reliability, Availability, Maintainability: Reliability during GAAT retrieval was relatively high. The most significant maintenance problem was worn seals on the rotating portion of the assembly; the solution was to replace the seals at the conclusion of operations in each tank. Seal replacement is recommended after every 100 hours of operation at the nominal rotation speed of 300 rpm and requires removal of the CSEE to a maintenance facility and then 6 – 12 hours of labor using special tools for disassembly/assembly and seal and bearing replacement. Because seal life is related to rotational friction, which increases with rotational speed, theoretically seal life could be extended by reducing the rotational speed, but there is no data to quantify this. Seal replacement during retrieval was generally accomplished during down-time (equipment relocation) between tanks to reduce schedule impact.

System Operability: For GAAT retrieval, the CSEE was deployed as the HMA's primary end effector. The HMA provided tether management for the waste transfer line, cutting jet water line, rotate motor power cable and signal cable. Water for the CSEE cutting jets was provided by an above-ground medium-pressure water pump capable of providing 10,000 psi at 10 gpm. Motor control for the CSEE rotate motor required 60 Hz, 208 VAC at 10 A continuous (50 A peak). Gross decontamination was provided by the HMA decontamination spray ring during withdrawal from the tank. Hand decontamination using portable high-pressure spray wand was required to reach all nooks and crannies of the CSEE.

Environmental Considerations: Operation of cutting jets can add significant volumes of process water to the waste stream. On average, the ratio of cutting jet process water volume to sludge volume removed was ~2:1. It was found that the ratio increased during operation, especially during final surface cleaning. The ratio of cutting jet process water volume to sludge volume removed during retrieval was higher than the 1:1 ratio measured during initial prototype testing at MUST, where only bulk retrieval efficiency was tested. Because the GAATs were not leaking, water minimization was not a limiting requirement.

Public/Worker Health & Safety: Negative pressure maintained in tank during CSEE operation. Decontamination of equipment was required when it was withdrawn from the tank. Precautions were required as associated with high-pressure hydraulic operations.

System Design Details: The CSEE sluicing end effector was equipped with three rotating cutting jets mounted 120 degrees apart. The jets, which were capable of delivering water at pressures of up to 69 MPa (10,000 psi), nearly converged at a point about 5 cm (2 in.) below the conveyance line intake on the end effector. As the jets rotated, hard waste was dislodged, removed by the motive force provided by a jet pump mounted upstream in the mast of the HMA.

The CSEE's rotating manifold was a 15-5 stainless steel weldment with the rotor section cut from a single block of plate and welded to the shaft. The manifold arms were normal to the rotation axis and the jets converged at an angle of 35° to the axis and a 5.5° lead angle with respect to the counterclockwise rotation. The water jet nozzles were Leech & Walker type carbide inserts (0.032-in. diameter) selected for their high-velocity coherent cutting-jet capability. They were mounted in a custom compression-seal holder that could be installed with just a socket wrench and also contained in-line flow straighteners placed behind the jets. The flow straighteners were used to enhance the jet coherence and compensate for the acute bend in the water path upstream of the jet.

A 10,000-psig rotary coupling adapted the manifold to the supply hose and was supported against bending moments by an external cage mounted on the motor case. The manifold and motor case were mounted to the main chassis, which included the protective fiberglass shroud ring, grab handles, and conveyance suction port. An inlet shroud with a 3/8-in. hex screen was fitted to the manifold.

The CSEE frameless DC servomotor used to drive the manifold rotation was powered by a 300-Vdc 10A (continuous), 45-A (peak) power supply operating through a DC servoamplifier. The motor stator was pressed into the aluminum canister and the bearings and seals at the canister bottom and upper end cap supported the rotor. The manifold armature passed through the large central bore of the rotor, to which it was keyed to transfer torque. The motor included Hall-effect sensors for feedback. The motor achieved rotational speeds from 60 to 600 rpm. During confined sluicing operations, 300 rpm was used because at lower speeds the motor tended to stall and at higher speeds the CSEE tended to sling sludge material. The motor umbilical was routed along with the waste transfer line through the HMA vertical deployment mast; therefore, no deployment reel was required.

The rotating cutting jets surrounded a vacuum head that connected to the waste conveyance system, integrated with the HMA. The dislodged waste was aspirated into the conveyance line through the central inlet system. Sludge retrieval rates as high as 8 gpm were observed during cold testing. The CSEE consumed about 10 gpm of process water, most of which was needed to drive the jet pump. The ratio of water volume used to sludge volume removed during retrieval was higher than the 1:1 ratio measured during initial prototype testing at UM-R, due to geometric design constraints imposed on the CSEE to fit into the 20-inch diameter tank riser.

CSEE controls and instrumentation included a power switch and emergency stop, rotational direction and speed controls, speed and torque (inferred from current) indicators, and data connections. The local CSEE controls, amplifier, and power supply were housed in a splash-proof enclosure on the equipment platform and interfaced to remote controls and instrumentation at the control room. The CSEE was demonstrated to tolerate 2000-psi wash-down and to be readily decontaminated by a tank riser DSR and a handheld spray wash gun inside the deployment system glovebox.

The CSEE, including one grab handle, weighed 46 lb. It generated only moderate dynamic forces during cold testing, so it was compatible with the structural capability of the MLDUA. The CSEE is made of aluminum, stainless steel, and selected polymers. It proved sufficiently resistant to the radiation levels and chemical environment of the ORNL tanks deployed. This is likely due to the fact that design/fabrication addressed material compatibility for radiation and chemical contact.

2.1.2.2 Axial Flow Jet Pump

An axial flow, water-powered eductor that uses up to 7000 psi process water to create a negative pressure was used to vacuum the waste from the tank via the CSEE. The jet pump portion of the HMA was a commercially available axial-flow pump that conveyed all the waste retrieved. The pump was modified with hardened stainless venturi nozzles after cold testing revealed that the standard aluminum bronze nozzle was prone to rapid erosion. Each of the three motive jet nozzles included a hardened steel insert with a short, steeply tapered inlet, set in hex-socket threaded inserts, with the jet discharging through the hex sockets. The pump was drilled for six nozzles, but no performance advantage was obtained with six versus three. Therefore, only three equally spaced nozzles were used and the three remaining nozzle ports were plugged. The jet pump generated the vacuum required at the CSEE inlet to retrieve the waste slurry and sufficient discharge pressure to remove the slurry from the tanks. The jet pump was rated at a motive pressure of 10,000 psig and 12 gpm but was typically operated at 7000 psig, consuming about 10 gpm of filtered process water for the motive jets. The jet pump was installed near the bottom of the HMA mast and discharged through a pipe straight to the top of the mast. A flexible-hose jumper was used to connect the jet discharge to the balance-of-plant piping.

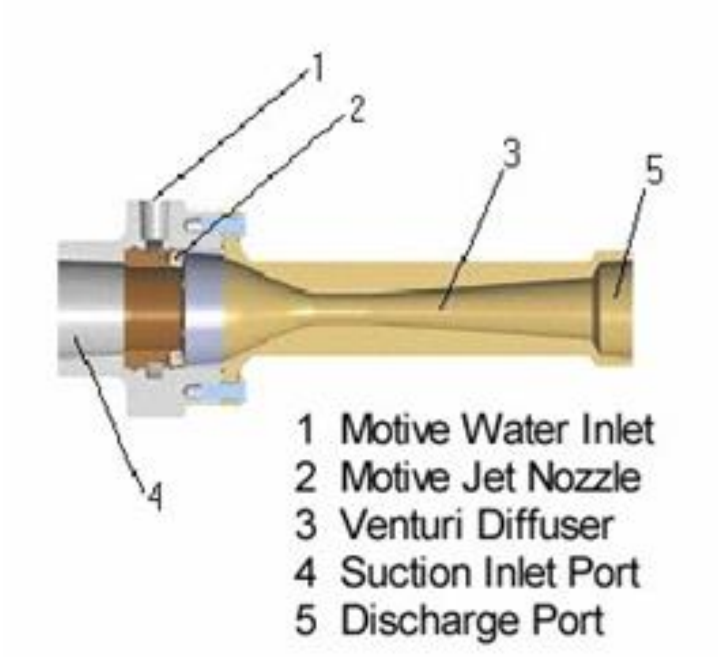

Figure 2.5. An Illustration of the Components of the Axial-flow Jet Pump

2.1.2.3 Hose Management Arm with Jet Pump Conveyance System

The HMA was designed to act both as a pipeline for the transfer of dislodged waste and as a hose-positioning system. ORNL and staff from The Providence Group Applied Technologies designed the HMA to provide access to all points within a 15-m (50-ft) or smaller diameter tank. The HMA would require redesign to accommodate a 75ft diameter tank (i.e., A-105). The arm had four degrees-of-freedom (DOF): mast vertical travel, mast rotation, shoulder pitch, and elbow yaw. The mast was constructed of a half section of 51-cm- (20-in.-) diameter, carbon steel pipe with a flat plate welded across the half section as a seal. The mast housed a variety of pipes and instrument cables, the CSEE and jet pump's motive water supply lines, the jet pump, and the waste conveyance line. The arm links of the HMA were constructed from Schedule 80 carbon steel pipe; the inner link was connected to the mast via an elbow swivel joint, while an in-line swivel between two 90-degree elbows connected the inner and outer links. A plate at the top of the mast interfaced with the mast evaluation table (MET). The MET provided support to the mast and was equipped with drive systems to control elevation and rotation of the HMA.

2.1.2.4 Flow Control Equipment Box and Confinement Box

Above-ground process piping, valving, and instrumentation attached to the waste stream discharge of the HMA included valves for flow control, flushing, and automatic in-line sampling of the waste stream. Instrumentation was incorporated to facilitate real-time monitoring of the waste stream flow rate, density and volume. The WD&CS interfaced with the destination tank and/or process piping and equipment. The confinement box provided secondary containment for the waste piping on the HMA and also allowed access via gloveports for operational and maintenance activities on the HMA and CSEE. The interface contained a 1.5- ton hoist for retracting the HMA and is used to store the arm during relocation operations. The flow control equipment was equipped with sluicing discharge piping, including valves for flow control, flushing, and automatic sampling of the waste being retrieved. Instrumentation in the flow control equipment allowed discharge flow rate and density to be measured as well.

2.1.2.5 Decontamination Spray Ring

The DSR contained a ring of spray nozzles that were used to wash down the HMA and CSEE as they were retracted from the tank. The DSR, designed by Southwest Research Institute, was located between the confinement box and the tank riser.

2.1.2.6 Graphical User Interface

The GUI linked to the low-level control systems of the CSEE, HMA, and flow control equipment and to the associated valves, water supplies, and medium-pressure pumps that form the balance-of-plant for the WD&C system. The GUI allowed an operator in the control room to monitor and control sluicing and decontamination activities.

The two CSEE deployment vehicles in tank are described below.

2.1.2.7 Modified Light Duty Utility Arm

The MLDUA was an 8-DOF robotic arm with a 200-lb payload and 15-ft horizontal reach. The base of the arm does not move laterally and would not be adequate for A-105 retrieval. It could deploy and operate a variety of tools and equipment in underground storage tanks. Arm joints were primarily hydraulically actuated. Two joints, wrist roll and mast roll, were actuated by electric motors.

2.1.2.8 Houdini Vehicles

The Houdini was a remotely operable, tracked vehicle with integral 6-DOF manipulator arm, onboard camera system, and plow blade. Manipulator arm had a 2 m reach and 240-lb payload capacity. Vehicle collapsed for deployment and retraction and was expanded to a 4 x 5-ft platform. Motivation was skid-steered with a maximum speed of 1 ft/s. Two vehicles (Houdini I and Houdini-II) were built. Houdini-II was a second-generation vehicle that incorporated lessons learned from its predecessor during early cold-testing and deployment in the GAAT.

2.1.3 Current Status of the System

A report (ORNL 2001 V1 & V2) states that the CSEE was “packaged and in interim storage at SWSA-6 awaiting disposal as contaminated metal.” Now 15 year later, the CSEE is likely disposed of and therefore not available for reuse.

2.1.4 System Performance

The CSEE system performance described below is specific to ORNL GAAT tank waste retrieval done in the late 1990s timeframe.

2.1.4.1 ORNL GAAT Retrieval

The information in this section is summarized from (ORNL 2001; ORNL 2003). Confined sluicing operations for ORNL GAAT waste retrieval with the CSEE were generally most productive in the deep, softer sludge encountered at the beginning of the waste retrieval operations, as is evident from the specific efficiency plots (Figure 2.6). In this figure, the secondary Y axis is the ratio of waste retrieved to water used. Referring to this figure, in W-6 tank retrieval, the initial day of sluicing operations resulted in an average retrieval rate of 7 gallons of sludge per gallon of water used. As the level of waste in the tank was reduced, it became more difficult to maintain ideal pumping conditions (a flooded suction inlet and low-viscosity slurry), which resulted in a reduction in the retrieval efficiency. The retrieval efficiency continued to decrease as the depth of the remaining sludge decreased; the sludge density and overall hardness of the waste increased; and more buried debris was exposed. The instantaneous efficiency typically dropped off quickly to about 4–5 gallons of water per gallon of waste. The CSEE was most efficient when partially submerged, although care was needed to avoid burying the CSEE to the point of clogging the rotating cutting-head seal. The most efficient shallow-sludge (1–3-in.) operation was found to be with the CSEE held stationary near the tank floor while the Houdini Remotely Operated Vehicle (ROV) plowed sludge toward the CSEE inlet. A chronological plot of the waste retrieval operations in tank W-6 is provided in Figure 2.7. This figure also indicates the approximate amount of water that was added to the tank during tank W-6 operations.

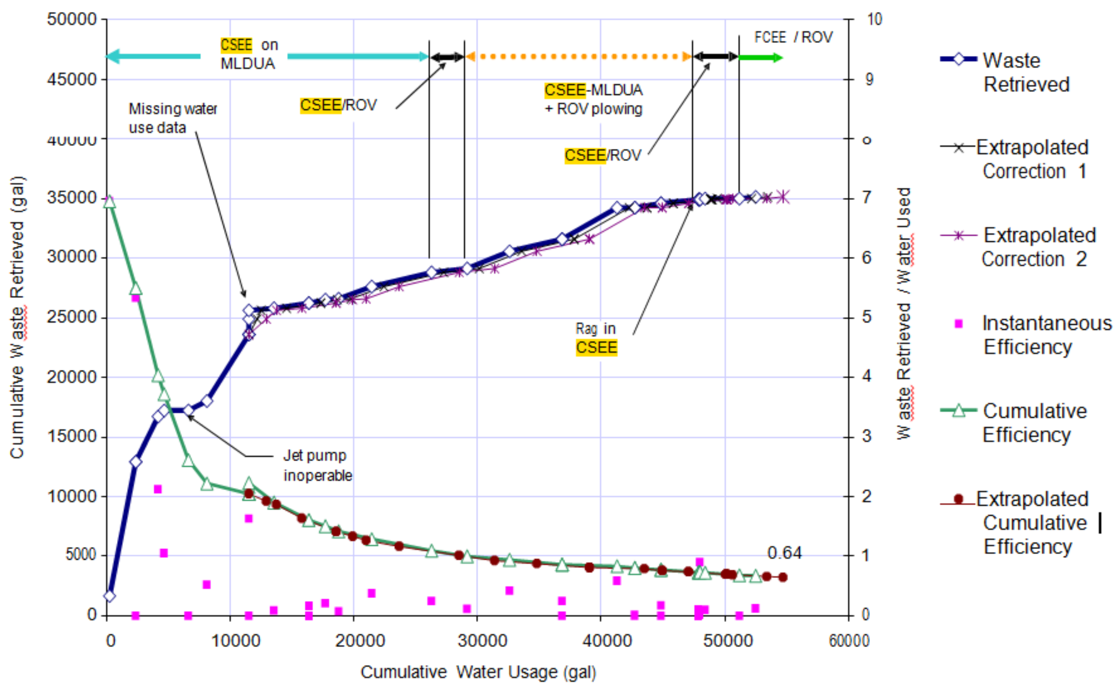

Figure 2.6. Waste Retrieval Efficiency for Operations in Tank W-6

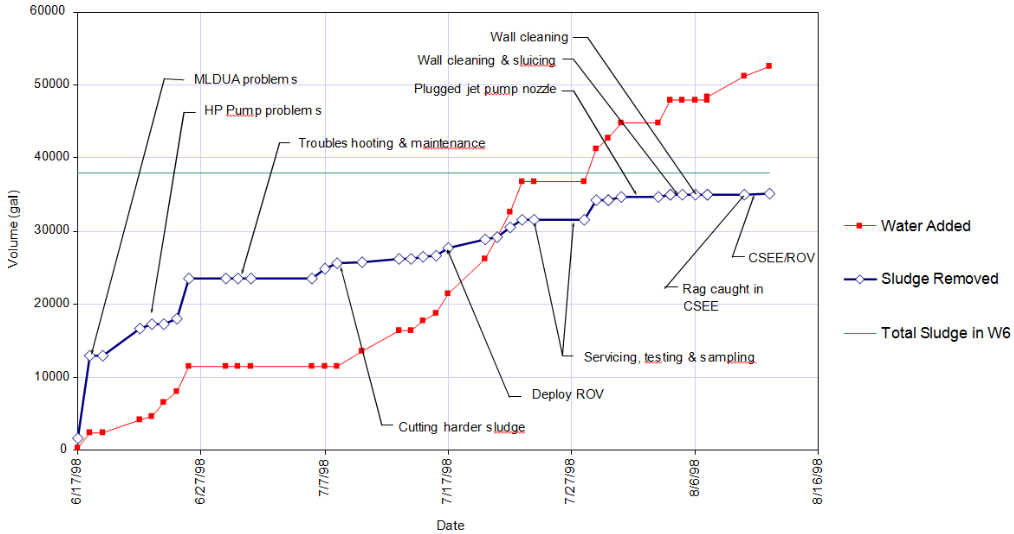

Figure 2.7. Chronological Plot of W-6 Retrieval Operations

Typical cutting jet pressures required during sludge removal ranged from 1000 to 4500 psi. Generally, higher pressures were found to be unnecessary for the soft sludge encountered and detrimental as they tended to cause undesirable behavior of the MLDUA and increased "fogging," which decreased visibility in the tank. The most efficient deep-sludge technique was found to be partial submersion of the CSEE, which prevented three phase flow. Care had to be taken to avoid burying the CSEE so deep that sludge could readily clog the rotating seal. The most efficient shallow-sludge (1-3 in) technique was found to be stationary placement of the CSEE by the MLDUA near the tank floor while the Houdini plowed sludge piles to the CSEE inlet. During supernatant removal, cutting jets were operated at low pressure (~150 psi) to prevent nozzle clogging. Toward the end of the project, clogged nozzles were found to contain what appeared to be rust particles. Most components were stainless steel, but there were a few carbon steel components on the high-pressure water supply side. The use of all stainless steel high-pressure supply components could have prevented this issue. Large quantities of in-tank debris could potentially reduce the efficiency of the CSEE significantly. The CSEE waste inlet was covered with a course (~3/8-in. grid) wire mesh screen that was prone to clogging with in-tank debris during sluicing operations. Initially, the primary method to dislodge clogs was back flushing with process water. Occasionally, this approach was not successful and the CSEE had to be retracted to the above-ground HMA confinement box for manual debris removal. Later in the project, a remote debris removal tool was developed for use by the Houdini (while the MLDUA maintained its grasp of the CSEE). The result was a significant increase in operational efficiency (reduced down-time and reduced freshwater usage).While cutting jets added a significant amount of water to the waste stream, they proved to be indispensable, increasing overall waste removal.

2.2 Other Confined Sluicing Types of Technology Development

2.2.1 Hanford Waste Retrieval End Effector

As part of the Hanford Tanks Initiative (HTI) Project, a contractor team led by Foster Wheeler proposed to deploy a device derived from the CSEE with a remote crawler to remove sludge and hardpan from Tank 241-C-106 during a retrieval demonstration. A test report for the WREE performance testing is provided in Appendix A of this report. The prototype, denoted the Waste Retrieval End Effector

(WREE), was fabricated by Oceaneering International, Incorporated in November 1998. This activity supported HTI and the Foster Wheeler team by providing prototype testing to validate the design and verify that performance objectives are met or exceeded. Under this task, PNNL staff installed the prototype WREE on the a robotic gantry, installed instrumentation to measure reaction forces and process parameters, prepared and characterized simulant materials, and implemented the test program. The completed tests involved retrieval of water, sludge, hardpan, and debris to determine pumping rate, dilution factors, and filter fouling rate. Following the retrieval tests, the WREE was cleaned with a 3000 psi waterjet to simulate a decontamination process. The WREE was then examined to determine the amount and location of residual sludge on the exterior portion of the WREE; the WREE was also disassembled to identify internal leakage, seal damage, and sludge residue.

The test objectives established in the test plan were successfully addressed except for measuring aerosol generation during floor scarification. The aerosol measurements were taken during short duration tests under somewhat uncontrolled conditions and may not be indicative of conditions during tank deployment. Short duration tests with wet sludge and hardpan were conducted to measure baseline performance. The retrieval goal for the WREE was 10 gpm, which was exceeded during retrieval of hardpan (without consideration of the time required to clean the inlet screen). The retrieval rate during sludge retrieval was 7 gpm, which is 30% lower than the target retrieval rate. However, because material did not accumulate in the conveyance line and the motor did not decelerate during the tests, higher retrieval rates are possible using a higher traverse speed or deeper WREE submersion in the sludge, especially after the sludge is diluted.

The WREE was to be used to fragment and dislodge waste and introduce the slurried waste into the inlet of a conveyance system. The design of the HTI WREE was based in large part on the CSEE; design changes were required due to differences in Hanford's waste physical properties, flammable gas requirements, radiation levels, and tank interfaces. The fundamental goal was to produce a highly reliable, compact, and lightweight end effector that could be decontaminated and maintained inside a glovebox. The performance of the WREE was expected to be somewhat better than the CSEE due to refinements in screen design and conveyance inlet geometry and the replacement of CSEE's electric motor with a high-torque hydraulic motor. The prototype WREE was fabricated by Oceaneering International, Incorporated and delivered to PNNL in November 1998. The weight of the end effector, measured before the tests were begun, was 87 lbs including the T-handle extension.

The status of the WREE system is unknown as it was delivered to the Hanford Tank Farm Operating Contractor upon completion of the work.

2.2.2 Silo Retrieval End Effector

In 2000, Foster Wheeler evaluated confined sluicing for retrieval of the bentonite cap and K-65 waste material inside the Fernald Silos. The system would be used to retrieve the bulk waste from the silos using past-practice sluicing though the use of a high-volume deployed nozzle through one peripheral riser and a retrieval pump through the second peripheral riser. A robotic arm denoted the Easily Manipulated Mechanical Arm™ (EMMA™) was to be used to deploy a Silo Retrieval End Effector (SREE) within the tanks for heel removal and floor cleaning. Note that this system was never deployed, due to issues with the EMMA™, but is described here for illustrative purposes.

The concept of operations of the retrieval system was as follows. The slurry from the SREE was sucked into a jet pump and was transported into a conditioning and transfer system that was located as close to the tank floor as possible. A hose management system between the end effector and the conditioning and transfer system ensured that the heel retrieval hoses did not create undue loading to EMMA™. Hose management was accomplished through a simple cable system to allow the SREE to be operated within the entire silo floor area.

The SREE was very similar to the CSEE and consisted of three rotating jets that were used to locally slurry material and direct the slurry to a central inlet that had a 2-inch diameter. The nozzles operated at up to a maximum 10,000 psi at approximately 10 gpm. To remove the slurry from the central inlet port, a radial waterjet pump was integrated as close to the SREE as possible. The jet pump required approximately 10,000 psi of water at approximately 10 gpm. A flexible skirt design is used on the SREE to confine spray when operating on hard surfaces at higher pressures during final floor cleaning. This design was known, through CSEE testing, to reduce mist generation and its impact on performance of visual surveillance systems. The SREE had flow passage geometry and a pressure/vacuum relief to maintain airflow in the event of a plugged inlet, thereby preventing settling in the conveyance line. The conveyance line had backflush capabilities to clear any plugs.

The SREE was constructed by PNNL and delivered to Foster Wheeler. The current status of the system is not known, but the SREE was not deployed in the silos, so no operational data is available.

3.0 Application of Confined Sluicing to A-105

3.1 Description of Tank A-105 and Waste

The target tank selected for alternative waste retrieval is 241-A-105. Tank 241-A-105 is a omillion gallon, SST, built in 1955, placed into service in 1962, and held PUREX waste. The tank is 75 ft. in diameter (I.D) and approximately 35 ft. high. It has a 42-inch riser located in the center of the dome. This tank was constructed with 4 in-tank airlift circulators, each 24-inches in diameter to enhance waste cooling capability.

Based upon operational data and information from operators (Girardot 2013) and potential steam excursions that occurred between the tank liner and the concrete in the 1960s, it is clear that there is a rip or tear in the tank liner. Figure 3.1 and Figure 3.2 below show the tear. An artist's rendition of the waste topography and tear are shown in Figure 3.3. Note that the tear is near the edge of the tank and appears to be around 75% of the inner circumference of the tank.

Figure 3.1. Tank A-105 Liner Bulge

Figure 3.2. Liner Separated from Tank Wall

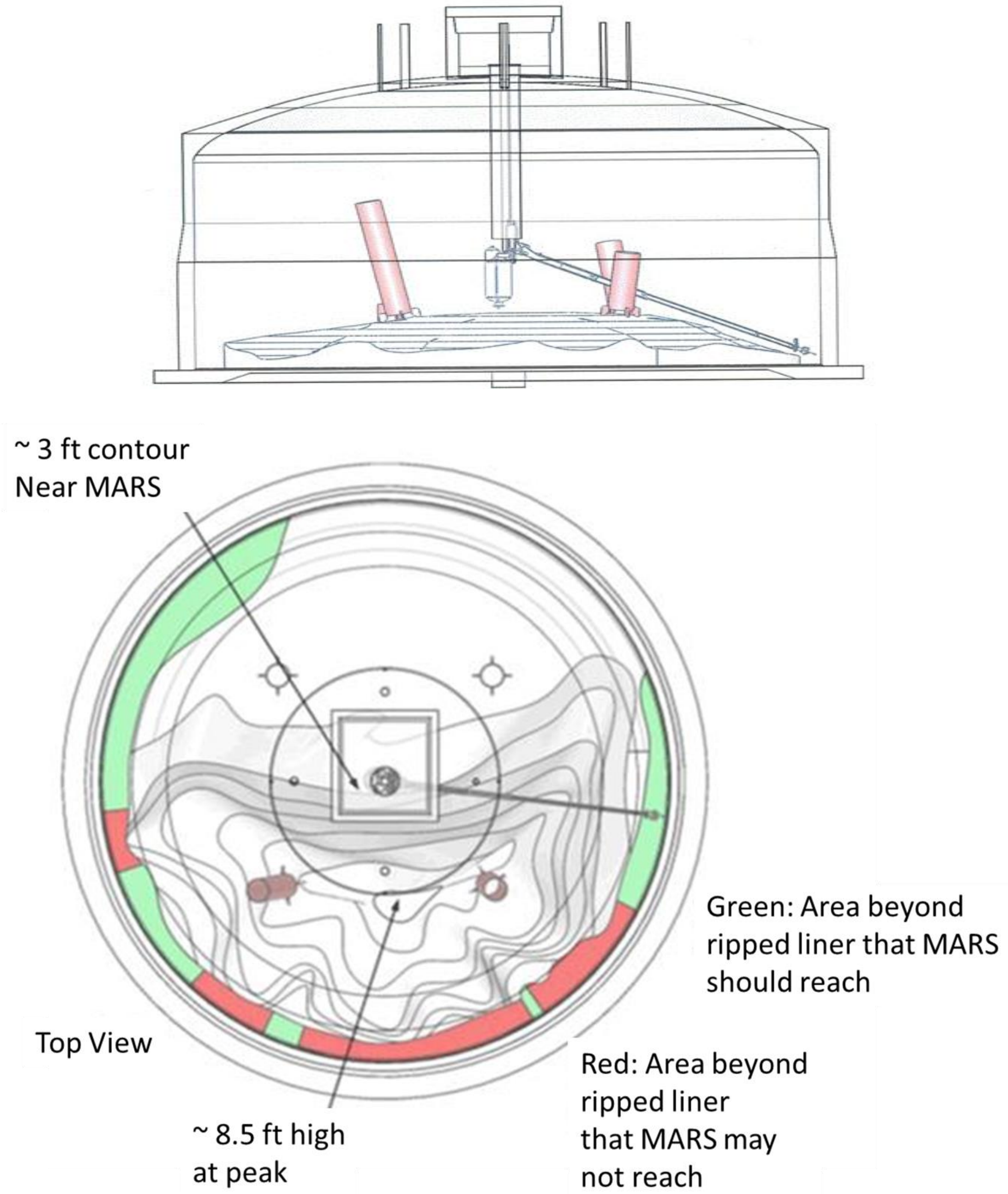

Figure 3.3. Example MARS-Vacuum-Bulge Interference and Waste Topology during Retrieval

In 1977, tank 241-A-105 liner was mapped to estimate the volume under the bulged liner and the waste volume in the tank. The volumes of sludge were estimated to be as follows using a model assuming an essentially dry waste. The volume of sludge between the bulged and ripped liner and the wall of the tank was estimated to be a least 28 kL (7.5 kgal) but not more than 34 kL (9.0 kgal), with an average of 31 kL (8.2 kgal). The volume of sludge on the liner was calculated to be 44.3 kL (11.7 kgal). The total tank waste volume obtained from summing the sludge volumes under the liner, between the liner and the tank wall, and on the liner is 139 kL (37 kgal). The entire waste volume is attributed to the dry sludge layer. A separate drainable interstitial liquid inventory was not determined for this tank because the remaining waste in the tank should be dry (as a result of the high heat waste; the temperature of the tank was reported to be above 100 degs C up until 1969 (Girardot 2013).

Little is known about the waste characteristics in A-105, but based upon operational data, there are several important factors that should be noted. The contents of A-105 waste was PUREX high-level waste; its characteristics are shown in Table 3.1. Initial additions early in A-105 operations were moderate temperatures. However, in 1965, the PUREX waste that was introduced into the tank was self-boiling as temperatures rose above 210F. At one point the tank was full when the suspected steam event occurred, ripping the bottom of the tank liner. Subsequent operations pumped out the liquid waste. In addition, there were several sluicing campaigns to remove as much of the waste as possible. Following those operations, samples were taken and lab experiments determined that sulfuric acid would help soften the waste. Two additions of small volumes sulfuric acid were added to A-105 to help soften the dried sludge for easier removal through additional sluicing campaigns. However, with additional detection of leaks, these operations were halted in the early 1970s and the waste has been left ever since, although there were some water additions to assist with air lift circulator cooling, although no specific data could be found to quantify this addition. While few conclusions can be made about the remaining sludge, we know that what is remaining was largely unaffected by sluicing operations that occurred in 1968. A second, more aggressive, sluicing campaign began August 1970 and was halted November 1970 after significant increases were detected in all the laterals underneath tank A-105. The waste has been drying out for several decades, which would likely indicate a fairly hard pan waste. Currently, there are no known samples of the sludge that have been taken other than for the early experiments with sulfuric acid. The comparisons (Harrington 2012) shown in Table 3.2 have been proposed to relate the simulant minerals to the waste materials.

Table 3.1. P2 PUREX High-level Wastes Generated between 1963 and 1967 (from Templeton 2016)

Waste Phase	Waste Type	Component Density (g/mL)	Component Wt% Water	Source
Sludge Solids	P2	1.54	44.2	1972 Sample results and P2 template

Table 3.2. Comparison between Simulant Minerals and Waste Materials

Simulant Material	Waste Material
Kaolin clay and plaster of paris	Gibbsite/Natrophosphate
Limestone	Gibbsite
Sand	Cancrinite or iron phase
Hematite	Iron phase

3.2 Potential Applicability and Known Challenges

3.2.1 Deployment

Various retrieval methods have been used to transfer waste from SSTs to double-shell tanks for safe storage, including: modified sluicing, enhanced sluicing using the Extended Reach Sluicing System, salt cake dissolution, and the Mobile Arm Retrieval System (MARS). The tank waste generally consists of a surface liquid layer (supernate/slurry), an intermediate layer of sludge material, and a bottom layer of solidified (hard-heel or salt cake) material. The waste slurry is pumped by the above mentioned systems from the SSTs to the double-shell tanks through a series of hoses, valve-boxes (which provide valving for switching to different transfer lines), and steel transfer lines.

To date, the Hanford tank farm operating contractor has used modified sluicing, enhanced sluicing using the Extended Reach Sluicing System, salt cake dissolution, and the MARS as the baseline waste retrieval technologies. Each process requires addition of liquids to the SSTs for heavy sludge and hard cake removal. The remaining materials can be granular like sand, hardened rock like materials (chunks), or a mixture of the sandy material with clay and the hardened chunks. Additionally, several of these tanks have very high radioactive dose rates (~24,000 R/hr total beta at the surface of the waste). The next series of tanks to be retrieved includes tanks that are known to have leaked. Although the liquid portion (supernate/slurry) is no longer present—leaving a heavy sludge, hard cake, or salt cake to be retrieved—reintroduction of liquids into the SSTs for retrieval presents environmental issues. An in-tank alternate retrieval system would allow removal of tank waste without introduction of any means that would allow waste to potentially leak from the tanks. The focus of this in-tank alternate retrieval technology maturation activity is to develop a system that will allow efficient and safe removal of tank waste, using an optimized waterjet pump educator and other system components to mobilize and remove waste simultaneously. This system ideally will control waste mobilization and conveyance in a way that mitigates the potential for any waste leakage from compromised tanks. Figure 3.3 shows the waste topography of Tank A-105 and the potential interferences between MARS and tank infrastructure.

3.2.2 System and Retrieval Requirements

In 1998, PNNL developed requirements for an end effector to support HTI. These draft requirements were developed for the WREE and will need to be evaluated against specific requirements for A105 retrieval. Specifically, requirements need to be in accordance with Design Loads for Tank Farm Facilities (TFC-ENG-STD-06). Those portions of the CSEE exposed to the interior environment of the waste tank must be designed to remain fully operational and achieve full design life when subjected to the following normal in-tank environment:

Temperature – Normal operation in temperatures that range from +25 degrees Fahrenheit to +115 degrees Fahrenheit

Chemical – Continuous exposure to waste material with a pH of 14

Physical – Normal operation in waste forms that include supernate, soft sludge, hard sludge (hardness similar to 100 psi grout), and hard salt cake (hardness similar to commercial salt block)

Humidity – Normal operation in environments with a relative humidity that ranges from 10% to 100%

Explosive Gases – Normal operation in environments containing potentially flammable gas concentrations

Pressure – Normal operation within a pressure range of +/- 7 inches of water

Radiation – Normal operation in a radiation field of 29,000 rad/hour

3.2.2.1 Environmental Design Requirements – Tank External

The CSEE shall be designed to be exposed to the following external environment of the waste tank and remain fully operational and achieve full design life.

Ambient Temperature – Normal operation in a temperature range from –20 degrees Fahrenheit to +120 degrees Fahrenheit.

Relative Humidity – Normal operation in a humidity range from 4% to 100%

Wind – Normal operation in wind speeds of up to 40 miles per hour. In addition, the CSEE shall be able to withstand, without damage, wind speeds up to 85 miles per hour.

Moisture – Normal operation in external rain environments with rainfalls at the rate of up to 2 inches per hour and snow environments with snowfall accumulations of up to 2 feet.

Dust – Normal operation in an environment which has periodic severe dust storms.

Storage – CSEE and support systems shall be designed to allow for storage in outdoor containers with internal temperatures ranging from –20-degrees Fahrenheit to +150-degrees Fahrenheit.

Water – A-105 is a known leaker and residual water must be minimized and/or eliminated.

3.2.2.2 Mechanical Design Requirements

General - The CSEE will be inserted into and removed from a tank by passing through the riser by means of the Waste Dislodging and Conveyance Umbilical Storage System. During operation, the CSEE will dislodge waste and cause it to enter into the Waste Conveyance System. The CSEE will be moved about inside the tank by the MLDUA and ROV.

Service Life - The CSEE shall be designed to operate for a minimum 200 hours without scheduled or planned maintenance. Service life of major structural components shall be adequate to support operation for three years. Service life of moving mechanisms, parts subject to wear or degradation, etc., shall be capable of supporting a minimum of 600 hours without replacement.

Tank Access Risers - The entry riser, through which the CSEE shall enter into the tank, shall be a 42-inch diameter riser, approximately 20-feet long. To assure free passage through the riser, the in-tank components of the CSEE were designed not to exceed a diameter of 36 inches when configured for entry/retraction operations.

Deployment - The CSEE, working in conjunction with the conveyance system and the ROV, shall have provisions to allow it to be attached to and detached from the MLDUA or ROV Gripper inside the tank. All such attachment/detachment operations shall be accomplished by the MLDUA or ROV Gripper with the CSEE being passive. When the CSEE is released by the ROV Gripper, the CSEE must reliably assume a configuration that permits it to be retracted from the tank.

Interfaces

Interface to MLDUA or ROV - The CSEE shall be attached and detached from the MLDUA or ROV gripper via a T-Handle. At least two T-Handles will be located on the CSEE that will allow the MLDUA or ROV to grip the CSEE from the side or from the top.

Interface to Conveyance System - The method of attachment/detachment between the CSEE and the Waste Dislodging and Conveyance Systems shall be accomplished with simple hand tools, using manual glovebox techniques. The CSEE shall remain attached to the Conveyance System Umbilical during deployment, gripping, and manipulation of the CSEE by the MLDUA or ROV and during retraction of the CSEE by the Conveyance System Umbilical winch.

Materials -In-tank components shall be constructed of materials resistant to the tank environment and qualified as spark resistant as much as practical to minimize the use of boots or coatings.

Utilities – The CSEE shall be designed to operate using the following described utilities:

½-inch ID	7,000 psi jet pump waterjets
½-inch ID	7,000 psi CSEE waterjets
½-inch ID	3,000 psi, 4 gpm, CSEE hydraulic motor (supply/return)
2-inch ID	200 psi jet pump discharge\suction

Contamination Control – The CSEE shall be designed to facilitate cleaning of contaminated surfaces. Design shall incorporate smooth surfaces and sealed segments for ease in decontamination.

Decontamination – The CSEE shall be designed to be decontaminated using the following chemicals and pressures:

Water spray (300 psi, decon ring or hand wand)

3 to 6 molar nitric acid (hand wipe or spray bottle)

3 to 6 molar oxalic acid (hand wipe or spray bottle)

Turco Cleaning Compound 4502 (hand wipe or spray bottle)

Note: As with the other candidate requirements, they need to be evaluated against the actual conditions in Tank A-105.

Maintenance – The CSEE shall be designed so the components that are most likely to fail are readily accessible and easily replaced as a unit or as a subassembly. The system shall be modular in design to facilitate fast repair cycles. All in-tank components shall be maintainable by personnel wearing anti-contamination clothing, including three pairs of latex gloves and likely working within an enclosure.

Lubricants – Nonvolatile radiation resistant lubricants shall be used.

3.2.2.3 Codes and Standards

Applicable codes and standards shall be used in the design of the CSEE. There will be a graded approach for applying codes and standards. The most current codes, standards, and orders shall be used.

Materials

All structural materials shall be in accordance with The American Society of Testing and Materials (ASTM) or American Society of Mechanical Engineering (ASME) standards.

Flammable Atmospheres

The CSEE shall be designed to meet the requirements of the National Fire Protection Association (NFPA), Code 70, "National Electric Code" defining requirements applicable to equipment to be used in Class I, Division 1, Group B environments.

Safety

The CSEE shall be designed to meet the requirements of 29 CFR 1910 (OSHA Latest edition).

Design

The CSEE shall be designed using the format\symbols as specified by the American National Standards Institute (ANSI) "Y" Series Standards and the American Welding Society (AWS) for welding. Structural Design shall be performed in accordance with the applicable requirements contained in American Institute for Steel Construction, Steel Construction Manual (AISC Latest edition).

Note that although the following system components were successfully used for tank retrieval at ORNL, use of these components to retrieve A-105 may require significant modifications prior to implementation. Table 3.3 details the CSEE specifications.

Table 3.3. Confined Sluicing End Effector Specification[1]

Specification	Criteria/limit	Explanation
Maximum working pressure	10,000 psi	

[1] These specifications are presented in this document for consideration only. The alternate retrieval technology chosen for A-105 retrieval may or may not replicate these design and construction parameters.

Specification	Criteria/limit	Explanation
Maximum operating pressure	7,000 psi 10 gpm	Testing has shown that 5,000 psi will provide adequate cutting of hardpan material. Having the capacity to use 7,000 psi will provide a performance margin if the heel is harder than expected. Pump technologies for 5,000 vs. 7,000 psi are similar, so the cost increment is minor.
Nozzle type	Hydrochem	Carbide insert type
Nozzle orifice size	0.044-0.058 inch	Nozzle size will depend on operating pressure. During sludge retrieval, pressure will be ~1,000 psi and large nozzles are required to provide enough cutting force and water lubrication. During hardpan retrieval, pressure will be 3,000 psi or higher and smaller nozzles can be used.
Number of nozzles	3	
Jet angle from vertical	35 deg	
Jet angle off radial	0 deg	
Conveyance inlet ID	3 inches	
Conveyance line screen size	≤ 0.25 inch openings	Screen pattern was modified during this design phase to increase accessibility and reduce fabrication cost while maintaining the same open area.
Conveyance line inlet pipe	2 inch	
Weight	104 lbs	Using stainless steel
Major dimensions	14.7 in Diameter 19.6 in High	Dimensions of envelope
Waterjet rotary speed	30-300 rpm nominal 1000 rpm maximum	
Motor type	Hydraulic	
Motor torque		
Motor fluid requirement	3000 psi 5 gpm	Hydraulic motor (supply/return) fluid, reversible. Return pressure not to exceed 400 psi.
Exposed metals	titanium, stainless steel, nickel/chrome-plated steel	Titanium will be coated with Hastelloy for spark prevention. Hydraulic motor may also have to be so coated, or jacketed in an elastomer.
Exposed non-metals	ETFE or UHMW	Seals and swivel support bushings

Specification	Criteria/limit	Explanation
Maximum radiation exposure rate	2000 rad/hour	
Ambient operating temperature	50°-150°F	
Maximum submersion depth in water	12 ft	
Maximum reaction forces measured, horizontal	135 Newtons	Resonant frequencies were noted at 6 and 20 Hz.
Maximum reaction forces measured, vertical	34 Newtons	Resonant frequencies were noted at 6 and 20 Hz

3.2.3 Technology Applicability

The CSEE technology, which was successfully deployed at the underground storage tanks at the Oak Ridge Reservation, is being considered as an alternative retrieval technology for A-105. A-105 represents a number of unique challenges. The first and foremost challenge, as previously discussed, is the significant tear in the bottom of the tank that goes around roughly 75% of the inside circumference of the tank. The second challenge, it is not clear what the status of the tank bottom is with respect to whether it is raised or not. During the steam bump events, an upward oil can type of buckling of the floor occurred, causing the bottom to buckle and become uneven. The third challenge is that there is a significant amount of debris, including level indicator tapes as well as other items that are likely to be found in the waste, although that challenge is not unique to A-105. A fourth challenge, along with the debris, in-tank structures such as 24-inch (in diameter) air lift circulators will need to be either removed or detached from the tank bottom and moved out of the way.

A fifth challenge is due to the extreme radioactivity. Tank A-105 has one of the highest radiation levels in the tank farms. However, it also has one of the best accesses due to the 42inch riser, which will open up options to enlarge the CSEE. There are likely other challenges that are unknown at this time

CSEE Parameters - Because the CSEE technology uses medium-pressure waterjets, the ability to simultaneously use the water to mobilize the waste and remove the waste to minimize the residual water left behind will be a goal that the technology will need to meet. This capability may be accomplished by minimizing the waterjet pressure to prevent overspray that can allow the waterjets to overshoot the waste inlet and not be removed from the tank. Higher-pressure waterjets will be used to erode and mobilize the waste when necessary. In addition, other parameters can be adjusted, including the rotational speed of the waterjets. Finally, the translational speed of the CSEE can be adjusted as necessary. These parameters will have to be carefully considered to determine applicability to minimize residual water in various waste conditions.

CSEE Size - The CSEE's size will be an important parameter to be considered for deployment in A-105. It should be noted that A-105 has an available 42" riser, which is already larger than the one used for

GAAT access. The CSEE was limited in size to be deployed into existing risers at GAAT. Hanford has demonstrated the ability to cut new risers into the tank dome, which may allow a larger diameter CSEE to be deployed. While a larger diameter CSEE could add weight to the system that has to be considered by the deployment system in terms of dynamic forces, a larger CSEE may be able to increase the retrieval rate, and as such, reduce the rate of residual water being left behind. The overall ratio or waste removed to water added may not change, unless the larger CSEE could more efficiently capture the water used for dislodging.

Tank Debris - A-105 and other tanks have a significant amount of tank debris. In many of the photos of A-105, a large number of level indicator tapes appear to have been dropped into the tanks during level measurements during operation. Because the CSEE rotates, careful consideration of whether that type of debris has to be removed in order to prevent a serious problem of wrapping the level indicator tapes around the CSEE while it rotates. This pre-retrieval step of removing debris may be significant. Either the technology will have to be designed to prevent tangling of level indicator tapes or a mechanical means of moving the tapes to other portions of the tanks out of the way will be necessary.

Mining Strategy and Tank Bottom Tear - A unique mining strategy will have to be developed in consideration of the location and size of the tear in the tank bottom. Essentially, the strategy may need to be one in which the initial retrieval of waste occurs far away from the damage near the tank wall, which is shown in Figure 3.4 extracted from (Girardot 2013). This strategy may require starting near the center of the tank and working outward. This approach allows for a “coffer” of sorts to be in place between the damaged area and the CSEE, thus minimizing any residual water from migrating towards the damaged area.   This approach will likely place an additional requirement on the deployment system (not the CSEE), but this must be considered.

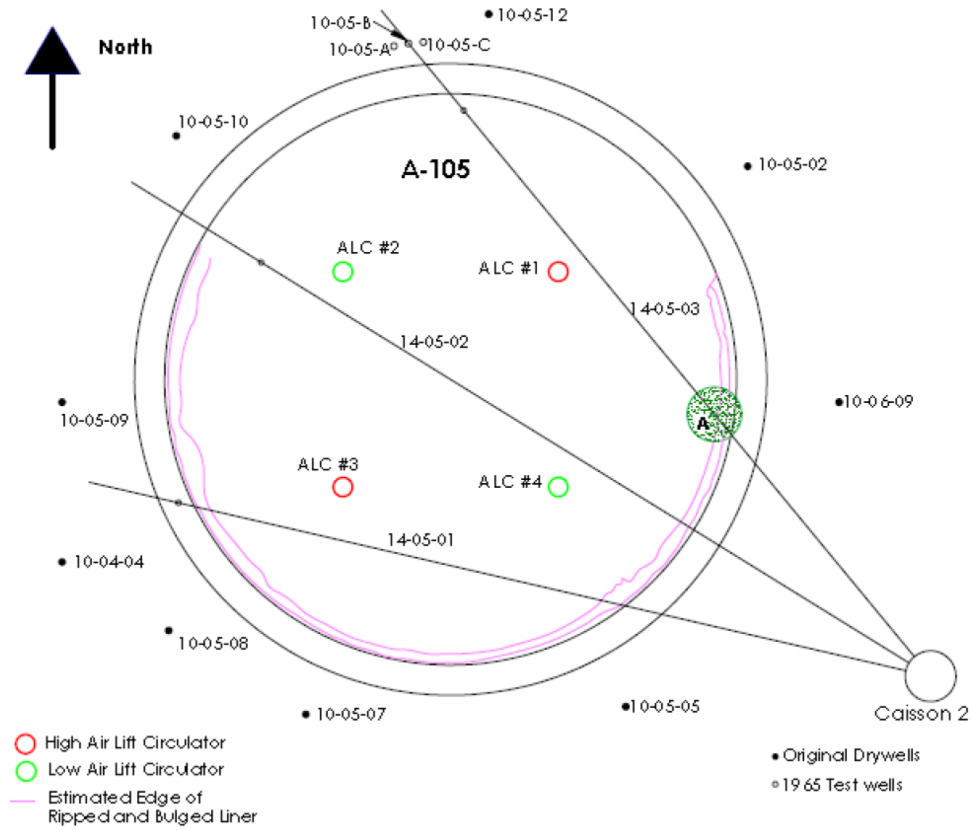

Figure 3.4. Tank A-105 Possible Leak Location

Mining Strategy and Raised Tank Bottom – If the tank bottom is significantly raised in the center of the tank due to the steam bump that occurred, then the mining strategy will have to be modified to allow for a non-level operation. This puts significant requirements on the deployment system to be able to dynamically raise and lower the CSEE during operations in order to prevent collisions with the floor. Because the operator interface cannot show the actual tank bottom interface until waste is removed, this also may change the requirements for the CSEE to be more damage resistant and also may create a requirement for the deployment system to have some sort of standoff sensor integrated into the system in order to maintain the appropriate standoff from the raised tank bottom.

A-105 Applicability Comments - A number of significant challenges need to be addressed in order to demonstrate that the system is applicable for use in A-105. Each of the challenges described above can be overcome one by one. There will be an "optimized" (or at least locally optimized) operational condition that could likely be successful for the CSEE to be deployed in A-105. However, new requirements on the deployment system may make the MARS deployment system or Extended Reach Sluicing System (ERSS) unusable (WRPS 2014). A new system for deployment may have to be considered, but a study of the MARS and ERSS will have to be undertaken by the Tank Farm Operating Contractor to determine whether the system can be successfully used to deploy the CSEE in A-105. The tests that will be performed for the demonstration that is expected in FY17 will not fully address all of the challenges, but the testing should include some parametric tests of the CSEE to determine how flexible the technology is for changing waste conditions while at the same time minimizing residual water.

4.0 Recommendations and Approach for Hanford A-105 Development and Deployment

A number of steps are necessary to ensure a successful retrieval campaign in any underground storage tank. In this section of the summary report, our approach to the important overall activities is identified for consideration. This approach includes developing system functional requirements and identifying the logical activities for the testing of the CSEE technology for potential application to Tank A-105.

4.1 Develop System Functional Requirements

In general, defining the system functional requirements is one of the first and most critical steps to selecting systems, subsystems, components, and tools that can successfully achieve the required project mission. Ultimately, the development of system-level functional requirements needs to be completed with the full involvement of the users, stakeholders, developers, and operators. Early stages of design and testing will not involve input from all parties. All the critical partners need to own the process and ultimate outcome. Assumptions should be clearly documented.

Requirements drive the design of the system and all ancillary equipment. Each requirement needs to be carefully scrutinized to define the basis for it, and then there needs to be an understanding of how that requirement is going to drive design and equipment decisions, and ultimately system operation and cost. A guide to the development of functional requirements for remote systems has been developed and could be used for the CSEE activities in support of A-105 tank waste retrieval (Bailey et al. 2009).

The potential development of the CSEE technology and associated retrieval system in support of A-105 retrieval in the future should be initiated with the system-level requirements to achieve a successful demonstration of the CSEE against one or more A-105 simulants. While functional requirements should not be changed prior to design of the A-105 retrieval system, the functional CSEE tests will help to determine if changes to the system functional requirements are needed and whether additional development is needed.

4.2 Logical Activities for Demonstration and Deployment of Retrieval Technology

Upon completion of the functional requirements, the major steps in a successful waste retrieval operation will not vary significantly from one tank to another. The overall steps are listed below.

- Perform tank inspections to identify geometry of open space, fragile components, and obstructions
- Perform waste sampling and characterizations to determine strength of waste and waste volume
- Determine waste removal goals, water addition restrictions
- Select waste retrieval equipment
- Test waste retrieval equipment using a bounding set of simulants
- Optimize alternative retrieval system
- Modify tank infrastructure to support retrieval operation
- Access waste using optimize alternate retrieval system

- Retrieve bulk waste
- Retrieve heel
- Perform final surface cleaning
- Mix waste
- Condition waste for transfer
- Determine water addition restrictions
- Remove debris and in tank obstructions

If a device like the CSEE is to be used for A-105, then the system and its usage could be modified to achieve better performance. The CSEE that was designed for the GAAT retrieval, which is less than 15 inches in diameter, was developed to fit through small tank risers using a lightweight manipulator. By varying the allowable diameter of the CSEE, greater performance and efficiency are possible. Specifically, if the diameter of the waterjets can be enlarge, the waterjet velocity near the inlet will be reduced, which will increase the ability of the suction to reclaim the water. Significant enhancement can be achieved by coupling the CSEE to an alternative waste removal or pumping device, because the removal capability of the jet pump is limited.

A variety of mining strategies were used at ORNL to retrieve waste with the CSEE. Initially, the MLDUA was used to traverse the CSEE through a serpentine mining strategy. Later, the CSEE was held in a stationary location, and a crawler was used to push the waste into the CSEE inlet.

For tank A-105, there are two primary challenges for retrieval using the CSEE. First, it will be necessary to reduce the risk of water flowing into the tear and damaged area on the floor of the tank. A possible approach to this is to use a mechanical method (using a crawler with an excavation tool, for example) to dislodge the waste near the damaged portion of the tank and place it into a small confinement tank placed on the tank bottom. Then the CSEE would be used to dislodge/slurry the waste without concern for water leakage. Another potential approach would be to remove the waste away from the damaged section first, so that waste near the damaged area could potentially act as a temporary coffer. A second peripheral challenge that will be required to be addressed is the removal of the level indicator tapes that litter the bottom of A-105. These present a significant hazard to the operability of the CSEE. The recommended approach to this challenge is to mechanically grasp and move those tapes to some other location within the tank away from the area being retrieved.

4.3 Recommended Initial Test Requirements to Mitigate Risks and Challenges

The goal of testing is to measure performance and evaluate failure modes and risks. The following describes an approach to testing based on prior development of the CSEE for ORNL.

4.3.1 Testbed

A testbed is truly required to support engineering development and gathering of process performance data. There is a need to validate the strategies used to effectively remove waste fields, to measure the dynamic reaction forces, maneuverability requirement of end effectors, and to define the requirements for instrumentation and automatic control. There is also a need to evaluate waste retrieval tool performance over various waste topography and types. Early testing capabilities include a 3-D deployment platform, waste simulant production equipment, pumps, conveyance piping, and test tanks. Testing with relatively small batches of simulant can be used to tune performance parameters; evaluate waste retrieval performance, water usage, and efficiency; and optimize the mining strategy.

A Hydraulic Test Bed (HTB) was developed at PNNL in FY1996 to support the development of the CSEE and other end effectors. A description of the HTB was documented (Hatchell 1995) and is shown in Figure 4.1. The HTB include several other major pieces of equipment not shown in Figure 4.1, including retrieved simulant tank, a medium-pressure pump, simulant production mixer, and a tent for aerosol containment. The equipment associated with the HTB has was excessed nearly a decade ago and is no longer available. In the short term, it is recommended that a commercial waterjet company be used to assemble a simple testbed environment and to coordinate the testing. However, the Hanford Tank Farm Operating Contractor should consider the investment of such a testbed over the long run to support the primary mission of waste retrieval from the SSTs. Once the retrieval process was validated using small batches of simulant, the testing should be moved to the cold test facility where full scale system tests can be performed.

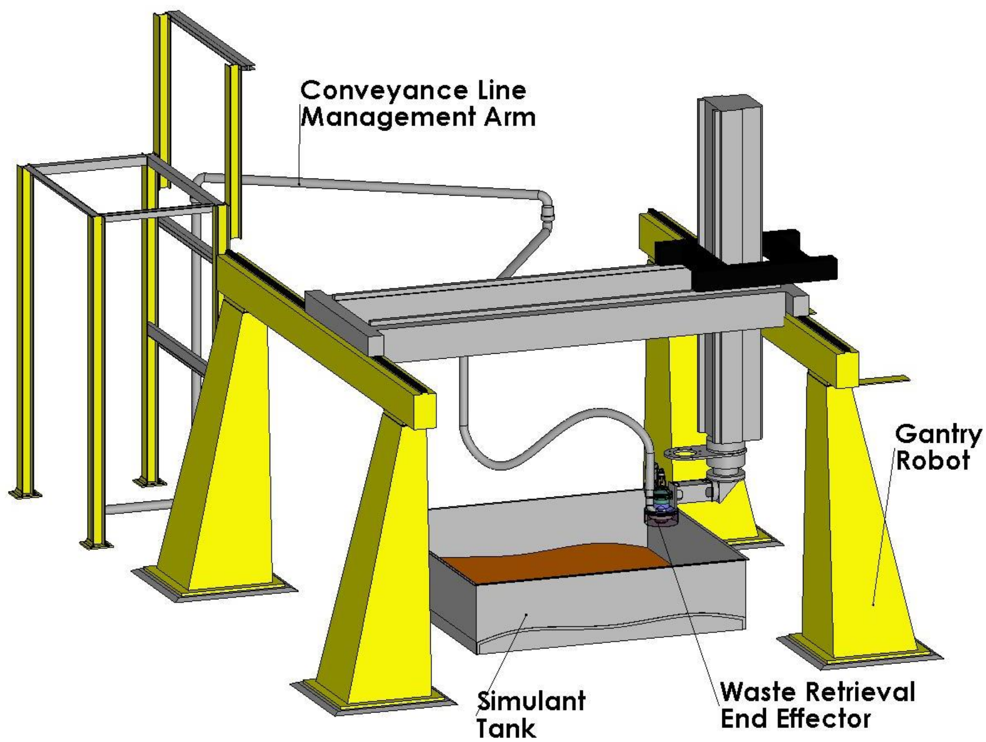

Figure 4.1. Hydraulic Test Bed Rendition

4.3.2 Simulants

Physical simulants have been prepared for testing the CSEE using relatively nonhazardous and inexpensive materials rather than the chemicals known to be in tank waste. Consequently, only some of the waste properties are matched by the simulant. Deciding which properties need to be matched and which do not requires a detailed knowledge of the physics of the process to be tested using the simulant. Developing this knowledge requires reviews of available literature, consultation with experts, and parametric tests. Once the relevant properties are identified, waste characterization data are reviewed to establish the target ranges for each property. Simulants are then developed that possess the desired ranges of properties.

Because simulants are designed with a specific retrieval process in mind, a simulant that is appropriate for testing one process might be inappropriate for another. For example, hard saltcake simulants prepared from potassium-magnesium sulfate were designed specifically for the testing of high-pressure waterjet scarifiers. The mechanical strength and porosity of this simulant can be related to waste characterization data. Other properties such as dissolution rate, solubility, and thermal conductivity were judged to be irrelevant and were not matched, so it is inappropriate to use the potassium-magnesium sulfate simulants to test processes for which these other properties are relevant.

Compromises are often required to develop simulant compositions used for testing. Not all the relevant physical and chemical property measurements have been made on waste samples, so estimates and assumptions must sometimes be made. Where possible, these assumptions are made conservatively so that process testing is more likely to result in over-designed than under-designed equipment. The need to test at large scale often requires that large quantities (tons) of simulants be prepared. In such cases, it is often required that nonhazardous, nonregulated materials be used to protect personnel and meet cost constraints.

Simulants for tank waste sludge, hardpan, saltcake, supernate, and slurry have been developed and used for testing (Powell et al. 1996). The compositions and properties of many of these simulants are given in this document along with preparation instructions for each. Where the relevant waste characterization data are available, a comparison between the waste and the simulants is also provided in this report. The following summarizes the simulant recipes that have been developed.

- Sludge Simulants
  - Kaolin Clay Simulants
  - Bentonite Clay in Water
  - Bentonite/$BaS0_4$
  - Kaolin/Bentonite
  - Kaolin/Plaster
  - Kaolin/Ludox®
  - Silica/Soda Ash
- Hardpan Simulants
  - Kaolin Plaster
- Saltcake
  - Hard Saltcake (K-Mag)
  - Soft Saltcake
- Supernatant Simulants
- Other Waste Simulants
  - ORNL Tank Gunite
  - SRS Tank 19 Zeolite Heel

Of these simulants, it is expected that the sludge and hardpan simulants would be most applicable to the retrieval of A105. Specifications of these simulants are provided below. Note that both cancrinite and iron oxide are predicted to exist in the waste be thermodynamic models (Laurenz 2016). These would most likely exist in the hard pan layer. Therefore, incorporating sand and hematite into the compositions proposed below should be investigated.

4.3.2.1 Wet Sludge Simulant

Composition:

66% wt EPK Pulverized Kaolin Clay

34% wt Water

Properties:

The mixed paste is very sticky and has a shear strength of approximately 3.5 kPa (0.51 psi). For comparison, creamy peanut butter has a shear strength of about 2.0 kPa (0.3 psi). The physical properties of the mixed kaolin clay are largely independent of temperature over the range of 15° to 80°C (59° to 176°F), but freezing temperatures must be avoided. No cure time is associated with this material. It may be used immediately after preparation. If it is to be stored, care should be taken to prevent evaporation. The bulk density of this simulant is 1.65 ± 0.03 g/cm^3

4.3.2.2 Hardpan/Dried Sludge Simulants

These hardpan simulants were developed as part of the ACTR project and used for the HTI project and to assess performance of technologies developed for hardpan/dried sludge retrieval. Because the sludge in Tank A-105 is dried sludge, it is believed that these simulants will bound the material in Tank A-105.

Composition #1:

30.0% wt Plaster of Paris

27.5% wt EPK Pulverized Kaolin Clay

42.5% wt Water

Composition #2:

40.0% wt Plaster of Paris

23.5% wt E P K Pulverized Kaolin Clay

37.5% wt Water

Properties:

Composition #1 reaches a peak shear strength of about 40 kPa (5.8 psi) after several hours of curing. This strength then decreases over a 5-10 hour period to a stable value of about 32 kPa (4.6 psi). Similarly, composition. #2 reaches a peak strength of about 200 kPa (30 psi) and a final strength of about 150 kPa (22 psi). Heat is released by the plaster of Paris hydration reaction. After the recommended cure time (16 h), the test materials may be used or stored. Long-term storage of these materials has not yet been evaluated, but it is expected that the properties will be stable provided that water evaporation is avoided. The density of simulant composition #1 is 1.48 ± 0.05 g/cm^3 and that of composition #2 is 1.65 ± 0.05 g/cm^3.

4.3.3 Retrieval Measurements

Testing will be used to collect key performance and reliability data. Even if performance is high, if the process is interrupted frequently due to plugging or process resets, efficiency will be affected. The following is a preliminary list of key retrieval measurement parameters that have been measured and collected for CSEE testing.

- Retrieval rate
- Water usage
- Real-time water capture efficiency
- Waste dilution ratio
- Conveyance pressure or vacuum
- Residual waste volume (limit of retrieval)
- Reaction forces
- Frequency of back flushing or cleaning
- Water volume used for back flushing or cleaning
- End effector stand-off distance from waste
- Aerosol generation and effect on visibility and ventilation system

4.3.4 Initial Test Matrix (Scaled/Full-scale)

An initial testing program that could be considered for the CSEE testing to provide an understanding of the applicability to A-105 is provided below and is based upon previous test matrices that were used for CSEE and Scarifier types of testing previously.

Table 4.1. Preliminary Testing Program Matrix

Test Focus	Test Parameters	Key Data Expected	Instrumentation or Analysis Approach
Reaction forces due to separate effects of waterjetting and waste removal	• Stand-off Distance • Traverse Velocity • Medium-Pressure Water Flow Rate	• Reaction forces due to suction, inertia, jet reaction • Pressure drop in conveyance line	• Force torque sensor • Pressure gauge

Test Focus	Test Parameters	Key Data Expected	Instrumentation or Analysis Approach
Initial system check-out and performance verification	• Simulant types (bounding) • Waterjet pressure • Traverse velocity • Medium-Pressure Water • Flow and pressure	• Retrieval rate • Reaction forces • Pressure drop in conveyance line • Retrieval rate required to sustain flow	• Material volume measurement • Force torque sensor • Pressure gauge • Pipeline setting sensor (TBD)
Retrieval testing	• Simulant types (bounding) • Mining strategy – serpentine and pit	• Retrieval rate • Reaction forces • Retrieval efficiency • Pressure drop in conveyance line • Conveyance line lubrication required • Process water confined versus lost	• Material volume measurement • Force torque sensor • Material volume measurement • Pressure gauge • Pipeline setting sensor (TBD) • Material Balance • Define the minimum particle size that the system could remove
Debris Testing	Simulant type debris type (rocks, tape rope	• Equipment response to debris • Backflush frequency	NA NA

4.4 Preliminary Description of Necessary Tasks to Demonstrate CSEE Functionality and Range of Costs

A number of tasks will be necessary to initiate cold testing of CSEE technology and complete some basic functional tests by the end of FY17. At the time of this report, it is assumed that there will be approximately nine months to complete this activity. Therefore, a careful and thoughtful planning effort will be necessary to complete this demonstration. Details of the effort will be provided in separate documentation to the Hanford Tank Farm Operating Contractor. The tasks below provide a preliminary set of high-level tasks necessary to conduct this work and an approximate time frame (in nine months, designated M-1 through M-9. Depending on the assumptions and level of complexity, the cost for this scope of work would range from $1,700K to $3,000K. Again, these estimates are ranges based upon the information provided below and need to be adjusted depending upon the scope required in FY17.

The purpose of the CSEE functionality demonstration is to gain an initial understanding of the applicability of such a system to the removal of waste in A-105, with special attention being provided to the fact that it is highly desired to not leave standing liquid during the retrieval process. Water will likely be introduced into the tank after retrieval due to the need to water flush transfer lines and systems. The exhauster will be run to dry out remaining water, as necessary. It is assumed that the retrieval arm or other system is effective in maneuvering within the tank and that items such as level indicator tapes, other significant debris, or structures (i.e., air lift circulators) have been either removed or moved out of the way of the CSEE. In addition, it is assumed that a range of simulants that bound the actual waste in A-105 may be adequate in light of the fact that there is no information regarding the physical properties of the waste.

- *Complete System-level Functional Requirements* – The system-level requirements need to be identified early in the effort to ensure that the project meets the mission needs of the Hanford Site for an A-105 demonstration. **This task should be completed by the Tank Farm Operating Contractor**. (M1-M3)
  Preliminary Cost Estimate: $200K - $300K (completed by Tank Farm Operating Contractor)
- *Procure or access the capacity to perform tests* – Ideally, this task would procure an adequate test bed that is functionally identical to the HTB that was developed in the mid-1990s. This HTB would be available to perform multiple functional tests on the CSEE as well as other devices as needed for future mission needs. However, to meet the accelerated schedule of testing required by the end of FY17, this effort will be required to be subcontracted. Several contractors have been identified who could potentially perform the types of tests that will be required, but at this time they have not been asked to provide estimates. The test bed used for the MARS way be available for use as a testbed. (M1-M6 – for subcontracting the testing effort – if an equivalent HTB were to be procured for use at Hanford, it would likely take will in excess of one year to procure, site, and integrate that capability). **There is a risk in this cost if there are not any vendors or universities who currently have a capability that will be adequate for the demonstration**.
  Preliminary Cost Estimate: Subcontract vendor to prepare their site for tests: $100K - $250K
  Preliminary Cost Estimate: Procure an equivalent HTB for use in the Hanford mission $500K - $1000K
- *Generate Simulant Development and Simulant Testing* – This task has been documented in a separate document to the Tank Farm Operating Contractor. It includes performing a number of bench scale tests on bulk simulants prepared for testing and ensuring that the demonstration tests have the appropriate simulant to test the parameters of interest (will be initiated before the start of other activities, and will be completed by M5)
  Preliminary Cost Estimate: Based upon previously submitted document $250K - 350K
- *Develop CSEE Functionality* – Because there is no CSEE physically available to perform the tests, there are two potential paths. The first is to obtain the CSEE drawings from the GAAT work and build an identical system. The second path is to develop the functionality of the CSEE without having an actual CSEE. (M1-M6)
  Preliminary Cost Estimate: To build an identical CSEE $400K – 500K (including subcontracting)
  Preliminary Cost Estimate: To develop a functional CSEE $300K – 400K (including subcontracting)
- *Develop Demonstration Plan* – The demonstration plan will include incorporating the appropriate information from the Functional Requirements, the desired outcomes and extent of the CSEE demonstration, and a Test Matrix/Plan that integrates the CSEE functionality (M2-M7)
  Preliminary Cost Estimate: $100K
- *Perform Demonstration Tests* – Tests, assumed to be at the subcontractor's facility, will be conducted. Initial testing to ensure functionality will be performed and will be followed by performing the tests within the test matrix. At this time, it is expected that there will be two test campaigns to complete the test matrix. This effort includes the procurement of the simulants,

following the recipe(s), and disposal costs for the simulant at the end of each campaign. (M6-M8)
Preliminary Cost Estimate: $400K – 500K

- *Analyze and Document Testing Results* – The results of the tests will be analyzed and documented as part of the demonstration. Statements as to the applicability or adaptability of the CSEE technology for A-105 waste removal will be included in the test report. (M6-M9)
Preliminary Cost Estimate: $100K – 200K

- *Project Management and Engineering* – This task will manage the activities related to the overall CSEE demonstration, report on those activities monthly, and ensure that all deliverables are completed. This task also provides an Engineering function to provide assistance and guidance to other tasks to ensure consistency across the effort. (M1-M9)
Preliminary Cost Estimate: $150K – 250K

Travel costs, if necessary, have not been incorporated into this estimate. Therefore, the estimate assumes that there is a local company in Richland, WA that has the capability/capacity to perform the tests. If the vendor resides in the Puget Sound or Portland area, travel costs could be as high as $10-$20K. If the vendor is far away (Midwest, Southeast, etc.) the travel costs could escalate to as high as $15-30K. It should also be noted that these preliminary costs have not been validated/verified at the time of this report. In addition, there is a potential risk that the Functional Requirements and CSEE demonstration test results will drive the need for a totally dry retrieval technology (i.e., CO_2 pellets, or some mechanical means of retrieval); if this is the case, then this estimate and tasks would likely change radically. Finally, it should be noted that a nine-month schedule is very aggressive to successfully demonstrate the CSEE technology, given that there is no infrastructure, no CSEE, or no current contracts with vendors to provide tests.

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6.0 Annotated Bibliography

This bibliography provides a listing of authors, reports, and a brief description of each report that is associated with the development and deployment of the Confined Sluicing End Effector technology as well as scarification technology. This bibliography is not meant to be an all-encompassing list, but covers the key information.

Bills, K.C., Love, L.J., Simulation Tools for Hazardous Waste Removal, CONF-970464-9, American Nuclear Society (ANS) Topical Meeting on Robotics and Remote Systems (7th), Augusta, GA (United States), 27 Apr - 1 May 1997. Sponsored by Department of Energy, Washington, DC.

> The primary mission of ORNL during World War 2 was the processing of pure plutonium metal in support of the Manhattan Project. By-products of this process include radioactive cesium-137 and strontium-90. Between 1943 and 1951, the Gunite and Associated Tanks (GAAT) at ORNL were built to collect, neutralize, and storage these by-products. Currently, twelve gunite tanks and four stainless steel tanks are located on the ORNL complex. Characterization studies of these tanks in 1994 indicated that the structural integrity of some of the tanks is questionable. These risks provided the motivation for remediation and relocation of waste stored in the ORNL tanks. A number of factors complicate the remediation process. The material stored in these tanks ranges from liquid to sludge and solid and is composed of organic materials, heavy metals, and radionuclides. Furthermore, the tanks, which range from 12 to 50 ft in diameter, are located below ground and in the middle of the ORNL complex. The only access to these tanks is through one of three access ports that are either 12 or 24 in. in diameter. These characteristics provide a daunting challenge: how can material be safely removed from such a confined structure. This paper describes the existing strategy and hardware projected for use in the remediation process. This is followed by a description of an integrated hardware system model. This investigation has isolated a few key areas where further work may be needed.

Billingsley, K., B. L. Burks, M. A. Johnson, C. Mims, J. Powell, and S. D. Van Hoesen, Large Underground Radioactive Waste Storage Tanks Successfully Cleaned at Oak Ridge National Laboratory, ORNL/CP-98309, Spectrum `98: Nuclear and Hazardous Waste Management International Topical Meeting, Denver, CO, 13-18 September 1998.

> Waste retrieval operations were successfully completed in two large underground radioactive waste storage tanks in 1997. The US DOE and the Gunite Tanks Team worked cooperatively during two 10-week waste removal campaigns and removed ~58,300 gal of waste from the tanks. About 100 gal of a sludge and liquid heel remain in each of the 42,500 gal tanks. These tanks are 25 ft. in diameter and 11 ft. deep, and are located in the NTF in the center of ORNL. Less than 2% of the radioactive contaminants remain in the tanks, proving the effectiveness of the Radioactive Tank Cleaning System, and accomplishing the first field-scale cleaning of contaminated underground storage tanks with a robotic system in the DOE complex.

Blank, J. A., Burks, B.L., Depew, R.E., Falter, D.D., Glassell, Glover, W. H., Killough, S. M., Lloyd, P. D., Love, L. J., Randolph, J. D., Van Hoesen. S.D., and Vesco, D. P., Use of the Modified Light Duty Utility Arm to Perform Nuclear Waste Cleanup of Underground Waste Storage Tanks at Oak Ridge National Laboratory, ORNL/CP-101283, ANS 8th International Topical Meeting on Robotics & Remote Systems, Pittsburgh, PA, April 1999.

> The MLDUA is a selectable seven or eight degree-of-freedom robot arm with a 16.5 ft (5.03 m) reach and a payload capacity of 200 lb (90.72 kg). The utility arm is controlled in either joystick-based

telerobotic mode or auto sequence robotics mode. The MLDUA was deployed vertically into GAAT at ORNL. The MLDUA grasps the CSEE, which is attached to the HMA. The utility arm positions the CSEE within the tank to allow the HMA to sluice the tank's liquid and solid waste from the tank. The MLDUA is used to deploy the CEE and GSEE into the tank. The CEE is used to survey the tank wall's radiation levels and the physical condition of the walls. The GSEE is used to scarify the tank walls with high-pressure water to remove the wall scale buildup and a thin layer of gunite, which reduces the radioactive contamination that is embedded into the gunite walls. The MLDUA is also used to support waste sampling and wall core-sampling operations. Other tools that have been developed for use by the MLDUA include a pipe-plugging end effecter, pipe-cutting end effecter, and pipe-cleaning end effecter. Washington University developed advance robotics path control algorithms for use in the tanks. The MLDUA was first deployed in June 1997 and has operated continuously since then. Operational experience in the first four tanks remediated is presented in this paper.

Blank, J. A., B. L. Burks, W. H. Glover, R. L. Glassell, J. D. Randolph, P. D. Lloyd, and V. Rule, Performance Assessment for Operation of the Modified Light-Duty Utility Arm and Confined Sluicing End Effector in Oak Ridge National Laboratory Tank W-3 Gunite and Associated Tanks Project, ORNL/TM-13646, Lockheed Martin Energy Research Corp., ORNL, Oak Ridge, Tennessee, September 1998.

This report presents a brief assessment of the initial performance of the MLDUA during the Treatability Study in GAAT W-3.

Blank, J. A., Burks, B.L., Depew, R. E., Falter, D. D., Glassell, R. L., Glover, W. H., Killough, S. M., Lloyd, P. D., Love, L. J., Randolph, J. D., Van Hoesen, S. D., and Vesco, D. P.,

Use of the Modified Light Duty Utility Arm to Perform Nuclear Waste Cleanup of Underground Waste Storage Tanks at Oak Ridge National Laboratory, ORNL/CP-101283, ANS 8th International Topical Meeting on Robotics & Remote Systems, Pittsburgh, PA, April 1999. The MLDUA is a selectable seven or eight degree-of-freedom robot arm with a 16.5 ft (5.03 m) reach and a payload capacity of 200 lb (90.72 kg). The utility arm is controlled in either joystick-based telerobotic mode or auto sequence robotics mode. The MLDUA was deployed vertically into GAAT at ORNL. The MLDUA grasps the CSEE, which is attached to the HMA. The utility arm positions the CSEE within the tank to allow the HMA to sluice the tank's liquid and solid waste from the tank. The MLDUA is used to deploy the CEE and GSEE into the tank. The CEE is used to survey the tank wall's radiation levels and the physical condition of the walls. The GSEE is used to scarify the tank walls with high-pressure water to remove the wall scale buildup and a thin layer of gunite, which reduces the radioactive contamination that is embedded into the gunite walls. The MLDUA is also used to support waste sampling and wall core-sampling operations. Other tools that have been developed for use by the MLDUA include a pipe-plugging end effecter, pipe-cutting end effecter, and pipe-cleaning end effecter. Washington University developed advance robotics path control algorithms for use in the tanks. The MLDUA was first deployed in June 1997 and has operated continuously since then. Operational experience in the first four tanks remediated is presented in this paper.

Burks, B. L. Gunite and Associated Tanks Treatability Study Equipment Testing at the Tanks Technology Cold Test Facility, ORNL/TM-13629, UT-Battelle, LLC, ORNL, Oak Ridge, Tennessee, February 2000.

This report provides a summary of the cold tests performed on the equipment to be used in the Gunite and Associated Tanks Treatability Study. The testing was performed from June 1996 to May 1997 at the Tanks Technology Cold Test Facility located at the 7600 complex at ORNL. Testing of specific equipment grouped into the following sections: (1) MLDUA Testing, (2) ROV Testing, (3) WD&CS and BOP Equipment Testing, (4) Camera and Lighting System Testing, and (5) CEE Testing.

Burks, B. L., D. D. Falter, R. L. Glassell, S. D. Van Hoesen, M. A. Johnson, P. D. Lloyd, and J. D. Randolph, A Remotely Operated Tank Waste Retrieval System for ORNL, Rad Waste Magazine, 4(2):10-16, March 1997.

This report provides a description of the design and cold testing of the arm-based and vehicle-based TWRSs planned for used in tank waste retrieval operations in the GAAT at ORNL.

Burks, B.L., Gunite and Associated Tanks Treatability Study Equipment Testing at the Tanks Technology Cold Test Facility, ORNL/TM-13629, UT-Battelle, LLC, ORNL, Oak Ridge, Tennessee, February 2000.

This report provides a summary of the cold tests performed on the equipment to be used in the Gunite and Associated Tanks Treatability Study. The testing was performed from June 1996 to May 1997 at the Tanks Technology Cold Test Facility located at the 7600 complex at ORNL. Testing of specific equipment grouped into the following sections: (1) MLDUA Testing, (2) ROV Testing, (3) WD&CS and BOP Equipment Testing, (4) Camera and Lighting System Testing, and (5) CEE Testing. Each section contains descriptions of a series of tests that summarize the test objectives, testing performed, and test results. General conclusions from the testing are also provided.

DeVore, J.R., Herrick. T.J., and Lott, K.E., Technology Study of Gunite Tank Sludge Mobilization at Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL/ER-286, Martin Marietta Energy Systems, Inc., ORNL, Oak Ridge, Tennessee, December 1994.

This study was initiated to support the Gunite Tank Treatability Study effort. The technology study surveyed the methods and technologies available for tank cleaning and sludge mobilization in a radioactive environment. Technologies were identified and considered for applicability to the GAATs problems. These were then either accepted for further study or rejected as not applicable. Technologies deemed applicable to the GAAT sludge removal project were grouped for evaluation according to (1) deployment method, (2) types of remotely operated end effector equipment applicable to removal of sludge, (3) methods for removing wastes from the tanks, and (4) methods for concrete removal. There were three major groups of deployment technologies: ``past practice`` technologies, mechanical arm-based technologies, and vehicle-based technologies. The different technologies were then combined into logical sequences of deployment platform, problem, end effector, conveyance, post-removal treatment required (if any), and disposition of the waste. Many waste removal options are available, but the best technology in one set of circumstances at one site might not be the best type to use at a different site. No single technology is capable of treating the entire spectrum of wastes that will be encountered in GAAT. None of the systems used in other industries appears to be suitable, primarily because of the nature of the sludges in the GAAT OU, their radiation levels, and tank geometries. Other commercial technologies were investigated but rejected because the authors did not believe them to be applicable.

DOE/EM-0368, Houdini™ I and II ROV Innovative Technology Summary Report, July 1998.

This report provides a description of the Houdini I and II ROV technology, performance, cost, and application. The Houdini robot addresses the need for vehicle-based, rugged, remote manipulation systems that can perform waste retrieval, characterization, and inspection tasks. Houdini-I was delivered to ORNL in September 1996, deployed in a cold test facility in November, and first deployed in the gunite tanks in June 1997. Houdini-I has proven rugged, capable of waste retrieval, and able to withstand high reaction force operations such as wall core sampling. Based upon the lessons learned at ORNL, Houdini's design has been completely overhauled. A second-generation system, Houdini-II, is now being built.

DOE/EM-0406, Light Duty Utility Arm Innovative Technology Summary Report, December 1998.

The Light-Duty Utility Arm (LDUA) System is a mobile, multi-axis positioning system capable of deploying tools and sensors (end effecters) inside radioactive waste tanks for tank wall inspection, waste characterization, and waste retrieval. The LDUA robotic manipulator enters a tank through existing openings (risers) in the tank dome of the underground tanks. Using various end effecters, the LDUA System is a versatile system for high-level waste tank remediation. The LDUA System provides a means to deploy tools, while increasing the technology resources available to the DOE. Ongoing end effecter development will provide additional capabilities to remediate the waste tanks.

DOE/EM-0595, Heavy Waste Retrieval System Innovative Technology Summary Report, July 2001.

This report provides a description of the Heavy Waste Retrieval System (HWRS) technology, performance, cost, and application. The HWRS was developed as an enabling technology to address the shortfalls of the existing waste-removal and transfer systems, which were already in service at the GAAT OU. The HWRS was designed to take advantage of the existing capabilities of the RCTS and to meet the requirements for transferring wastes from the GAAT waste consolidation tank, W-9. This system was used in final waste retrieval operations from tank W-9.

DOE/EM-0610, Gunite Scarifying End Effector Innovative Technology Summary Report, September 2001.

The GAAT Remediation Project deployed a suite of technologies to successfully retrieve waste and clean the GAATs. The Gunite Scarifying End-Effector (GSEE) was adapted from the Confined Sluicing End-Effector (CSEE) to clean the GAAT walls at ORNL. The GSEE is part of an integrated retrieval and cleaning system that includes the Ultra-High Pressure Pump (UHPP), Tank Riser Interface and Containment (TRIC), MLDUA, a Hose Management Arm and tether, and the Collimated Analyzing Radiation Probe (CARP). The GSEE uses three powerful high-pressure water jets capable of both scaling and scarifying gunite tank walls. Jet pressures of 6000–10,000 pounds per square inch (psig) were used to remove surface scales. Jet pressures up to 22,000 psig were used to scarify gunite walls. Jet pressure was supplied by a UHPP with a 40,000-psig capability; however, water jet pressure was limited to 22,000 psig to avoid unacceptable lateral stress to the MLDUA and to avoid excessive removal of gunite. This report provides a description of the GSEE technology, performance, cost, and application at the GAAT.

DOE OST. Tanks Focus Area. Innovative Technology Summary Report - Confined Sluicing End Effector, OST Reference #812, September 1998. U.S. Department of Energy Office of Science and Technology. TFA-DOE-EM-0372

A CSEE was field tested during the summer of 1997 in Tank W-3, one of the GAATs at the Oak Ridge Reservation (ORR). It should be noted that the specific device used at the Oak Ridge Reservation demonstration was the Sludge Retrieval End-Effector (SREE), although in common usage it is referred to as the CSEE. Deployed by the Modified Light-Duty Utility Arm (MLDUA) and the Houdini ROV, the CSEE was used to mobilize and retrieve waste from the tank. After removing the waste, the CSEE was used to scarify the gunite walls of Tank W-3, removing ~0.1 in. of material. The CSEE uses three rotating water-jets to direct a short-range pressurized jet of water to effectively mobilize the waste. Simultaneously, the water and dislodged tank waste, or scarified materials, are aspirated using a water-jet pump-driven conveyance system. The material is then pumped outside of the tank, where it can be stored for treatment. The technology, its performance, uses, cost, and regulatory issues are discussed.

Emison, J. A., B. B. Spencer, and B. E Lewis, Gunite™ and Associated Tanks Waste Conditioning System: Description and Operational Summary, ORNL/TM-2001/149, UT-Battelle, LLC, ORNL, Oak Ridge, Tennessee, February 2002.

This report describes the function, operational performance, problems encountered, lessons-learned, and provides an overall assessment of the performance of the waste conditioning system (WCS) use in the GAAT remediation project at the ORNL. The GAAT WCS was used to condition the radiochemical sludge slurry and supernatant from nine of the inactive gunite tanks located in ORNL's main plant area in the Bethel Valley watershed and transfer it to the MVSTs. The sludge was removed from each tank, to the extent practical, with available technologies and consolidated into tank W-9 for cross-site transfer to the MVSTs. The GAAT sludge will be stored at the MVSTs and treated for eventual, permanent disposal as part of a separate action along with other ORNL wastes.

Falter, D. D., S. M. Babcock, B. L. Burks, P. D. Lloyd, J. D. Randolph, J. E. Rutenber, and S. D. Van Hoesen, Remote Systems for Waste Retrieval from the Oak Ridge National Laboratory Gunite Tanks, ANS 1997 Winter meeting, San Francisco California, CONF-951006—33, October 29-November 2, 1995.

As part of a CERCLA Treatability Study funded by the DOE, the ORNL is preparing to demonstrate and evaluate two approaches for the remote retrieval of wastes in underground storage tanks. This work is being performed to identify the most cost-effective and efficient methods of waste removal before full-scale remediation efforts begin in 1998. System requirements are based on the need to dislodge and remove sludge wastes ranging in consistency from broth to compacted clay from gunite tanks that are approaching fifty years in age. Systems to be deployed must enter and exit through the existing 0.6 m (23.5 in.) risers and conduct retrieval operations without damaging the layered concrete walls of the tanks. Goals of this project include evaluation of confined sluicing techniques and successful demonstration of a telerobotic arm-based system for deployment of the sluicing system. As part of a sister project formed on the OHF tanks at ORNL, vehicle-based tank remediation will also be evaluated.

Fitzgerald, C. L., D. Falter, and R. E. Depew, Linear Scarifying End-Effector Developed for Wall Cleaning in Underground Storage Tanks, American Nuclear Society Ninth International Topical Meeting on Robotics and Remote Systems, Seattle, Washington USA, March 4-8, 2001.

This paper describes the development and performance of a Linear Scarifying End-Effector (LSEE) designed and fabricated for deployment by a ROV. The end-effector was designed to "blast" or "scarify" in-grained residual contamination from gunite tank walls using high-pressure water jets after the bulk sludge had been removed from the tanks using an integrated suite of remotely operated tools. Two generations of the LSEE were fabricated, tested, and deployed in the gunite tanks at the ORNL, with varying levels of success. Because the LSEE was designed near the end of a four-year project to clean up the gunite tanks at Oak Ridge, a number of design constraints existed. The end-effector had to utilize pneumatic, hydraulic, and electrical interfaces already available at the site; and to be deployable through one of the containment structures already in place for the other remote systems. Another primary design consideration was that the tool had to effectively extend the reach of an existing ROV from 6 ft. to at least 10 ft. to allow cleaning the tank walls from floor to ceiling.

In addition, the combined weight and thrust of the LSEE had to be manageable by the manipulator mounted on the vehicle. Finally, the end-effector had to follow an autonomous scarifying path such that the vehicle was only required to reposition the unit at the end of each pass after the mist had cleared from the tank. The prototypes successfully met each of these challenges, but did encounter other difficulties during actual tank operations.

Glassell, R.L., Killough, S.M., Lloyd, P.D., Love, L.J., Randolph, J.D., Van Hoesen, S.D. Use of the Modified Light Duty Utility Arm to Perform Nuclear Waste Cleanup of Underground Waste Storage Tanks at Oak Ridge National Laboratory. 1999. ORNL-CP-101283.

The Modified Light Duty Utility Arm (MLDUA) is a selectable seven or eight degree-of-freedom robot arm with a 16.5 ft (5.03 m) reach and a payload capacity of 200 lb. (90.72 kg). The utility arm is controlled in either joystick-based telerobotic mode or auto sequence robotics mode. The MLDUA deployment system deploys the utility arm vertically into underground radioactive waste storage tanks located at Oak Ridge National Laboratory. These tanks are constructed of gunite material and consist of two 25 ft (7.62 m) diameter tanks in the North Tank Farm and six 50 ft (15.24 m) diameter tanks in the South Tank Farm. After deployment inside a tank, the utility arm reaches and grasps the confined sluicing end effecter. (CSEE) which is attached to the hose management arm (HMA). The utility arm positions the CSEE within the tank to allow the HMA to sluice the tank's liquid and solid waste from the tank. The MLDUA is used to deploy the characterization end effecter (CEE) and gunite scarifying end effecter (GSEE) into the tank. The CEE is used to survey the tank wall's radiation levels and the physical condition of the walls. The GSEE is used to scarify the tank walls with high-pressure water to remove the wall scale buildup and a thin layer of gunite which reduces the radioactive contamination that is embedded into the gunite walls. The MLDUA is also used to support waste sampling and wall core-sampling operations. Other tools that have been developed for use by the MLDUA include a pipe-plugging end effecter, pipe-cutting end effecter, and pipe-cleaning end effecter. Washington University developed advance robotics path control algorithms for use in the tanks. The MLDUA was first deployed in June 1997 and has operated continuously since then. Operational experience in the first four tanks remediated is presented in this paper.

Glassell, R. L., B. L. Burks, and W. H. Glover, System Review of the Modified Light Duty Utility Arm After the Completion of the Nuclear Waste Removal from Seven Underground Storage Tanks at Oak Ridge National Laboratory, Providence Group, Knoxville, Tennessee, Proceedings of the American Nuclear Society Ninth International Topical Meeting on Robotics and Remote Systems, Seattle, Washington, March 4-8, 2001; 15 pp.

The MLDUA is a custom seven-degree-of-freedom long-reach manipulator system developed, designed, and built by SPAR Aerospace, Ltd. The MLDUA was delivered to ORNL in November 1996. After operational tests and training cold tests, the MLDUA was moved to the first underground tank (W-3) in May 1997. After the completion of tank W-3, the MLDUA was used in cleanup operations of six other underground tanks, in this order, tanks W-4, W-6, W-7, W-10, W-8, and finally on tank W-9. Tank W-9 was completed in September 2000. Tanks W-3 and W-4 are 25-ft diameter tanks and the other five tanks are 50-ft diameter tanks. The MLDUA was deployed only in one tank riser for the 25-foot tanks. For the 50-ft tanks, the MLDUA was deployed in either two or four tank risers. The MLDUA performed the following types of operations in support of the underground tank waste cleanup operations: grasping the sluicer to allow deployment of the Hose Management Arm (HMA) into the tanks, holding and maneuvering the sluicer to remove tank water and waste material, tank wall radiation surveys, tank wall material sample collection, tank wall cleaning operations with high-pressure water jets, vertical pipe cutting operations, pipe plugging operations and support for tank wall coring operations. The MLDUA performed exceptionally well considering it is a one-of-a-kind long-reach manipulator prototype design. The MLDUA operations included over 7400 hours of in-tank exposure to radiation fields with an estimated total dose of

77,000 rads. Total working time within the tanks was over 2250 hours. While the MLDUA performed exceptionally well, a relatively few problems developed during tank cleanup operations. The most serious problem that developed during operations was the loss of the manipulator's wrist roll operation. The wrist roll drive motor's power supply cable developed an internal short within the manipulator's umbilical cable during operations on tank W-6. The MLDUA operators compensated for operations without an operating wrist roll by pre-planning the MLDUA jobs and presetting the wrist position. The MLDUA was never a delay in tank operations. Also, many "lessons" were learned in both manipulator operations within the tanks and manipulator design. Many design modifications were identified that would have made the MLDUA a better machine. The design modifications include changes to make setup and take down of the MLDUA easier, to perform maintenance easier, reduce operator's radiation exposure during MLDUA support operations within the Tank Riser Interface Containment (TRIC), and the operator's computer graphic interface. Overall, the MLDUA performed exceptionally well and has a proven track record.

Hatchell, B.K., Smalley, J.T., and Tucker, J.C. Retrieval Process Development and Enhancement Hydraulic Test Bed Integrating Testing FY 1995 Technology Development Summary Report-PNNL-11105-UC2030-HTB Summary 417618.

The Retrieval Process Development and Enhancements Program (RPD&E) is sponsored by the U.S. Department of Energy Office of Science and Technology to investigate existing and emerging retrieval processes suitable for the retrieval of high-level radioactive waste inside underground storage tanks. This program, represented by industry, national laboratories, and academia, seeks to under- stand retrieval processes, including emerging and existing technologies, gather data on these technologies, and relate the data to specific tank problems such that end-users have requisite technical bases to make retrieval. Part of this program has involved the development of the Hydraulics Test Bed (HTB) to evaluate a high-pressure waterjet dislodging system and pneumatic conveyance integrated as a scarifier. In fiscal year (FY) 1994 and FY95, the HTB was completed through a cooperative effort involving the U.S. Department of Energy (DOE), Tanks Focus Area, Pacific Northwest National Laboratory, Westinghouse Hanford Company (WHC), and Quest Integrated, Inc. The HTB provides a facility for testing of waste dislodging and conveyance processes at scales which support engineering development and gathering of process performance data necessary for program decisions about deployment of that process to be made. Although the Hydraulic Test Bed was originally used to test the high-pressure scarifier, the HTB addresses technology needs that drive retrieval requirements at multiple DOE sites, including Oak Ridge National Laboratory (ORNL), Savannah River National Laboratory, and Idaho National Engineering Laboratory (INEL). There is a strong need to validate the mining strategy used to remove waste fields; to measure the dynamic reaction forces, accuracy, repeatability, and maneuverability requirements of end effectors; and to define the requirements for instrumentation and automatic control. There is also a need to evaluate waste retrieval tool performance over various waste types and topography. The Hydraulic Test Bed addresses these needs by providing longer duration, multiple pass tests on large waste simulant fields using a three-dimensional deployment platform. The mission of the HTB is not to develop new technologies, but to sup- port DOE Environmental Management programs, industry, and academia by providing key testing capabilities to allow full-scale cold testing of waste retrieval tools. The HTB will allow DOE retrieval programs to evaluate alternative established and emerging retrieval processes in a standardized, cost-effective, and timely manner.

Hanford Tanks Initiative, HNF-SD-WM-PMP-022, Rev. 0 – HTI Plan, July 1997

The Hanford Tanks Initiative (HTI) is a five-year project resulting from the technical and financial partnership of the U.S. Department of Energy's Office of Waste Management (EM-30) and Office of Science and Technology Development (EM-50). The HTI accelerates activities to

gain key technical, cost performance, and regulatory information on two high-level waste tanks. The HTI will provide a basis for design and regulatory decisions affecting the remainder of the Tank Waste Remediation System's tank waste retrieval Program.

Lewis, B.E., Lloyd, P.D., Spencer, B.B., Van Housen S.D., Billingsley, S.D., Mullen, O.D., Burks, B.L., Higdon, C., Emison, J.A., Johnson, M.A. The Gunite and Associated Tanks Remediation Project Tank Waste Retrieval Performance & Lessons Learned ORNL-TM-2001-142-V1 & ORNL-TM-2001-142-V2, 2003.

The Gunite and Associated Tanks (GAAT) Remediation Project was the first of its kind performed in the United States. Robotics and remotely operated equipment were used to successfully transfer almost 94,000 gal of remote-handled transuranic sludge containing over 81,000 Ci of radioactive contamination from nine large underground storage tanks at the Oak Ridge National Laboratory (ORNL). The sludge was transferred with over 439,000 gal of radioactive waste supernatant and ~420,500 gal of fresh water that was used in sluicing operations. The GAATs are located in a high-traffic area of ORNL near a main thoroughfare.

A phased and integrated approach to waste retrieval operations was used for the GAAT Remediation Project. The project promoted safety by obtaining experience from low-risk operations in the North Tank Farm before moving to higher-risk operations in the South Tank Farm. This approach allowed project personnel to become familiar with the tanks and waste, as well as the equipment, processes, procedures, and operations required to perform successful waste retrieval. By using an integrated approach to tank waste retrieval and tank waste management, the project was completed years ahead of the original baseline schedule, which resulted in avoiding millions of dollars in associated costs.

This report is organized in two volumes. Volume 1 provides information on the various phases of the GAAT Remediation Project. It also describes the different types of equipment and how they were used. The emphasis of Volume 1 is on the description of the tank waste retrieval performance and the lessons learned during the GAAT Remediation Project. Volume 2 provides the appendixes for the report, which include the following information:

A—Background Information for the Gunite and Associated Tanks Operable Unit

B—Annotated Bibliography

C—Comprehensive Listing of the Sample Analysis Data from the GAAT Remediation Project

D—GAAT Equipment Matrix

E—Vendor List for the GAAT Remediation Project

The remediation of the GAATs was completed ~5.5 years ahead of schedule and ~$120,435,000 below the cost estimated in the Remedial Investigation/Feasibility Study for the project. These schedule and cost savings were a direct result of the selection and use of state-of-the-art technologies and the dedication and drive of the engineers, technicians, managers, craft workers, and support personnel that made up the GAAT Remediation Project Team.

Lewis, B. E., P. D. Lloyd, S. M. Killough, R. F. Lind, D. E. Rice, M. A. Johnson, and O. D. Mullen, Basis for Selection of a Residual Waste Retrieval System for Gunite and Associated Tank W-9 at the Oak Ridge National Laboratory, ORNL/TM-2000/251, UT-Battelle, LLC, ORNL, Oak Ridge Tennessee, September 2000.

This report provides a description of the requirements and recommendations for the final waste retrieval system for use in GAAT W-9. The report also provides a summary of the sample analysis data for the waste transfer samples from W-9 through March 30, 2000 and a list of options for use in the final waste retrieval operations in W-9.

Lewis, B.E. Gunite Tanks Waste Retrieval and Closure Operations at Oak Ridge National Laboratory. Presentation on Gunite Tanks Remediation Project

Lloyd, P. D., C. L. Fitzgerald, H. Toy, J. D. Randolph, R. E. Depew, D. D. Falter, and J. A. Blank, Performance Assessment of the Waste Dislodging and Conveyance System During the Gunite and Associated Tanks Remediation Project, The American Nuclear Society Ninth International Topical Meeting on Robotics and Remote Systems, Seattle, Washington USA, March 4-8, 2001.

The Waste Dislodging and Conveyance System (WD&CS) and other components of the Tank Waste Retrieval System (TWRS) were developed to address the need for removal of hazardous wastes from USTs in which radiation levels and access limitations make traditional waste retrieval methods impractical. Specifically, these systems were developed for cleanup of the GAAT OU at the ORNL. The WD&CS is comprised of a number of different components. The three primary hardware subsystems are the Hose Management System (HMS), the CSEE, and the Flow Control Equipment and Containment Box. In addition, a DSR and a control system were developed for the system. The WD&CS is not a stand-alone system; rather, it is designed for deployment with either a long-reach manipulator like the Modified Light Duty Utility Arm (MLDUA) or a ROV system such as the Houdini. Oak Ridge National Lab., Tennessee, 2001.

Love, L. J., R. L. Kress, and K. C. Bills, Simulation Tools for Robotic and Teleoperated Hazardous Waste Removal, ORNL/CP-95937 and CONF-970469: 1997 International Conference on Robotics and Automation, USDOE Office of Energy Research, Washington, DC, February 28, 1997.

The primary mission of ORNL during World War II was the processing of pure plutonium metal in support of the Manhattan Project. Between 1943 and 1951, the Gunite and Associated Tanks (GAAT) at ORNL were built to collect, neutralize, and store the radioactive by-products. Currently, twelve gunite tanks and four stainless steel tanks are located on the ORNL complex. These tanks hold ~75,000 gal of radioactive sludge and solids and over 350,000 gal of liquid. Characterization studies of these tanks in 1994 indicated that the structural integrity of some of the tanks is questionable. Subsequently, there is presently an aggressive program directed towards the remediation and relocation of waste stored in the ORNL tanks. A number of factors complicate the remediation process. The material stored in these tanks ranges from liquid to sludge and solid and is composed of organic materials, heavy metals, and radionuclides. The tanks, which range from 12 to 50 ft in diameter are located below ground and in the middle of the ORNL complex. The only access to these tanks is through one of three access ports that are either 12 or 24 in. in diameter. These characteristics provide a daunting challenge: How can material be safely removed from such a confined structure. This paper describes the existing strategy and hardware presently used in the remediation process. This is followed by a description of an integrated hardware system model. This investigation has isolated a few key areas where further work is needed.

Mynatt, F.R., Webster, C. C., , An Analysis of the South Tank Farm and the Potential Hazards Associated with Continued Use of the Tanks as Part of the Intermediate-Level Liquid Waste Disposal System, ORNL/TM-604, ORNL, Oak Ridge, Tennessee, August 1963.

This report provides information about the GAATs as originally constructed in 1943. Similar tanks at other sites are also discussed. A description of the use of the tanks and information on how the tanks fit into the ORNL waste disposal system is provided along with the potential problems associated with their continued use. Recommendations pertinent to their continued use and possible alternatives are also presented.

Mullen, O. D. Engineering Development of Waste Retrieval End Effectors for the Oak Ridge Gunite Waste Tanks, PNNL-11586, Battelle, Inc., PNNL, Richland, Washington, May 1997.

The GAAT Treatability Study at ORNL selected the waterjet scarifying end effector, the jet pump conveyance system, and the Modified Light Duty Utility Arm and Houdini ROV deployment and manipulator systems for evaluation. The waterjet-based retrieval end effector had been developed through several generations of test articles targeted at deployment in Hanford underground storage tanks with a large robotic arm. The basic technology had demonstrated effectiveness at retrieval of simulants bounding the foreseen range of waste properties and indicated compatibility with the planned deployment systems. This report describes the engineering development and test results of two versions of the retrieval end effector tailored to the Oak Ridge tanks, waste and deployment platforms.

Mullen, O. D. Field Performance of the Waste Retrieval End Effectors in the Oak Ridge Gunite Tanks, PNNL-11688, Battelle, Inc., PNNL, September 1997.

Waterjet-based tank waste retrieval end effectors have been developed through several generations of test articles targeted at deployment in Hanford underground storage tanks with a large robotic arm. The basic technology has demonstrated effectiveness for retrieval of simulants bounding a wide range of waste properties and compatibility with foreseen deployment systems. The ORNL selected the waterjet scarifying end effector, the jet pump conveyance system, and the MLDUA and Houdini ROV deployment and manipulator systems for evaluation in the GAAT TS. This report describes the development of a version of the retrieval end effector tailored to the Oak Ridge tanks, waste, and deployment platforms. The conceptual design was done by the University of Missouri-Rolla in FY 1995-96. The test article was extensively evaluated in the Hanford Hydraulic Testbed and the design features were further refined. Detail design of the prototype item was started at Waterjet Technology, Inc. before the development testing was finished, and two of the three main subassemblies were substantially complete before final design of the waterjet manifold was determined from the Hanford hydraulic testbed testing. The manifold on the first prototype was optimized for sludge retrieval; assembled with that manifold, the end effector is termed the SREE.

Mullen, O. D. Functions and Requirements for a Waste Conveyance Jet Pump for the Gunite and Associated Tanks at Oak Ridge National Laboratory, PNNL-11876, Battelle Inc., PNNL, September 1998.

The ORNL GAAT Treatability Study project was initiated in fiscal year (FY) 1994 to support a record of decision in selecting from seven different options of technologies for retrieval and remediation of these tanks. This decision process is part of a Comprehensive Environmental Response, Compensation, and Liability Act of 1980, Remedial investigation and Feasibility Study presented to DOE and the Tennessee Department of Environment and Conservation. As part of this decision process, new waste retrieval technologies were evaluated at the 25-ft diameter gunite tanks in the NTF. This report provides a listing of the functions and requirements for the jet pump for use in waster retrieval operations in the GAAT.

Nobel-Dial, J. R., G. Riner, B. L. Burks, S. M. Robinson, B. E. Lewis, G. Ganapathi, M. Harper, D. Bolling, and K. M. Billingsley, Use of Multiple Innovative Technologies for Retrieval and Handling of Low-Level Radioactive Tank Wastes at Oak Ridge National Laboratory, Waste Management 02 Conference, Tucson, AZ, February 24-28, 2002.

The U.S. Department of Energy (DOE) successfully implemented an integrated tank waste management plan at ORNL (1), which resulted in the cleanup, removal, or stabilization of 37 inactive USTs since 1998, and the reduction of risk to human health and the environment. The integrated plan helped accelerate the development and deployment of innovative technologies for the retrieval of radioactive sludge and liquid waste from inactive USTs. It also accelerated the pretreatment of the retrieved waste and newly generated waste from ORNL research and development activities to provide for volume and contamination reduction of the liquid waste. This paper summarizes the successful waste retrieval and tank stabilization operations conducted during two ORNL tank remediation projects (The Gunite Tanks Remediation Project and the Old Hydrofracture Facility (OHF) Tanks Remediation Project), the sludge retrieval operations from the active Bethel Valley Evaporator Service Tanks (BVESTs), and pretreatment operations conducted for the tank waste. This paper also provides the status of ongoing activities conducted in preparation of treating the retrieved tank waste for final disposition, and the efforts to improve monitoring capabilities for waste collection and storage tanks that will remain in long-term service at ORNL.

ORNL, Sampling and Analysis Plan for the Gunite and Associated Tanks Interim Remedial Action, Wall Coring and Scraping at Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL/ER-412/R1. Oak Ridge, Tennessee, 1998.

The establishment of a systematic means of collecting wall coring and scraping samples to support estimates of residual contamination remaining in GAAT tanks in the STF after the sludge has been removed. The data quality objectives process, based on US Environmental Protection Agency guidance, was applied to identify the objectives of this sampling and analysis. The results of the analysis will be used to (1) validate predictions of a strontium concrete diffusion model, (2) estimate the amount of radioactivity remaining in the tank shells, (3) provide information to correlate with measurements taken by the GIMP and the CEE, and (4) estimate the performance of the wall cleaning system. This revision eliminates wall-scraping samples from all tanks, except tank W-3. The tank W-3 experience indicated that the wall scrapper does not collect sufficient material for analysis.

Platfoot, J. H. Technical Safety Requirements for the South Tank Farm Remediation Project, Oak Ridge National Laboratory, ORNL/ER-404/R2,Oak Ridge, Tennessee, Bechtel Jacobs Company LLC, ORNL, Oak Ridge Tennessee, January 1999.

The GAATs are currently being maintained under a Surveillance and Maintenance Program, which includes activities such as level monitoring, vegetation control, High Efficiency Particulate Air filter leakage requirement testing/replacement, sign erection/repair, pump-out of excess liquids, and instrument calibration/maintenance. A technique known as confined sluicing, which uses a high-pressure, low-volume water jet integrated with a jet pump, will be used to remove the sludge. The Technical Safety Requirements (TSRs) are those operational requirements that specify the operating limits and surveillance requirements, the basis thereof, safety boundaries, and the management of administrative controls necessary to ensure the safe operation of the STF remediation project. Effective implementation of TSRs will limit to acceptable levels the risks to the public and workers from uncontrolled releases of radioactive or other hazardous material.

Potter, J. D. and O. D. Mullen, Functions and Requirements for a Waste Dislodging and Conveyance System for the Gunite and Associated Tanks Treatability Study at Oak Ridge National Laboratory, WHC-SD-WM-FRD-024, Westinghouse Hanford Co., Richland Washington, September 1995.

Functions and requirements for the WD&CS to be deployed in GAATs and tested and evaluated as a candidate tank waste retrieval technology by the GAAT TS.

Potter, J. D. and O. D. Mullen, Functions and Requirements for a Waste Dislodging and Conveyance System for the Gunite and Associated Tanks Treatability Study at Oak Ridge National Laboratory, PNNL-11492, Battelle, Inc., PNNL, Richland, Washington, February 1997.

The ORNL GAAT TS project was initiated in FY 1994 to support a record of decision in selecting from seven different options of technologies for retrieval and remediation of these tanks. As part of this decision process, new waste retrieval technologies will be evaluated at the 25-foot diameter gunite tanks in the NTF. Work is currently being conducted at Hanford and the University of

Missouri-Rolla to evaluate and develop some technologies having high probability of being most practical and effective for the dislodging and conveying of waste from underground storage tanks. The findings of these efforts indicate that a system comprised of a dislodging end effector employing jets of medium-pressure fluids, coupled to a water-jet conveyance system, all carried above the waste by a mechanical arm or other mechanism, and is a viable retrieval technology for the GAAT TS tasks.

Powell, M.R., Golcar, G.G., Geeting, J.H. Retrieval Process Development and Enhancements Waste Simulant Compositions and Defensibility – PNNL-11685.

The purpose of this report is to document the physical waste simulant development efforts of the EM-50 Tanks Focus Area at the Hanford Site. Waste simulants are used in the testing and development of waste treatment and handling processes because performing such tests using actual tank waste is hazardous and prohibitively expensive. This document addresses the simulant development work that supports the testing of waste retrieval processes using simulants that mimic certain key physical properties of the tank waste. Development and testing of chemical simulants are described elsewhere (Elmore et al. 1992; LaFemina 1995).

This work was funded through the EM-50 Tanks Focus Area as part of the Retrieval Process Development and Enhancements (RPD&E) Project at the Pacific Northwest National Laboratory (PNNL). The mission of RPD&E is to understand retrieval processes, including emerging and existing processes, gather performance data on those processes, and relate the data to specific tank problems to provide end users with the requisite technical bases to make retrieval and closure decisions.

Randolph, J. D., B. E. Lewis, J. R. Farmer, and M. A. Johnson, Fabrication of a Sludge-Conditioning System for Processing Legacy Wastes from the Gunite and Associated Tanks, ORNL/TM-2000/222, UT-Battelle, LLC, ORNL, Oak Ridge, Tennessee, August 2000.

This report provides a description of the Sludge Conditioning System design and installation at the GAAT STF, including the fabrication schedule and approximate costs.

Randolph, J. D., P. D. Lloyd, and B. L. Burks, Development of a Waste Dislodging and Retrieval System for Use in the Oak Ridge National Laboratory Gunite Tank, CONF-970464-14, American Nuclear Society topical meeting on robotics and remote systems (7th), Augusta, GA (United States), 27 Apr - 1 May 1997.

As part of the GAAT Treatability Study the ORNL has developed a TWRS capable of removing wastes varying from liquids to thick sludges. This system is also capable of scarifying concrete walls and floors. The GAAT Treatability Study is being conducted by the Department of Energy Oak Ridge Environmental Restoration Program. The WD&CS was developed jointly by ORNL and participants from the TFA. The WD&C system is comprised of a four degree-of-freedom arm with back drivable motorized joints. A cutting and dislodging tool, a jet pump and hose management system for conveyance of wastes, CSEE, and a control system, and must be used in conjunction with a robotic arm or vehicle. This paper describes the development of the WD&CS and its application for dislodging and conveyance of ORNL sludges from the GAAT tanks. The CSEE relies on medium-pressure water jets to dislodge waste that is then pumped by the jet pump through the conveyance system out of the tank. This paper describes the results of cold testing of the integrated system.

Rinker, M. W., J. A. Bamberger, and D. G. Alberts, EM-50 Tanks Focus Area Retrieval Process Development and Enhancements. FY97 Technology Development Summary Report, PNNL11734, USDOE Office of Environmental Restoration and Waste Management, Washington, DC, September 30, 1997.

The Retrieval Process Development and Enhancements (RPD and E) activities are part of the US Department of Energy (DOE) EM-50 Tanks Focus Area, Retrieval and Closure program. The purpose of RPD and E is to understand retrieval processes, including emerging and existing technologies, and to gather data on these processes, so that end users have requisite technical bases to make retrieval decisions. Technologies addressed during FY97 include enhancements to sluicing, the use of pulsed air to assist mixing, mixer pumps, innovative mixing techniques, confined sluicing retrieval end effectors, borehole mining, light weight scarification, and testing of Russian-developed retrieval equipment. Furthermore, the Retrieval Analysis Tool was initiated to link retrieval processes with tank waste farms and tank geometric to assist end users by providing a consolidation of data and technical information that can be easily assessed. The main technical accomplishments are summarized under the following headings: Oak Ridge site-gunite and associated tanks treatability study; pulsed air mixing; Oak Ridge site-OHF; hydraulic testbed relocation; cooling coil cleaning end effector; light weight scarifier; innovative tank mixing; advanced design mixer pump; enhanced sluicing; Russian retrieval equipment testing; retrieval data analysis and correlation; simulant development; and retrieval analysis tool (RAT).

Rule, V. A. B. L. Burks, and S. D. Van Hoesen, North Tank Farm Data Report for the Gunite and Associated Tanks at Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL/TM13630. Lockheed Martin Energy Research Corp., ORNL, Oak Ridge, Tennessee, May 1998.

The US DOE Office of Science and Technology, in cooperation with the Oak Ridge Environmental Management Program, has developed and demonstrated the first full-scale remotely operated system for cleaning radioactive liquid and waste from large underground storage tanks. The remotely operated waste retrieval system developed and demonstrated at ORNL is designed to accomplish both retrieval of bulk waste, including liquids, thick sludge, and scarified concrete; and final tank cleaning. This report provides a summary of the NTF operations data and an assessment of the performance and efficiency of the waste retrieval system during NTF operations data and an assessment of the performance and efficiency of the waste retrieval system during NTF operations.

Thompson B. and A. Slifko, Houdini™: Reconfigurable In-Tank Mobile Robot. Final Report, June 1995--January 1997, DOE/MC/32092-5630, Redzone Robotics, Inc., Pittsburgh PA, December 1998.

This report details the development of a reconfigurable in-tank robotic cleanup system called Houdini™. Driven by the general need to develop equipment for the removal of radioactive waste from hundreds of DOE waste storage tanks and the specific needs of DOE sites such as ORNL and Fernald, Houdini represents one of the possible tools that can be used to mobilize and retrieve this waste material for complete remediation. Houdini is a hydraulically powered, track driven, mobile work vehicle with a collapsible frame designed to enter underground or above ground waste tanks through existing 24 inch riser openings. After the vehicle has entered the waste tank, it unfolds and lands on the waste surface or tank floor to become a remotely operated mini-bulldozer. Houdini utilizes a vehicle mounted plow blade and 6-DOF manipulator to mobilize waste and carry other tooling such as sluicing pumps, excavation buckets, and hydraulic shears. The complete Houdini system consists of the tracked vehicle and other support equipment (e.g., control console, deployment system, hydraulic power supply, and controller) necessary to deploy and remotely operate this system at any DOE site. Inside the storage tanks, the system is capable of performing heel removal, waste mobilization, waste size reduction, and other tank waste retrieval and decommissioning tasks. The first Houdini system was delivered on September 24, 1996 to ORNL. The system acceptance test was successfully performed at a cold test facility at ORNL. After completion of the cold test program and the training of site personnel, ORNL will deploy the system for clean-up and remediation of the gunite storage tanks.

Van Hoesen, S. D., D. Bolling, and K. Billingsley, Robot System Goes Underground at Oak Ridge – Technology Integration Ensures Successful Storage Tank Remediation, Pollution Engineering, pp 14-17, March 1999.

This paper provides a description of the GAAT Remediation Project, the tank cleaning system, and results from waste retrieval operations in the two smaller waste tanks (W-3 and W-4) during the CERCLA Treatability Study.

Weeren, H. O. Sluicing Operations at Gunite Waste Storage Tanks, Martin Marietta Energy Systems, Inc., ORNL/NFW-84/42, ORNL, Oak Ridge, Tennessee, September 1984.

This report provides a description of the initial bulk sludge removal operations from the six tanks in the GAAT STF. Limited characterization data on the waste is provided along with descriptions of the tanks, sluicing operations and equipment, sludge grinder, drilling rig for the addition of access holes, work platforms, instrumentation, and summary of the results.

Appendix A: Prototype Waste Retrieval End-Effector Test Report

Prepared For: Hanford Tanks Initiative
C-106 Heel Retrieval Demonstration
Lockheed Martin Hanford Company
Post Office Box 1500
Richland, Washington 99352
Task Order 621, Release 33

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December, 1998

Executive Summary

This report describes the testing program of the prototype Waste Retrieval End Effector (WREE) conducted by the Pacific Northwest National Laboratory (PNNL) at the Hydraulics Test Bed (HTB). As part of the Hanford Tanks Initiative (HTI) Project, a contractor team led by Foster Wheeler proposes to deploy the WREE with a remote crawler to remove sludge and hardpan from Tank 241-C-106 during a retrieval demonstration. The prototype WREE was fabricated by Oceaneering International, Incorporated and delivered to PNNL during November, 1998. This activity supports HTI and the Foster Wheeler team by providing prototype testing to validate the design and insure that performance objectives are met or exceeded. Under this task, PNNL staff installed the prototype WREE on the HTB's robotic gantry, installed instrumentation to measure reaction forces and process parameters, prepared and characterized simulant materials, and implemented the test program. The completed tests involved retrieval of water, sludge, hardpan, and debris to determine pumping rate, dilution factors, and filter fouling rate. Following the retrieval tests, the WREE was cleaned with a 3000 psi waterjet to simulate a decontamination process. The WREE was then examined to determine the amount and location of residual sludge on the exterior portion of the WREE; the WREE was also disassembled to identify internal leakage, seal damage, and sludge residue.

The test objectives established in the test plan were successfully addressed with the exception of measuring aerosol generation during floor scarification. The aerosol measurements were taken during short duration tests under somewhat uncontrolled conditions and may not be indicative of conditions during tank deployment. Short duration tests with wet sludge and hardpan were conducted to measure baseline performance. The retrieval goal for the WREE was 10 gallons/minute, which was exceeded during retrieval of hardpan (without consideration of the time required to clean the inlet screen). The retrieval rate during sludge retrieval was 7 gallons/minute, which is 30% lower than the target retrieval rate. However, since material did not accumulate in the conveyance line and the motor did not decelerate during the tests, higher retrieval rates are possible using a higher traverse speed or deeper WREE submersion in the sludge, especially after the sludge is diluted.

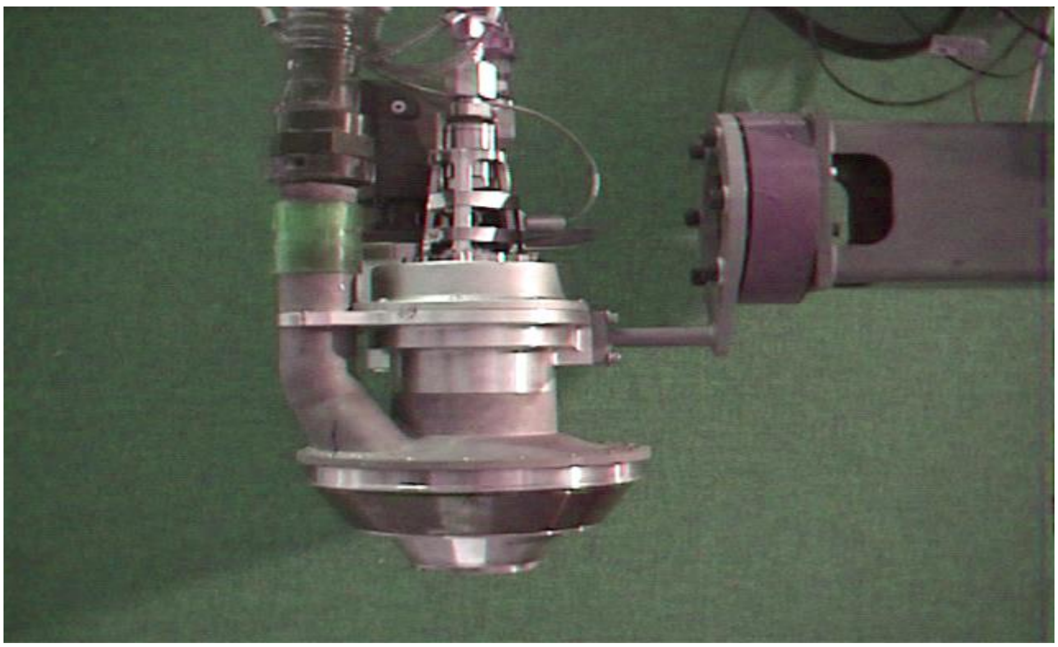
Based on our observations of the WREE during the performance of the various tests, it appears to be a reliable and rugged device that is well suited for remote retrieval in tank C-106. The unit has benefited from design enhancements resulting from lessons learned with the original Sludge Retrieval End Effector at ORNL, including a higher torque hydraulic motor, higher flow area screen, and refined conveyance inlet. Initial test performance does indicate the need to address the areas of seal wear and enhanced screen cleaning. It is believed that minor changes to tolerances and surface finish specifications will alleviate the seal problems. Another design change will be required to reduce the rate that the screen is fouled during hardpan retrieval. The screen became plugged with clumps of dislodged material that were too large to pass through the 0.25 inch opening in the screen. Using a combination of back-flushing with water and mechanical brushing, the screen was successfully cleaned remotely, although the rate of screen fouling is unacceptably high. Another nozzle will need to be added to the WREE to clean the screen on a continuous basis. Additional tests could be conducted with a modified prototype to select the best alternative.

1.0 Introduction

This report describes the testing program of the prototype Waste Retrieval End Effector (WREE) conducted by the Pacific Northwest National Laboratory (PNNL) at the Hydraulics Test Bed (HTB). As part of the Hanford Tanks Initiative (HTI) Project, a contractor team led by Foster Wheeler proposes to deploy the WREE with a remote crawler to remove sludge and hardpan from Tank 241-C-106 during a retrieval demonstration. This activity supports HTI and the Foster Wheeler team by providing prototype testing to validate the design and insure that performance objectives are met or exceeded. Under this task, PNNL staff installed the prototype WREE on the HTB's robotic gantry, installed instrumentation to measure reaction forces and process parameters, prepared and characterized simulant materials, and implemented the test program. The completed tests involved retrieval of water, sludge, hardpan, and debris to determine pumping rate, dilution factors, and filter fouling rate. Following the retrieval tests, the WREE was cleaned with a 3000 psi waterjet to simulate a decontamination process. The WREE was then examined to determine the amount and location of residual sludge on the exterior portion of the WREE; the WREE was also disassembled to identify internal leakage, seal damage, and sludge residue.

2.0 Waste Retrieval End-Effector Description

The WREE will be used to fragment and dislodge waste and introduce the slurried waste into the inlet of a conveyance system. Conceptually, the WREE (Figure 1) is an array of small waterjets rotating around a central conveyance inlet. The design of the HTI WREE was based in large part on the Sludge Retrieval End Effector (SREE) developed by the PNNL EM50 Tanks Focus Area (TFA) Retrieval Program for ORNL. Design changes were required due to differences in Hanford's waste physical properties, flammable gas requirements, radiation levels, and tank interfaces. The fundamental goal was to produce a highly reliable, compact, and lightweight end effector that could be decontaminated and maintained inside a glove box. It was expected that the performance of the WREE would be somewhat better than the SREE due to refinements in screen design and conveyance inlet geometry, which were design changes based on lessons learned at ORNL (Mullen, 1997). The design of the WREE is described in (Mullen et al 1998). The prototype WREE was fabricated by Oceaneering International, Incorporated and delivered to PNNL during November, 1998. The weight of the end effector, measured before the tests were begun, is 87 lbs including the T-handle extension.

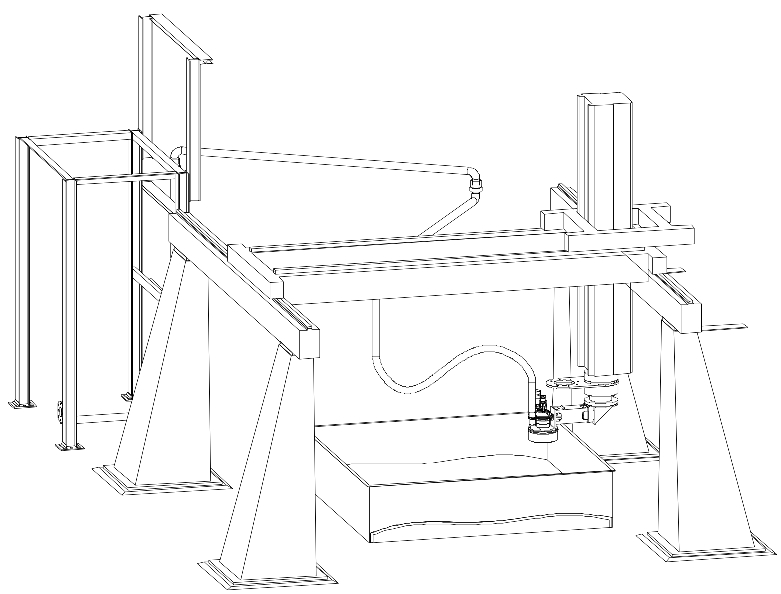


3.0 Test Approach

The WREE was installed in the PNNL Hydraulic Test Bed, located in the 338 Building at the Hanford Site. The test set-up, equipment, instrumentation, and simulants are discussed in the following sections.

3.1 Test Setup

Prior to the initiation of retrieval testing, the WREE was static pressure tested in a hydrostatic pressure apparatus. The apparatus included a pressure generator produced by the High Pressure Equipment Company and a pressure gauge. The hydrostatic leak test was performed per ASME B31.3-1996, paragraph 345.4, using a test pressure of 1.5 times the design pressure, or 15,000 psi. This equipment was also used to qualify the EM50 TFA retrieval jet pump developed by PNNL for service at ORNL. The WREE was then installed on the HTB gantry using an adaptor plate. An overview of the test set-up is provided in Figure 2. The gantry, conveyance line management arm, jet pump, and ancillary equipment near the WREE were enclosed in a large tent. A high pressure pump located in a pump house adjacent to the 338 Building supplied water for the WREE, jet pump, and decontamination spray-lance. A material receipt hopper located outside the test facility collected test slurry. Hoses connected the pump to the WREE and jet pump, while facility piping connected the outlet of the jet pump to the hopper. Instrumentation was installed to measure process parameters, reaction forces, and retrieval performance. Simulant materials were prepared and characterized in the Simulant Development Laboratory, located in the 336 Building.



3.2 Test Equipment and Instrumentation

The following sections provide a description of the test equipment and instrumentation.

3.2.1 Equipment

Test equipment used during WREE prototype testing is listed below.

- Robotic Gantry The gantry system provided a horizontal work space of 8 ft by 10 ft at speeds up to 36 in/min.

- High Pressure Pump A positive displacement triplex pump constructed by National Liquid Blaster was used to supply high pressure water to the jet pump and WREE. The capacity of the pump was 25 gallons/min at 10,000 psi. The pump included a pressure reducing station to regulate the discharge pressure.

- Control Valves The output from the high pressure pump was directed to two air actuated control valves.

- High Pressure Hose Two high pressure hoses were routed from the high pressure control valves to the WREE and jet pump. The pressure and flow rate was regulated in each line independently.

- Pressure Regulator A secondary pressure regulator was installed in the high pressure line connected to the WREE to allow the pressure to be reduced below the pump pressure, if desired.

- Conveyance Line Management Arm (CLMS) A passive two-link arm was used to support the conveyance line and high-pressure hoses in the vicinity of the WREE. A two inch diameter translucent flexible hose connected the end of the CLMS to the WREE and the CLMS to the jet pump.

- Jet Pump A high pressure jet pump produced by Butterworth (Model 70-8500) was used during the tests to provide suction and transport of dislodged slurries. Six 0.031 inch diameter nozzles were installed in the jet pump nozzle ports. The jet pump was operated at approximately 7000 psi during the tests, which required 12.5 gpm.

- Conveyance Hose Two inch diameter pipe connected the jet pump discharge to a collection hopper. The length of line from the end of the jet pump to the hopper was 40 ft and included a lift of 15.3 ft.

- Hopper The conveyance line terminated into a cyclone separator, which separated the air from the slurry and allowed the slurry to drain into a collection hopper. Air was vented through a 2 inch pipe attached to the hopper.

- Hydraulic Power Unit A small hydraulic power unit was installed in the 338 Building to operate the WREE hydraulic motor. Hydraulic hoses were routed from the HPU to the WREE using the gantry's cable carriers.

- Simulant Tank Simulant was placed in a square shaped steel tank with dimensions 8 ft by 2 ft deep.

- Test Enclosure The gantry and CLMS were enclosed in a large tent; the top of the test was open to allow coverage by fire protection sprinklers(12).

3.2.2 Instrumentation

A Measurement and Test Equipment list is provided in Appendix A, while a Piping and Instrumentation Diagram (P&ID) is provided in Appendix B. The instrumentation is briefly described below.

- Data Acquisition System (DAS) The sensors were connected to a National Instruments Labview™ data conditioning module, which converted the sensor signals to analog voltages. This module also provided electrical isolation between the data acquisition computer and the sensors, which reduced the risk of electrical overload at the computer. The computer platform was a 120 MHZ Pentium-based PC running Windows NT 4.0, which allowed rapid sampling (up to 200 Hz) of instrumentation and process control signals.

- Waterjet Pressure Transducers A visual pressure gauge was included in the high pressure pump. The gauge was downstream of the pressure reducing valve, so that the gauge could be used to set the discharge pressure. Pressure transducers were installed near the end of the high pressure hoses to monitor the pressure of water entering the jet pump and WREE.

- Waterjet Flow Meters High pressure water flow meters were installed in both high pressure lines to measure the flow of water to the WREE and jet pump independently. One of these flow meters was temporarily inserted in the hydraulic fluid high pressure line to measure the flow of hydraulic fluid to the WREE motor.

- Force-Torque Sensor To measure dynamic forces due to suction, inertia, and waterjet reaction, a sensor which measures forces and torques along three axes was attached to the WREE mounting beam. At the beginning of each test, the sensor was "zeroed" to eliminate steady state offset due to the weight of the end effector and loading from the hoses.

- WREE Speed Sensor A tachometer was installed on the WREE during preliminary tests to calibrate the hydraulic pump flow rate and valve position with manifold speed.

- Hopper Load Cells Load cells were installed on the hopper mounting locations to measure the weight of process water and waste simulant entering the hopper.

[2] Initially, the top of the tent was to be covered to capture aerosols during tests. The complexity of this task, coupled with funding limits, made this impractical.

- Annubar Air Flow Measuring System An air flow system from Dietrich's Standard was installed in the hopper air bleed line to measure the amount of air entrained in the slurry discharge during retrieval. The sensor measured the pressure drop across a small, diamond-shaped probe positioned across the pipe. This pressure drop has been calibrated with flow rates at a number of configurations. Included in the system was an absolute pressure transducer and a temperature probe. The various measurements were transmitted to a local computer, which calculates air flow and transmitted the signals to the main data acquisition computer.

3.2.3 Simulant Development

Wet sludge and hardpan simulants were prepared for the test program using the procedures in (Powell 1996). Tapes, rocks, and other debris were added to the simulants in latter stages of the test program. Table 1 provides the simulants that were used during the testing program. Samples of each batch of simulant were taken to determine actual density and shear strength. Slurry samples were taken from the hopper after retrieval tests to determine particle size distribution.

Table 1. Simulant used in the Test Program

Simulant	Shear Strength	Density
Sludge 67 wt.% EPK Pulverized Kaolin Clay 34 wt.% Water	3.5 kPa	1.65 g/cm^3
Hardpan/Dried Sludge Composition #2 40.0 wt.% Plaster of Paris 22.5 wt.% EPK Pulverized Kaolin Clay 37.5 wt.% Water	200 kPa	1.65 g/cm^3

4.0 Prototype Testing

Table 2 describes the various tests that were undertaken during prototype testing. The test objectives established in the test plan (Hatchell et al 1998) were successfully addressed with the exception of measuring aerosol generation during floor scarification[13]. Test results are presented in the sections that follow.

Table 2. WREE Prototype Test Objectives

Test Phase	Test Focus	Test Parameter	Key Data Expected
Manifold Static Pressure Test	Hydrostatic pressure test to 1.5 times design pressure	· Static pressure test with water to 15,000 psi for 15 minutes	· Verify structural integrity of manifold per requirements for ASME B31-3-1996
Hydraulic Motor Tests	Measure motor speed and torque	· Measure motor speed versus hydraulic fluid valve position and flow rate. · Measure motor torque characteristics	· Measure motor speed remotely · Verify that motor has sufficient torque
WREE Baseline Retrieval Tests	Sludge and Hardpan Retrieval Tests	· Short duration tests with sludge and hardpan · Flat topography	· Verify basic operating parameters · Identify plugging problems · Water usage · Aerosol generation · Slurry density · Slurry output rate · Maximum particle size at hopper · WREE reaction forces · Motor speed variation during retrieval · Air flow rate through conveyance line · Final surface cleaning · Debris management · Screen and shroud plugging
Decontamination	Flushing and wash down	· Internal flushing · External wash down with 3000 psi water · WREE disassembly	· Amount of internal and external residual sludge and liquid. · Assess damage caused by wash down · Evaluate seal wear

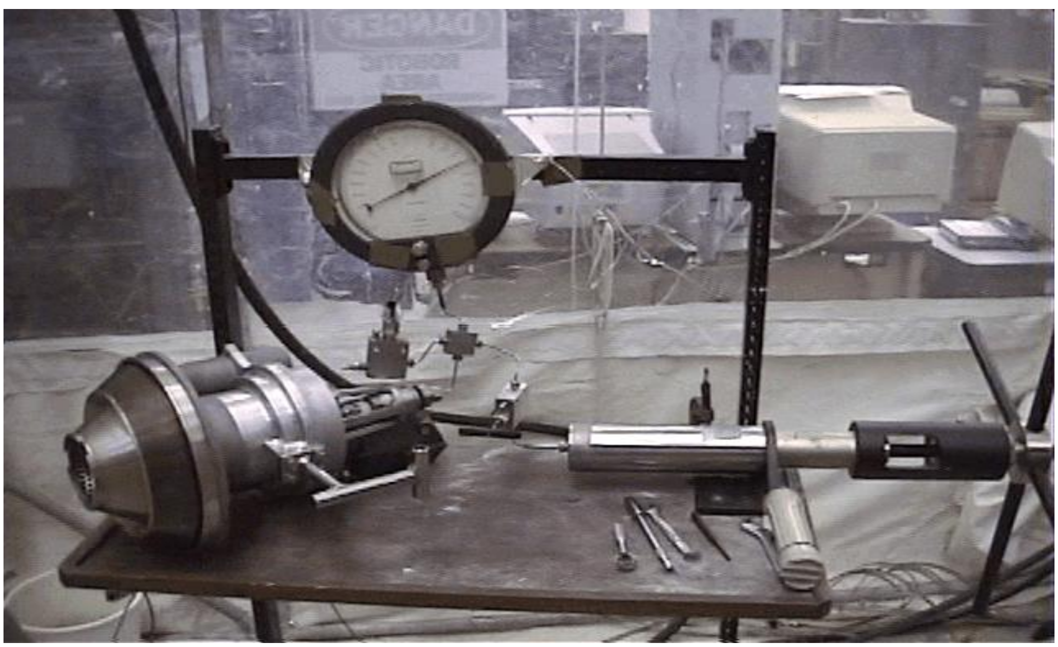
[3] - The aerosol measurements were taken during short duration tests under somewhat uncontrolled conditions and may not be indicative of conditions during tank deployment. See Section 4.3.3.

4.1 Manifold Static Pressure Test

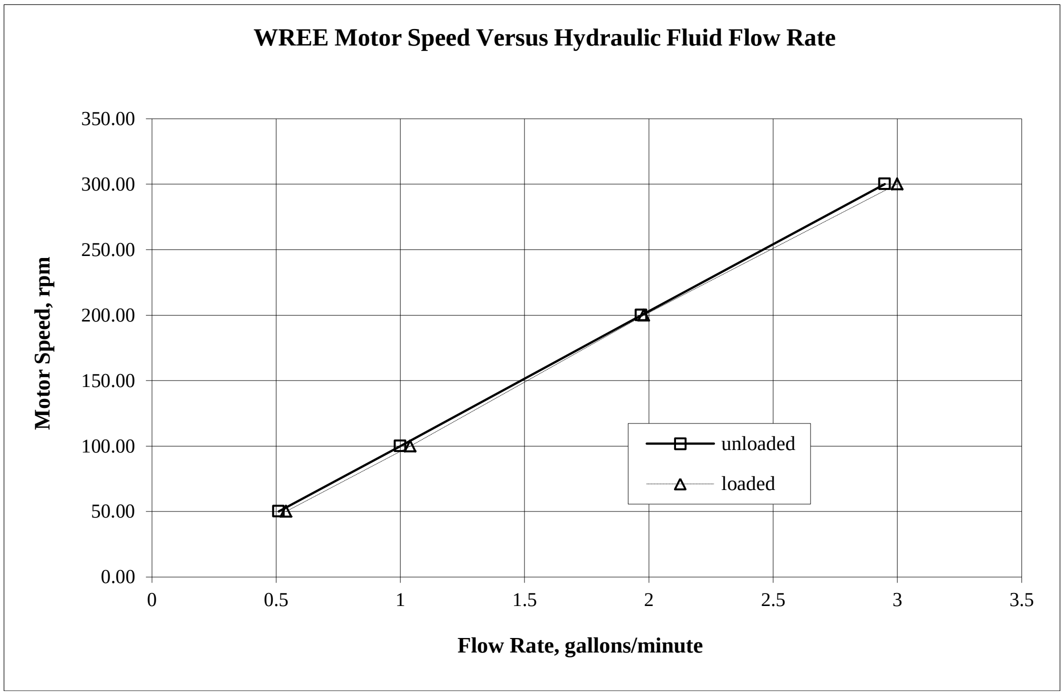
Prior to the initiation of retrieval testing, the WREE was static pressure tested per the requirements of ASME B31.3-1996 in a hydrostatic pressure apparatus using a test pressure of 1.5 times the design pressure, or 15,000 psi. The apparatus included a pressure generator and pressure gauge (see Figure 3). For this test, the WREE nozzles were replaced with plugs. The test pressure was maintained for over 15 minutes with no visible leaks. During the test, the pressure declined at a very slow rate, apparently due to the displacement of a nozzle plug with respect to its mount. To compensate, the applied pressure was increased approximately 200 psi three times to maintain a test pressure above 15,000 psi. The rate of pressure decay reduced over the course of the test to the point where little adjustment was required.

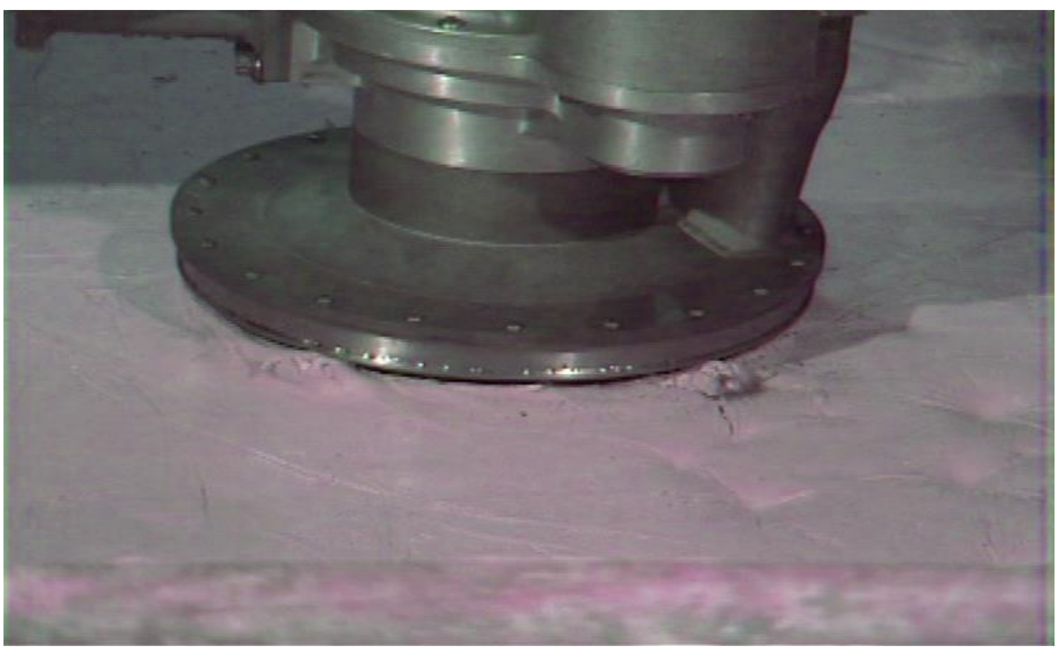
4.2 Hydraulic Motor Tests

During the initial rotational test, the shroud-manifold seal and the outer manifold shaft bottom seal overheated. Thin strips of material were evident around the manifold seal surfaces. After rotation was stopped, the seals fused to the manifold and re-starting rotation was not possible with the hydraulic motor. It was necessary to liberate the seals by strapping a lever to the manifold arm and applying approximately 60 ft-lbs of torque. After rotation was restored, the rotational friction was reduced to approximately 5 ft-lbs and testing continued.



The hydraulic speed test determined if the relationship between hydraulic flow, rotational speed, and valve position (assuming constant seal leakage) was linear regardless of load. The hydraulic fluid flow rate required to achieve the desired motor speed was measured for an unloaded motor and a lightly loaded motor (approximately 3 ft-lbs). The results, provided in the Figure 4 below, indicate that the rotational speed of the end effector correlates well with the hydraulic fluid flow rate, at least in the case of an unloaded and lightly loaded motor. To test motor torque performance, the WREE was plunged into undisturbed sludge to the upper level of the manifold (Figure 5). The hydraulic motor was activated and reached maximum speed without difficulty. The maximum torque measured by the force-torque sensor during start-up was 22 ft-lbs.





4.3 WREE Baseline Retrieval Test

4.3.1 Mining Strategies Tested

Short duration retrieval tests focused on measuring retrieval performance during sludge and hardpan retrieval. For these tests, the size of the field was approximately 5-6 inches deep, 2 feet wide, and 8 feet long. The WREE was generally used to remove thin layers of material (1-3 inches). Testing with the WREE was conducted with a serpentine path in which the end effector was swept over the waste surface in a regular pattern, removing waste in horizontal planes. For sludge and hardpan testing, it was possible to submerge the WREE slightly below the surface of the material, as the WREE was able to clear a path ahead of itself. During sludge retrieval, the surface of the sludge field was approximately level and the WREE left a somewhat indiscernible path. The waterjets apparently agitated the surrounding waste field to the extent that the sharp edges of the cutting path collapsed somewhat. Excess water was absorbed by the waste, and splatter from the waterjets was minimal, especially when lower water pressure was used. In hardpan retrieval, the waterjets cut channels in the material approximately 4.3 inches wide, which dictated a distance between adjacent passes of 4.3 inches.

4.3.2 Retrieval Performance

Table 3 contains performance parameters that were collected during retrieval tests with sludge and hardpan material. Retrieval rate refers to the rate of sludge or hardpan removal. Water usage divided by retrieval rate (dilution ratio) is the number of gallons of water used to power the jet pump and WREE waterjets per gallon of material retrieved. Slurry flow rate and density is the total flow and fluid density in the conveyance line downstream of the jet pump, respectively. During the tests, the jet pump was operated continuously at approximately 7000 psi and used 12.5 gallons/minute of water. The hydraulic motor speed was 300 rpm for these tests.

Sludge retrieval was accomplished using 0.054 inch diameter waterjet nozzles operated at 150-1020 psi (see Figure 6) and a traverse speed of 300 inches/minute. The waterjet pressure was set to 1000 psi for the initial pass, but as successive layers were removed and the sludge became diluted, the waterjet pressure was reduced to approximately 200 psi. The WREE was lowered 1 inch before each pass was initiated, which resulted in a retrieval rate of approximately 7 gpm, which is somewhat below the target retrieval rate of 10 gpm. However, since material did not accumulate in the conveyance line and the motor did not decelerate during the tests, higher retrieval rates are possible using a higher traverse speed or deeper WREE submersion in the sludge, especially after the sludge is diluted. Waterjet pressure did not effect retrieval rate, as the WREE retrieved a path defined by the inlet shroud regardless of pressure. Based on this test, it is possible to use 0.038 inch diameter nozzles for sludge retrieval (the same size used for hardpan retrieval) and a slightly higher pressure, if desired, to avoid nozzle change-out. At the conclusion of the sludge tests, the tank floor was clearly visible, and only a thin layer of dilute sludge remained. The test was conducted without a skirt installed on the WREE; using the skirt may have reduced the splattering and resulted in an even cleaner tank surface.

Hardpan retrieval was accomplished using 0.038 inch diameter waterjet nozzles and a traverse speed of 225 inches/minute. Initial runs were conducted to determine the relationship between waterjet penetration depth and waterjet pressure. Waterjet pressure of 2000, 2200, 2600, and 3200 psi resulted in cutting depths of 1.7, 1.9, 2.1, and 2.6 inches, respectively. Since it was desirable to achieve a relatively shallow depth of cut using as low a pressure as possible (to avoid spatter), a reasonable operating pressure was 2250 psi for a traverse speed of 225 inches/minute. Note that the dilution ratio (12th column of data in Table 3) decreases with increasing jet pressure, so it may be advantageous to use a higher pressure to reduce overall water consumption. Hardpan retrieval rates ranged from 8.9-14.0 gallons/minute. This rate does not account for the time required to clean the inlet shroud, which will reduce efficiency. The WREE skirt was installed during the hardpan tests, and reduced the amount of over-spray considerably.

During hardpan retrieval, the screen became plugged with clumps of dislodged material that were too large to pass through the 0.25 inch opening in the screen (Figure 7). Using a combination of back-flushing with water and mechanical brushing (Figure 8), the screen was successfully cleaned remotely (Figure 9). Flushing with water alone did not clean the screen completely, especially in the upper recesses of the conical cone. The screen plugged after retrieving approximately 1.0 cubic feet; in an attempt to reduce the size of the dislodged particles and the plugging rate, additional tests were conducted with a slower traverse speed of 150 inches/minute. The screen plugged at approximately the same rate during these tests as well. The inlet of the shroud typically contained one or two very large chunks, which inevitably would block the flow. The final pass was conducted with a 0.25 inch stand-off to reduce the size of material that could enter the inlet, which was a more successful method for reducing the screen fouling rate. However, this method resulted in a significant amount of hardpan being left behind (0.3 ft^3 out of a total of 15 ft^3 retrieved) after the final pass was complete. The remaining chunks could be broken up readily with WREE waterjets at large stand-off and then conveyed from a stationary point at close stand-off, a routine practice at ORNL using the SREE.

Following the basic retrieval tests, various types of debris (large rocks, pea gravel, metal tape, rope, and plastic gloves) was added to the remaining sludge. The debris eventually plugged the screen during retrieval, but was, in general, easily removed with back-flushing. Rope fibers proved to be the hardest to remove from the screen, and required manual intervention. During this test, the hydraulic motor never stalled and in fact maintained the 300 rpm setting (+/- 20 rpm) even during brief collisions with the tank floor and debris.

Reaction forces from the WREE were measured during the tests and are summarized in Table 4. Reaction forces were low during sludge retrieval (≤20 lbs), moderate during hardpan retrieval (≤90 lbs), and highest during sludge retrieval with debris (≤200 lbs). Higher forces are attributed to collisions with the simulant surface or debris. The magnitudes of these forces are representative of forces collected during previous end effector tests involving hard simulant and debris (e.g. Lightweight Scarifier). Since the reaction forces depend on the compliance of the deployment device, the reaction forces for the WREE deployed on the Houdini crawler will be different. However, the tests have shown that the WREE is a robust device capable of withstanding moderately high forces without failure.

At the conclusion of the retrieval tests, samples of settled sludge were obtained from the hopper. The solid material that had settled to the bottom was very fine and had a paste-like consistency. The jet pump obviously breaks up the larger hardpan particles that pass through the 0.25 screen openings. No debris was found in the hopper.

Table 3. WREE Retrieval Performance Parameters

Simulant Type	Pass	Pass Width inches	WREE Nozzle Size inches	WREE Nozzle Pressure psia	WREE Nozzle Flow gpm	Speed of Rotation rpm	Traverse Rate inch/min	Jet Pump Pressure psia	Jet Pump Flow gpm	Retrieval Rate gpm	Water Usage / Retrieval Rate	Slurry Flow Rate gpm	Slurry Density lb/ft^3
sludge	1	4.3	0.054	1020	6.56	300	300	6930	12.63	7.10	2.70	26.29	73.35
sludge	2	4.3	0.054	178	2.83	300	300	7200	12.83	7.10	2.21	22.76	75.05
sludge	3	4.3	0.054	261	3.44	300	300	7060	12.80	7.10	2.29	23.34	74.74
sludge	4	4.3	0.054	164	2.71	300	300	7233	12.92	7.10	2.20	22.73	75.07
sludge	5	4.3	0.054	157	2.15	300	300	7256	13.02	7.10	2.14	22.27	75.33
sludge	6	4.3	0.054	0	0	300	300	7386	13.02	0		13.02	62.40
hardpan	1	4.3	0.038	3257	5.76	300	225	6890	12.83	13.99	1.33	32.58	79.82
hardpan	1	4.3	0.038	2583	5.25	300	225	6879	12.88	10.92	1.66	29.05	77.65
hardpan	1	4.3	0.038	2188	4.84	300	225	7008	12.91	10.12	1.75	27.87	77.13
hardpan	1	4.3	0.038	1992	4.62	300	225	7075	12.95	8.92	1.97	26.49	76.06
hardpan	2	4.3	0.038	2446	5.11	300	150	6933	12.88	NA			
hardpan	2	4.3	0.038	1990	4.62	300	150	7005	12.91	NA			

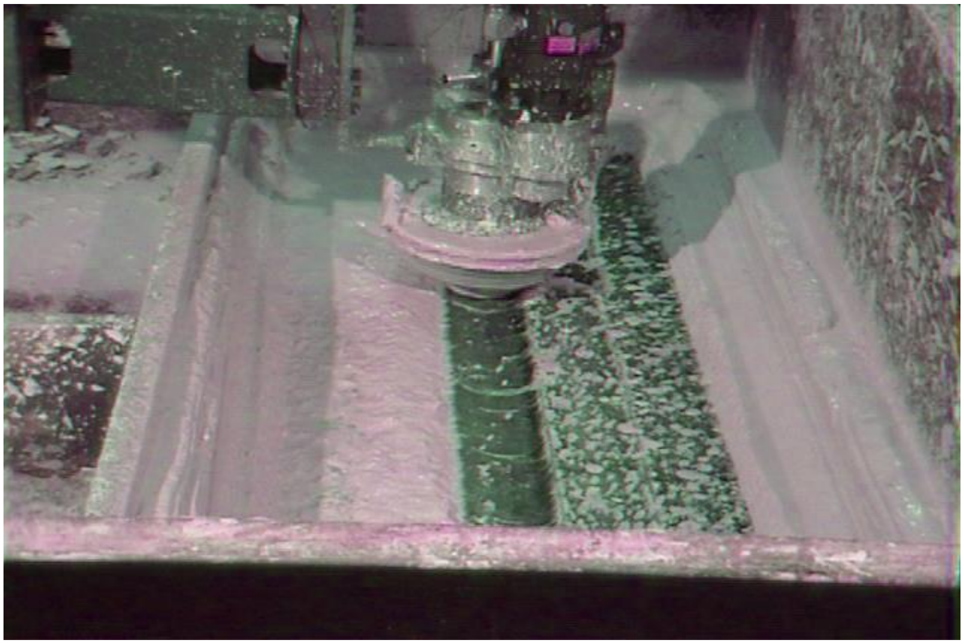


Table 4. Maximum Forces Measured during Retrieval Tests

Simulant Type	Extreme	Pass Width inches	WREE Nozzle Size inches	WREE Nozzle Pressure psia	WREE Nozzle Flow gpm	Speed of Rotation rpm	Traverse Rate inch/min	Fx * lbf	Fy * lbf	Fz * lbf	Mx * lbf-lb	My * lbf-lb	Mz * lbf-lb
sludge	max	4.3	0.054	1020	6.56	300	300	-14.4	5.6	7.1	-5.3	-12.4	10.2
	min							-20.1	3.0	1.9	-7.6	-21.2	6.1
hardpan	max	4.3	0.038	2583	5.25	300	225	33.7	90.9	35.9	-11.0	45.4	12.3
	min							-2.6	6.8	14.2	-63.7	4.1	-81.6
sludge debris	max	4.3	0.054	178	2.83	300	300	197.1	90.1	75.1	55.6	136.8	82.3
	min							-32.2	-74.1	-119.3	-75.1	-6.04	-70.9

* - The X-axis of the force-torque sensor was oriented in the vertical direction, the Y-axis was oriented in the direction of travel, and the Z-axis was oriented along the longitudinal axis of the attachment arm

4.3.3 Aerosol Measurements

Tank floor scarification tests were conducted to qualify the amount of aerosols generated. During these scoping tests, the waterjet pressure was varied from 3000-7000 psi and the stand-off distance was varied from 0.25 to 2 inches. The waterjets collided with a clean steel tank floor, although the floor was at times covered with a thin layer of water. The jet pump was turned off for one of these tests to determine the effect of increasing the liquid level. During these tests, an aerosol monitor provided by Monitoring Instruments for the Environment, Inc. was positioned beside and slightly below the test tank. The device had a continuous read-out. The instrument was monitored periodically during the tests to establish a range of aerosol readings. The results, shown in Table 5, indicate that aerosols were higher during tests at high pressure and close stand-off. Visibility was not diminished during these tests, although visible aerosol spray was at times apparent. The rubber skirt on the WREE was effective in reducing splatter and over-spray. Note that these tests were conducted under uncontrolled conditions and may not be indicative of conditions during tank deployment. For example, the tests were not completely enclosed, and the flow of air into the test area was not monitored. The tests were also brief (approximately 2 minutes), and aerosol loading could have potentially increased with time to a higher steady state value under different environmental conditions. The tests do indicate that aerosol measurements are readily obtainable if the testing environment can be controlled and sufficiently long test durations can be achieved.

Table 5. Aerosol Measurement during Floor Cleaning

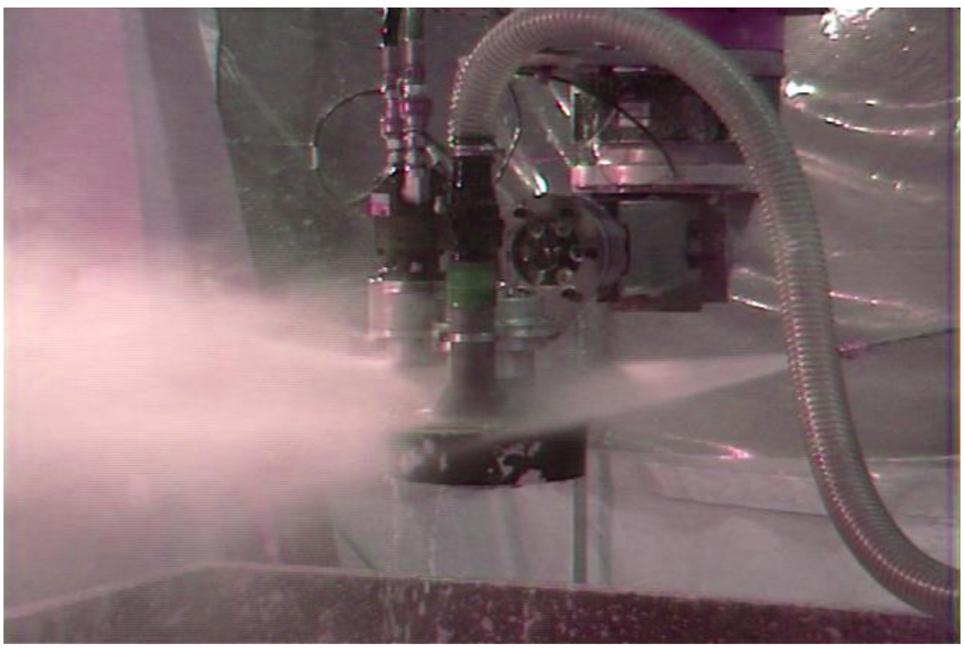
Waterjet Pressure, psi	Stand-off, inches	Aerosol Readings, Mg/m^3	Target Visibility
6000	0.25	0.1-2.0	Unlimited
6000	2.0	1.1-1.6	Unlimited
6000	2.0 (jet pump off)	0.6-0.8	Unlimited
3000	0.25	0.4-0.8	Unlimited

4.4 Decontamination and Wash-down Tests

At the conclusion of retrieval testing, the WREE was sprayed externally with a 3000 psi waterjet to simulate a decontamination process (Figure 10). The decon test first simulated the action of an array of fixed nozzles and then the action of a concentrated jet. Using a hand-held spray wand, the exterior of the WREE shroud was cleaned by aiming the wand upward at 30 degrees and spraying around the circumference of the inlet. The main body of the WREE was cleaned using slow overlapping vertical sweeps, a stand-off distance of approximately 6 inches, and a horizontal nozzle orientation. Any remaining sludge was cleaned by concentrating the jet as required. The most difficult area to clean was inside the shroud and skirt. After the decontamination test, the WREE was inspected. A small amount of sludge residue remained on the exterior surfaces of the end effector as noted below. Item numbers refer to numbers on the WREE parts list (drawing PNNL-28463-100, Rev. 0).

- A small amount of sludge was found in the top of the truncated conical shroud inlet screen.

- A small amount of sludge was found behind the swivel support legs.
- Smear remained on the rubber skirt. Sludge residue was also found under the skirt retainer band clamp. The band clamp used on the prototype was a conventional hose clamp which could not be tightened as well as the designed item and afforded many more pockets and crevices.
- A light film or crust of kaolin was left on much of the case, especially on the aluminum parts. Experience has shown that kaolin has a chemical affinity for aluminum. Adjacent stainless steel parts, even with grit-blasted surfaces, were visibly cleaner than the aluminum parts.
- One button-head screw hex socket (59) was filled with simulant.
- A small amount of clay was found between the inlet screen-shroud (6) and the manifold (5). This could be excluded with a sealant but the screen-shroud is subjected to mechanical abuse and might require occasional replacement in the field.



4.5 Post-Test Disassembly and Inspection

After the wash-down test, the WREE was then disassembled and inspected. Overall, internal surfaces were clean and free of sludge residue or water. Sludge residue was found in the mating surfaces of several parts, including the motor and motor flange interface. The application of anaerobic sealant during installation would have prevented this contamination. Signs of damage were noted on several of the seals: the shroud-manifold seal (46), the outer manifold shaft bottom seal (45), and the upper pinion shaft seal. Seal damage may have been caused by a number of factors, including 1) high surface roughness on metal mating surfaces, 2) excessive radial run-out, and 3) inadequate space for seals due to tolerance stack-up in the axial direction. During manifold rotation, the velocity of the sliding surfaces was below the velocity recommended by the seal vendor. The motor bearing case was drained and no sludge or water was observed in the oil.

4.6 Design Enhancements under Consideration

Initial test performance indicates the need to address the areas of seal wear and enhanced screen cleaning. The frequency of screen fouling during hardpan retrieval indicate that enhancement to the screen cleaning capability of the WREE is desirable. A stationary fan-jet installed in the WREE body or a rotating nozzle in the inlet are two possible alternatives envisioned at this time. Seal damage will be addressed through adherence to a more descriptive manifold fabrication procedure and tighter tolerance on seal surfaces and surface finish. Both areas appear to be readily solvable with the incorporation of minor design modifications prior to fabrication of the in-tank unit. Minor design changes also need to address the following areas.

- Skirt Length: The original skirt did not pass over uncut hardpan in front of the WREE easily, and created enough friction to stop gantry movement. The skirt length should be reduced 1 inch to eliminate this problem.

- Manifold Rotation Lock: A mechanical lock-out is needed to prevent manifold rotation during nozzle replacement. A lock position on the hydraulic control valve or simple ball valves in each of the hydraulic lines would also be an effective means to prevent manifold rotation during service operations.

- Swivel Access: The current design of the swivel support doesn't provide adequate wrench access. The design should be changed to increase access to the area.

- Housing Disassembly Features: Jack screws or pry points should be included in housing designs to remove the motor and break the case and seal housing joints.

- Assembly Tolerances: The gear/shaft tolerances should be changed to a light press fit to enable removal of the manifold.

5.0 Conclusions

The test objectives established in the test plan were successfully addressed with the exception of measuring aerosol generation during floor scarification. The aerosol measurements were taken during short duration tests under somewhat uncontrolled conditions and may not be indicative of conditions during tank deployment. Short duration tests with wet sludge and hardpan were conducted to measure baseline performance. The retrieval goal for the WREE was 10 gallons/minute, which was exceeded during retrieval of hardpan (without consideration of the time required to clean the inlet screen). The retrieval rate during sludge retrieval was 7 gallons/minute, which is 30% lower than the target retrieval rate. However, since material did not accumulate in the conveyance line and the motor did not decelerate during the tests, higher retrieval rates are possible using a higher traverse speed or deeper WREE submersion in the sludge, especially after the sludge is diluted. A longer duration test was planned with a matrix of simulants as suggested in (Yount, FitzPatrick 1997), but this test was not conducted due to funding limitations.

Based on our observations of the WREE during the performance of the various tests, it appears to be a reliable and rugged device that is well suited for remote retrieval in tank C-106. The unit has benefited from design enhancements resulting from lessons learned with the original Sludge Retrieval End Effector at ORNL, including a higher torque hydraulic motor, higher flow area screen, and refined conveyance inlet. Initial test performance does indicate the need to address the areas of seal wear and enhanced screen cleaning. Seal damage may have been caused by a number of factors, including 1) high surface roughness on metal mating surfaces, 2) excessive radial run-out, and 3) inadequate space for seals due to tolerance stack-up in the axial direction. A detailed geometric inspection of the unit will need to be conducted to isolate the exact cause of the seal wear. It is believed that minor changes to tolerances and surface finish specifications will alleviate the problems. Despite the seal damage, the unit functioned well during the tests and the worn seal permitted little internal contamination. Other design charges to make the unit easier to operate and maintain are also included in this report.

Another design change will be required to reduce the rate that the screen is fouled during hardpan retrieval. The screen became plugged with clumps of dislodged material that were too large to pass through the 0.25 inch opening in the screen. Using a combination of back-flushing with water and mechanical brushing, the screen was successfully cleaned remotely, although the rate of screen fouling is unacceptably high. Another nozzle will need to be added to the WREE to clean the screen on a continuous basis. A stationary fan-jet installed in the WREE body or a rotating nozzle in the inlet are two possible alternatives envisioned at this time. Additional tests could be conducted with a modified prototype to select the best alternative.

6.0 References

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Mullen, O.D., 1997. *Field Performance of the Waste Retrieval End Effectors in the Oak Ridge Gunite Waste Tanks*. PNNL-11688, Pacific Northwest Laboratory, Richland, Washington.

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Powell, M.R. 1996. *Initial ACTR Retrieval Technology Evaluation Test Material Recommendations*. PNNL-11021, Pacific Northwest Laboratory, Richland, Washington 99352.

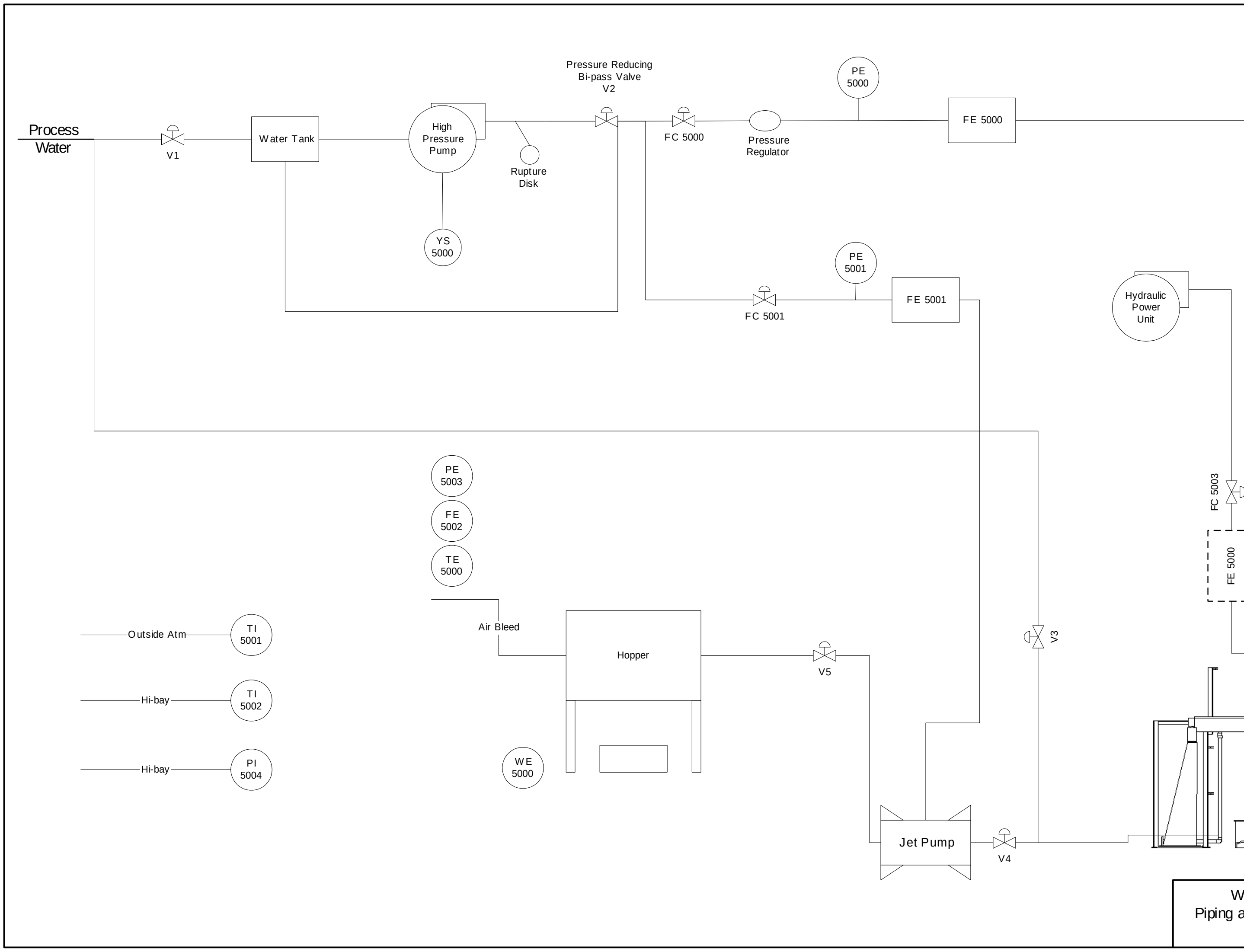
Yount, J.A., V.F. FitzPatrick, 1997. Tank 241-C-106 Waste Retrieval Services Statement of Work.

Appendix A -Measuring and Test Equipment List

Measured Parameter	Range Units	Tag #	Sensor / Control Element	Signal Conditioning
PUMP OUTLET VALVE CONTROL,WATERJET	ON, OFF	FC-5000	NLB V-685AE	Manual
PUMP OUTLET VALVE CONTROL, JET PUMP	ON, OFF	FC-5001	NLB V-685AE	Manual
HYDRAULIC FLUID VALVE	ON, OFF	FC-5003		Manual
FLOW SENSOR, WATERJET	0-20 GPM	FE-5000	AW COMPANY ZHM-04 W/ VTEK	EMO-1005/1
FLOW SENSOR, JET PUMP	0-20 GPM	FE-5001	AW COMPANY ZHM-04 W/ VTEK	EMO-1005/1
FLOW SENSOR, JET PUMP AIR BLEED	0-100 ACFM	FE-5002	DIETERICH STANDARD DCR-15	DART COMPUTER
PRESSURE, WREE WATERJET	0-20,000 PSI	PE-5000	SENSOTEC TJE, AP121EL, 2A	In transmitter
PRESSURE, JET PUMP, HIGH PRESSURE INLET	0-20,000 PSI	PE-5001	SENSOTEC TJE, AP121EL, 2A	In transmitter
CONVEYANCE LINE PRESSURE	0-30 in Hg	PE-5002	Vacuum Gauge	None - visual only
CONVEYANCE LINE PRESSURE	0-15 PSIA	PE-5003	ROSEMONT 2000AP	DART COMPUTER
HIGH BAY ATMOSPHERIC PRESSURE	0-30 in Hga	PI-5004	Mensor 15000 DPGII	None - visual only
SPEED SENSOR, DRIVE MOTOR	0-15000 RPM	SE-5000	Magnetic Sensor	TR400 Ratemeter
TEMPERATURE, JET PUMP AIR BLEED	0-100 °F	TE-5000	RTD, AXIAL HEAD	DART COMPUTER
OUTSIDE ATMOSPHERIC TEMPERATURE	0-125 °F	TI-5001	Thermometer	None - visual only
HIGH BAY ATMOSPHERIC TEMPERATURE	0-125 °F	TI-5002	Thermometer	None - visual only

Measured Parameter	Range Units	Tag #	Sensor / Control Element	Signal Conditioning
HOPPER WEIGHT, SUMMED	0-20000 LBS	WE-5000	REVERE 5123-D3-5K-20PI	DEMARCO 5123
FORCE/TORQUE SENSOR (FORCES AND TORQUES IN THREE DIRECTIONS	+/- 600 LBS +/- 7000 IN-LBS	XE-5000	ATI Omega Model	ATI F/T Controller
HIGH PRESSURE PUMP	ON, OFF	YS-5000		
GANTRY E-STOP		YT-5000		

Appendix B - Piping and Instrumentation Diagram


Process Water
V1
Water Tank
High Pressure Pump
YS 5000
Rupture Disk
Pressure Reducing Bi-pass Valve V2
FC 5000
Pressure Regulator
PE 5000
FE 5000
PE 5001
FE 5001
FC 5001
Hydraulic Power Unit
FC 5003
FE 5000
PE 5003
FE 5002
TE 5000
Air Bleed
Hopper
V5
V3
Outside Atm
TI 5001
Hi-bay
TI 5002
Hi-bay
PI 5004
WE 5000
Jet Pump
V4
W
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