INNOVATIVE TECHNOLOGY
Summary Report

Houdini™ I and II

Remotely Operated Vehicle

OST Reference #s 2085 and 98

Industry Programs
Robotics Technology Development Program

MASTER

Demonstrated at
Gunite and Associated Tanks Operable Unit
Oak Ridge National Laboratory
Oak Ridge, Tennessee

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

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

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

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

All published Innovative Technology Summary Reports are available on the OST Web site at http://em-50.em.doe.gov under "Publications."

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SECTION 1

SUMMARY

Technology Summary

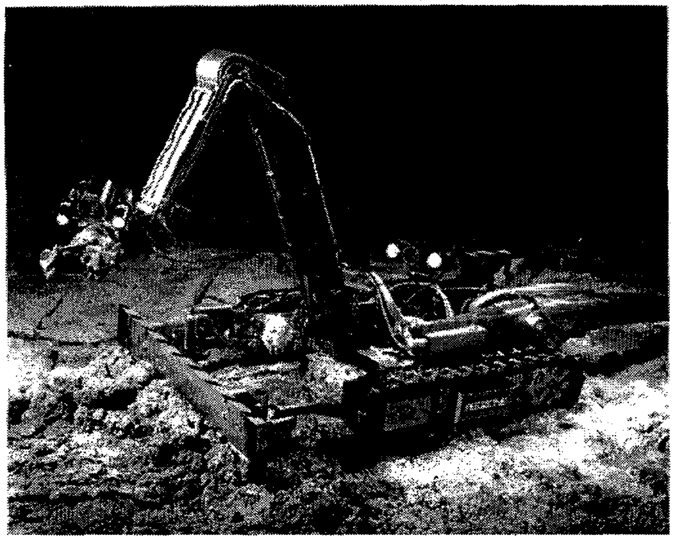

Figure 1. Houdini unfolded for work.

Problem

The U.S. Department of Energy (DOE) is responsible for cleaning up and closing 273 large, aging, underground tanks the department has used for storing approximately 1 million gal of high- and low-level radioactive and mixed waste. The waste's radioactivity precludes humans from working in the tanks. A remote-controlled retrieval method must be used. The Houdini robot (as pictured in Figure 1) addresses the need for vehicle-based, rugged, remote manipulation systems that can perform waste retrieval, characterization, and inspection tasks.

Houdini folds up for entry through 24-in risers (as pictured in Figure 2), which are openings in the tanks' ceilings. After entry, Houdini unfolds for work. Houdini allows work to be performed that would otherwise be difficult if not impossible to accomplish due to confined spaces and radiological and hazardous environments.

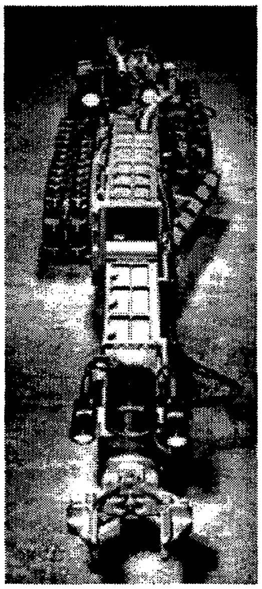

Figure 2. Houdini folded for entry through risers.

While several bulk waste retrieval techniques are available, Houdini offers a unique solution for removal of the remnant "heel" material left behind after sluicing. The system has also proven effective at removing discarded non-pumpable objects and in-tank hardware. The need for this technology is immediate, as standard sluicing has already been attempted and the only alternative—manned entry to these confined and hazardous spaces—would be costly and impractical.

How it works

Houdini is a remotely controlled, folding work platform that can pass through 24-in openings called risers and then open to a 4 x 5-ft mini-bulldozer, complete with a plow blade; a dextrous, high-payload manipulator; and remote camera systems. A single-operator control console can be located up to a few hundred feet away. Though training is straightforward with no special qualifications needed, inexperienced operators can easily damage the system; therefore, obtaining practice in cold tests is critical to mission success.

Houdini can deploy a variety of tools fitted with appropriate grasp points and can manipulate objects up to 250 lb. It can shovel waste or deploy localized sluicing systems for heel removal, cut and remove in-tank debris, deploy tools to obtain core samples, and perform characterization and inspection missions. It has successfully and extensively manipulated a localized sluicer that uses high-pressure water to dislodge and then pump a variety of physical waste forms.

Houdini is lowered from an enclosed and shielded deployment package, which houses the tether reel and the robot for stowage and maintenance. Power to control and hoist Houdini's in-tank remote hardware is provided by an external unit. Hydraulic fluid and electrical power pass to Houdini through a customized tether.

If there is a loss of power, the system has a fail-safe feature that allows the robot to collapse under gravity so it can then be extracted from the tank. The system is designed for full submersion in radiological and hazardous environments although the tether in Houdini-I has experienced some in-leakage that will be corrected in a subsequent unit. Houdini's primary limitations are that it can only reach about 6 ft up tank walls, and its capability to travel over deep waste is uncertain at this time.

Potential markets
Houdini is designed primarily for radioactive waste retrieval in underground storage tanks and has direct applicability to a number of sites in the DOE complex, including Oak Ridge National Laboratory, Fernald, Hanford, the Idaho National Engineering and Environmental Laboratory (INEEL), and the Savannah River Site.

Houdini-I
A first prototype, Houdini-I, has now been demonstrated and operated at the Gunite and Associated Tanks (GAAT) Operable Unit (OU) at Oak Ridge National Laboratory (ORNL). A Houdini-II unit is being built, taking advantage of lessons learned in early system usage. Houdini is manufactured by RedZone Robotics, Inc., a small business in Pittsburgh.

Houdini-I was designed under a Research Opportunity Announcement from the Industry Programs at the Federal Energy Technology Center (FETC) in Morgantown, West Virginia. Research staff at Carnegie Mellon University's Robotics Institute first proposed the concept of a folding robotic work platform in 1992 for use at Fernald. Carnegie Mellon researchers collaborated with RedZone during early design stages of the Houdini-I project.

The final product reflects significant input, from conception to completion, of DOE's Office of Environmental Restoration (EM-40) remediation contractors at both ORNL and Fernald. System requirements were derived from technical needs for remediation of K-65 silos at Fernald's OU4 although the unit was subsequently redirected to ORNL, with some minor modifications, to meet schedule requirements for the gunite tanks project. DOE field office counterparts at those sites have endorsed and supported the project, along with two Office of Science and Technology (OST, EM-50) organizations—the Robotics Technology Development Program (RTDP) and the Tanks Focus Area (TFA).

Commercial availability
Houdini is manufactured by RedZone Robotics, and its development has been fostered by a multiple-site and multiple-program team funded by OST. Based upon lessons learned during the demonstration of the robot at Oak Ridge National Laboratory's North Tank Farm, RedZone is overhauling the design of Houdini-I. During the summer of 1998, Houdini-II will be delivered to ORNL for demonstration and deployment at the South Tank Farm.

Demonstration Summary

This report covers Houdini-I and Houdini-II project activities from inception in fiscal year (FY) 1995 to February 1998.

Gunite and Associated Tanks (GAAT) demonstration at ORNL
The GAAT Operable Unit (OU) contains 16 tanks of varying size, a majority of which are in two areas—the North Tank Farm (NTF) and the South Tank Farm (STF). Constructed during the 1940s and 1950s, 12 underground tanks are made of a specialized type of concrete, gunite, and are 20, 25, or 50 ft diameter and 15 ft deep with few access ports, none larger in diameter than 30 in. The tanks have been taken out of service due to their age and uncertain condition.

The bulk of the waste was removed during the 1980s using standard hydraulic sluicing techniques. However, a waste "heel" remains to be removed, along with objects left in the tanks after previous campaigns. The heel consists of sludge of varying consistency, with depths of up to 3 ft and radiation levels up to 100 R/h. Each tank also has supernatant water above the sludge at depths ranging from inches to several feet deep.

Because of NTF's location in the heart of the ORNL complex, aggressive targets were set for removing waste from NTF tanks as part of the GAAT Treatability Study. NTF tanks have lower radioactivity levels, and there was no sluicing of those tanks in the 1980s. Since Houdini's use has now been proven in the less hostile NTF tanks, remaining tanks in STF and environs are subsequently being completed under the GAAT remediation project.

Demonstration status

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. Since then, it has seen continuous (still on-going) service at ORNL, providing a critical role in the cleanup of two gunite tanks, W-3 and W-4, in the GAAT NTF. Houdini-I has proven rugged, capable of waste retrieval, and able to withstand high reaction force operations such as wall core sampling. It's even able to operate while hanging, which was the case when Houdini was used to cut and remove cables and steel pipes hanging below manways in Tank W-3.

A full suite of remote technologies has now been put to the test in NTF and has been found to work well together, with each technology making unique and important contributions to overall mission success. Houdini has interfaced with other retrieval equipment developed by TFA, such as the mini-sluicer and the Modified Light Duty Utility Arm (MLDUA), a programmable long-reach robot arm.

Advantages over baseline

Advantages of Houdini over the baseline technology of manned entry are self-evident but were not specifically measured. It would be too dangerous, impractical, and costly to send workers into the tanks just to compare approaches. A cost model in Section 5, however, calculates a possible payback of better than 10 to 1 for OST's investment in this technology—through the use of Houdini at the ORNL GAAT OU alone. The basis of the calculation is the dollar value of avoided radiation exposure. The model is presented with disclaimers as to its absolute accuracy.

Regulatory concerns

Regulatory issues are limited to the selection of hydraulic fluid type for the system. Under many circumstances, petroleum-based fluids normally used are unacceptable because of the potential to affect waste classification if sufficient quantities leaked into the tank. Fortunately, several water- and mineral-oil-based products are available and have been used in these systems as alternative working fluids.

Houdini-I limitations

As could be expected from any first generation system, Houdini-I has demonstrated a number of deficiencies and areas for improvement during the GAAT deployment.

- Maintenance has been much more difficult and more frequently required than desirable.
- The vehicle is not always centered over the riser.
- The robot stowage compartment is too small, making system deployment and retrieval difficult for the operators and occasionally hazardous to the equipment.

Based upon the lessons learned at ORNL, Houdini's design has been completely overhauled. A second generation system, Houdini-II, is now being built with funds from the OST Robotics Technology Development Program (RTDP). It will offer improved system modularity, reliability, durability, and maintainability. Fernald has continued to support and participate in the project although it cannot commit to use Houdini at this time due to changes in project schedules and contracting approach. Houdini-II will be delivered to ORNL in the summer of 1998. It will be deployed in the more challenging ORNL STF in late FY98. Additional Houdini units will then be obtainable by placing orders with RedZone Robotics.

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Licensing information
This system is available for purchase from RedZone Robotics.

Other
All published Innovative Technology Summary Reports are available on the OST Web site at http://em-50.em.doe.gov under "Publications." The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST Reference # for Houdini-I is 98; the # for Houdini-II is 2085.

SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process Definition

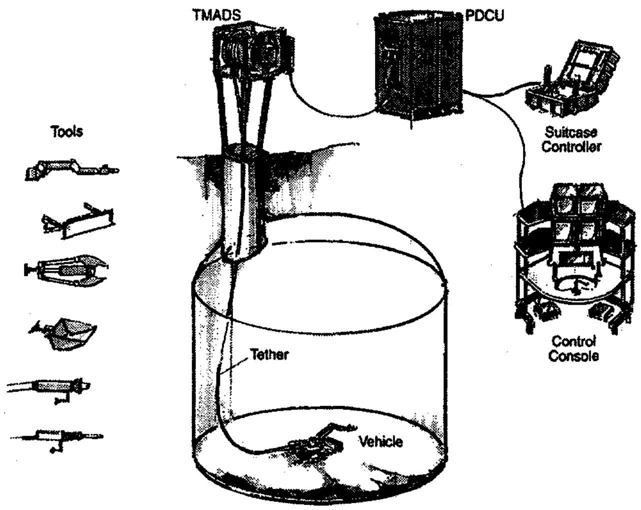

Figure 3. Houdini system elements.

Components
Houdini consists of five main components: the vehicle, tether, Tether Management and Deployment System (TMADS), Power Distribution and Control Unit (PDCU), and the control console. Figure 3 is a conceptual drawing of the Houdini system, and it shows some of the tools that can be deployed. A suitcase controller or button box facilitates maintenance in case of controls failure.

The centerpiece and workhorse of the Houdini system is the vehicle. With a 22.5-in-diameter profile when folded, it is designed to pass through openings as small as 24 in. Once deployed, it expands to provide a powerful work platform with a substantial footprint. It can turn in place, climb a 35° ramp and remain stable on slopes up to 45°.

Applications
Houdini was developed to provide mobile waste retrieval capability for remediating radioactive material storage tanks across the DOE complex, with specific emphasis on ORNL and Fernald requirements. Rugged design and sturdy construction make it well suited for heavy work and waste mobilization.

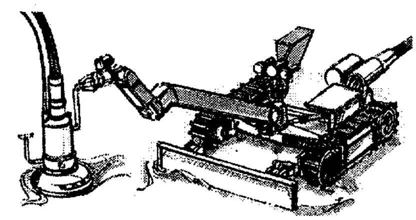

Figure 4. Manipulating the Confined Sluicing End-Effector.

Houdini can withstand high-pressure water decontamination. It is designed to be relocated between tank risers and can be deployed in enclosed spaces, such as the equipment rooms proposed for Fernald silos remediation, as well as fully exposed to the elements as is the case on the open equipment platforms erected for the ORNL GAAT project. References 2, 7, and 8 in Appendix A give design details for interested readers.

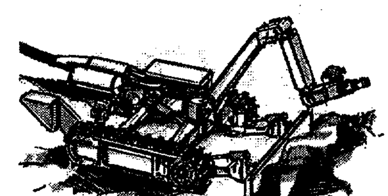

Figure 5. Plowing and using a squeegee.

Figures 4 through 9 illustrate a few of the many waste retrieval and tool deployment tasks that Houdini can tackle. The system has been designed to be outfitted optionally with the Position and Orientation Tracking System (POTS)—an ORNL-developed, OST-funded sensor technology that can precisely report vehicle position within the tank. With the exception of expendable camera elements, Houdini is designed to operate in rad fields of up to 100 R/h with cumulative exposures of up to 10^5 R.

Houdini vehicle details
The 1,000-lb vehicle is *teleoperated*, which means it is controlled directly by an operator in a remote location with no pre-programmed routines. It is also *skid-steered*; its speed and direction are controlled by the relative position of two joysticks, each of which corresponds to one tread's motion. The treads are commercially available and easily replaced. Maximum speed is 1 ft/s.

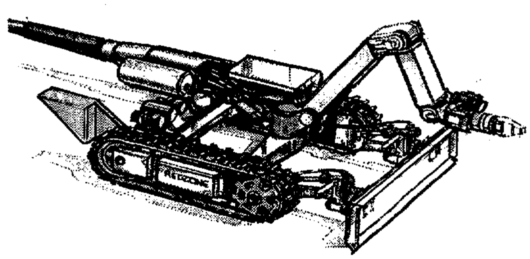

Figure 6. Closeup of Houdini-I vehicle.

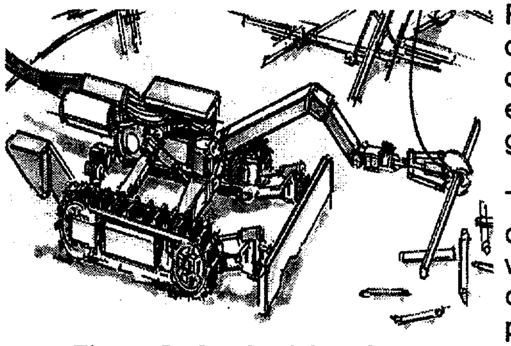

Figure 7. Cutting/shearing.

Four vehicle frame members form a parallelogram that is opened by a hydraulic cylinder pushing across diagonal corners. Should power be lost and the robot require extraction, the plow, frame, and manipulator collapse under gravity for easy removal from the tank.

The manipulator is a Schilling Titan-III, controlled from the console by the master arm, a small multi-link input device with the same kinematics as the in-tank slave arm. The arm can lift 240 lb (113 kg) at a full reach of 76 in (1.9 m). The plow blade has a squeegee attached and can be raised or lowered.

Two cameras and a microphone are provided to give operators a telepresence in the tank. One camera is directly fixed to the wrist of the robot arm, with the other mounted on a moving pan/tilt platform on the rear of the vehicle. A system feature allows fouled camera lenses to be cleaned with a shot of water followed by a burst of air sprayed through installed nozzles.

The nearly 3-in-diameter tether terminates at the rear of the vehicle. It is pivoted to reduce reaction forces. A counterweight is provided to assist in heavy manipulation and locomotion. On Houdini-I, the controller for the robot arm is mounted in this area; on Houdini-II, the controller has been moved into the tether reel in the TMADS.

The tether is the vehicle's lifeline. It provides hydraulic fluid, electrical power, signal lines, and a small water circuit for camera cleaning. The tether is rated at 10,000-lb strength, insuring that the machine will not get stuck inside the tank.

The tether is payed out from the TMADS, which also serves as the interface for the robot between the in-tank and external environments. The TMADS is shielded and enclosed with a sealed door that leads to the tank riser. Glove ports, a spray wand, and access features are provided for maintenance and decontamination.

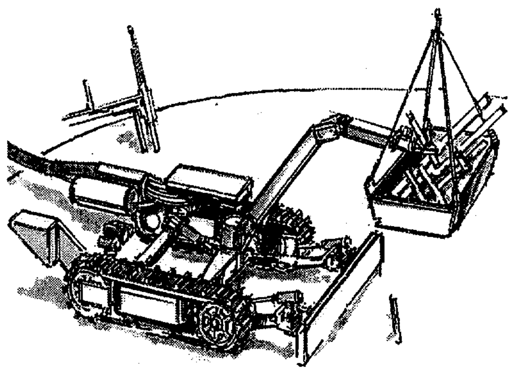

Figure 8. Non-pumpable object removal.

Support systems

At the PDCU, the switchgear, programmable controls, and hydraulic power supply are situated well away from the radiological exclusion zone. Tether lines from the vehicle to the TMADS pass from the rotating tether reel to fixed bulkhead connections, using slip rings and rotary hydraulic unions. Electric, water, and compressed air utility feeds are made at the PDCU. Commands are sent to the controller in the PDCU from the operator control station.

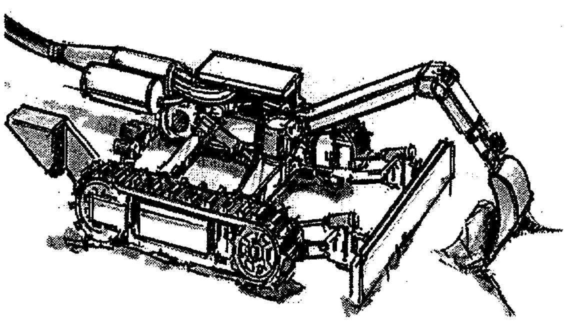

Figure 9. Scooping waste.

The TMADS provides a convenient docking area for the robot, allowing operators to remotely manage and store the vehicle and tether. Sealed and shielded, it simplifies installing and relocating the system to multiple tanks in a waste retrieval campaign. Lexan panels, glove ports, and pass-through ports on the TMADS allow many maintenance activities to be performed on the system without breaking containment.

A spray wand is provided for decontamination and crud removal. Additional structural elements include a containment bezel, a riser interface, and a TMADS stand, which is a steel structure for support against potentially high winds and for mating below the TMADS. A decontamination spray ring and riser sleeve then lead the rest of the way into the tank.

Installation and deployment

TheTMADS is where the generically capable Houdini system meets the specific physical limitations for deployment at a particular location. At ORNL, the TMADS is hoisted onto its stand on the GAAT project bridge structure. The TMADS can also be suspended overhead or laid on its side if some other application warrants. Sitting directly over a riser is the riser interface, a simple, spool-like piece that mates to the containment bezel and from there directly to the TMADS.

To deploy Houdini, the TMADS door is opened, the manipulator is uncurled, and the folded robot is slowly lowered into the tank. Once it reaches an open area, the frame unfolds in mid-air and the vehicle is then lowered to the tank floor.

The manipulator is configured so that the elbow touches down first, allowing the vehicle to pivot around the elbow and plow until the tracks touch, at which point they are driven slowly forward so that the vehicle lands in the right orientation. Video from cameras in the TMADS, mounted in the tank and on the robot, help guide the operators.

Once landed, Houdini can then start its mission of plowing and object retrieval. During operation, the tether is payed out manually as the vehicle is driven around in the tank.

Large ports on the containment bezel below the TMADS allow passage of tools, non-pumpables, and other objects in and out of the tank using glove bags. Tools with T-Handles can be lowered down and then grabbed and operated.

Some operations are possible with the robot arm while Houdini is hanging by its tether. For instance, cables were cut from around a riser at ORNL while Houdini was suspended. However, the unit tended to sway so good operator skills were required.

System retrieval is basically the reverse of deployment, with the additional step of aligning the plow before folding the vehicle. Waste on the treads and vehicle is washed off in a high-pressure water spray ring below the riser interface. The arm is then folded and raised back into the TMADS for further decontamination with the spray wand or for maintenance.

System Operation

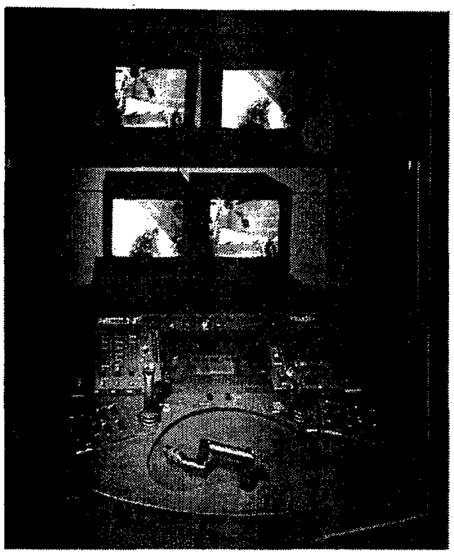
Figure 10. Houdini controls.

The Houdini console consists of two joysticks to control vehicle motion, a robot arm master controller, video displayed from two on-board cameras and up to two off-board cameras, as well as status displays and other controls. (See Figure 10.) The system can be run by a single operator. Foot pedals can be provided to override and replace joystick control of vehicle motion. Access to the programmable controller that runs the overall system is possible with an additional PC and appropriate software. This level of control, down to individual devices such as sensors and actuating cylinders, has been found to be useful at the GAAT project for troubleshooting and maintenance.

Data from the robot arm can be integrated with sensor data to report the status of the robot's configuration as well as location within the tank. The Position and Orientation Tracking System (POTS) is an ORNL-developed, RTDP-funded technology that provides the capability to sense and then display the robot's position, orientation, and configuration to 1-in accuracy in 80-ft-diameter tanks.

Although not yet needed for application at the gunite tanks project, provision has been made to install a target box on Houdini and pass POTS signals through the tether. The POTS system works by using tilting laser pods in two risers to spread structured light around a target box mounted on Houdini, where the timing of signals arriving from each pod and triangulation are used to deduce vehicle position.

SECTION 3

PERFORMANCE

Demonstration at the Gunite and Associated Tanks Operable Unit

Project Background

Beginning in the 1940s, the gunite tanks at ORNL were built to collect, neutralize, store, and transfer the liquid portion of radioactive and/or hazardous chemical wastes. The 12 gunite tanks and four stainless steel tanks vary in size and construction although they are 25 or 50 ft diameter with 12-ft-high walls. The tanks are high on the list of remediation priorities at ORNL because of their age and the potential risk of the contaminants they contain (e.g., 63,000 curies (Ci) of various isotopes). They are located in the center of the laboratory complex, adjacent to the main pedestrian and traffic thoroughfares, with office buildings, research facilities, and the cafeteria nearby. (See Figure 11.) Because of uncertainties surrounding remediation technologies, ORNL is conducting a CERCLA Treatability Study that will provide data for use in evaluating potential alternatives for waste removal while transferring the material contents out of the tanks and consolidating them for future remedial action. References 3 and 5 give additional details.

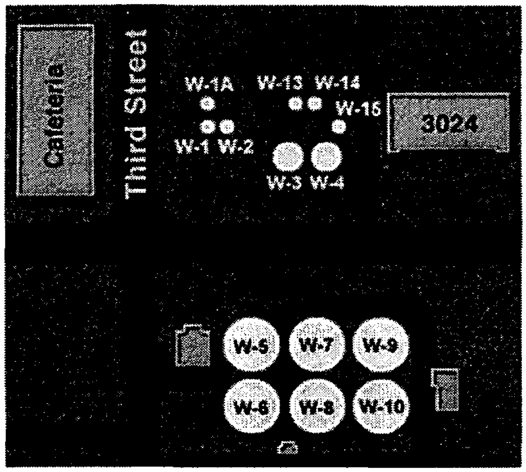

Figure 11. Gunite tanks in central Oak Ridge National Laboratory

The Gunite and Associated Tanks Operable Unit (GAAT OU) include four gunite tanks and attached accessory equipment in the North Tank Farm (NTF), six gunite tanks and attached accessory equipment in the South Tank Farm (STF), and two separate gunite tanks and four smaller stainless steel tanks. Although most of the accumulated liquid and solid waste material was removed in 1982 through 1984 during a sludge disposal campaign, a quantity of residual liquid, sludge, solid waste material, and additional liquids from infiltration (fluids leaking into the tanks from the environment) remain in most of the tanks. Today, approximately 88,000 gal of radioactive sludge and solids and approximately 250,000 gal of liquid remain in the tank farms. They contain organics, heavy metals, and various radionuclides including transuranics.

Characterization of the gunite tank contents indicates that the liquid contains 4,000 Ci of radioactivity and the sludge contains 59,000 Ci. Based on content and location, three groups of tanks have been classified.

- Group 1 Liquids with small amounts of contamination but no sludge
- Group 2 Liquids and low-contamination sludge
- Group 3 Liquids and high-level sludge (99.6 percent of the GAAT radioactive inventory)

Demonstrating remote waste retrieval at GAAT

Many factors significantly complicate GAAT tank remediation, including the high concentration of radionuclides and the location of the tanks below ground and in the middle of the ORNL complex. These factors led to the requirement for remotely operated systems to ensure worker safety. In early 1994, the Oak Ridge Environmental Restoration Program recognized the need to conduct a proof-of-principle demonstration of remote methods for cleaning the GAAT before finalizing milestone agreements between DOE, the U.S. Environmental Protection Agency, and the state of Tennessee.

At approximately the same time, OST's Tanks Focus Area (TFA) completed a feasibility study to determine the applicability of emerging technologies for use at ORNL tanks. The feasibility study determined that a sufficient number of the required technologies existed or were near enough to completion that a demonstration of tank waste retrieval could be performed at low technological risk.

A plan was developed to remove sludge and liquid wastes and transfer them to the ORNL Melton Valley Storage Tanks. Non-pumpable objects in the tanks would also be retrieved and a layer of scale removed from the inner tank surfaces to reduce contamination. To support closure decisions, surfaces were to be characterized using sensors and remotely collected samples, including wall corings. Remote systems would first be used on Group 2 tanks W-3 and W-4 in NTF, before moving to Group 3 tanks in STF. The consolidated waste would be treated, packaged, and eventually shipped to the Waste Isolation Pilot Plant. This approach was recently incorporated into an Interim Record of Decision.

A partnership was formed that resulted in TFA, RTDP, and FETC OST organizations providing much of the hardware and controls technology, including Houdini, that together compose the GAAT Remotely Operated Tank Waste Retrieval System. The Oak Ridge EM-40 Program funded tank sampling and analysis, site preparation, and balance-of-plant activities and shared retrieval system development costs with EM-50 programs. The net result was that only 30 months after the GAAT Treatability Study was initiated, the entire system was assembled and undergoing operational tests.

System development started in May 1994 and culminated in December 1996 when all major hardware systems were integrated for testing at ORNL's Tanks Technology Cold Test Facility (TTCTF). An open house in December 1996 demonstrated the Remotely Operated Tank Waste Retrieval System to more than 230 people from across the DOE complex. System operability evaluations and operator training then continued at TTCTF until spring 1997.

The equipment, along with operations, support, and radiological control trailers, was then relocated to GAAT NTF, where it was installed on a platform erected over tanks W-3 and W-4. Waste retrieval from Tank W-3 was begun on July 30, 1997 and was completed in September 1997. The equipment was then relocated to Tank W-4, where operations were started in November 1997 and concluded in February 1998. In March 1998, equipment was relocated to STF, where operations are scheduled to begin in Tank W-6 by early May 1998.

GAAT waste retrieval equipment

The major remotely operated systems for retrieving waste from the gunite tanks include Houdini; the Waste Dislodging and Conveyance subsystem, featuring the Confined Sluicing End-Effector (CSEE); a large robotic manipulator called the Modified Light Duty Utility Arm (MLDUA); balance-of-plant systems; and Instrumentation and Control systems. These systems can be operated independently or cooperatively in other potential applications.

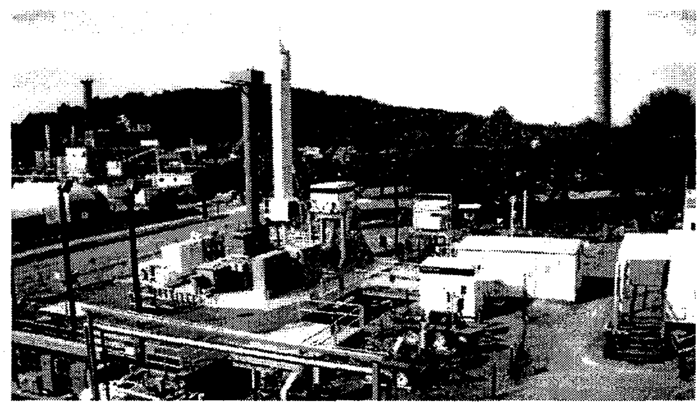

Figure 12. Waste retrieval equipment at ORNL.

Auxiliary systems for containment, decontamination, remote lighting, and observation have been developed for each major system, along with tools that can be deployed by the arm or vehicle for tank and waste characterization and wall scarifying. The layout of equipment at the GAAT project NTF is shown in Figure 12. An Innovative Technology Summary Report (ITSR) is being prepared in early 1998 by TFA that more fully describes the overall integrated retrieval system. See Reference 9.

Confined sluicing, in which waste in a localized area is broken up and then pumped out using high-pressure water, was selected because it offered an effective means of mobilizing a wide variety of waste densities from liquids to thick sludges or even material as hard as concrete. Deployment options included Houdini and the MLDUA—a large, fully programmable manipulator system. ORNL demonstrated both systems and has since found them to be complementary, with each retaining advantage in certain applications. See Reference 6 for more information.

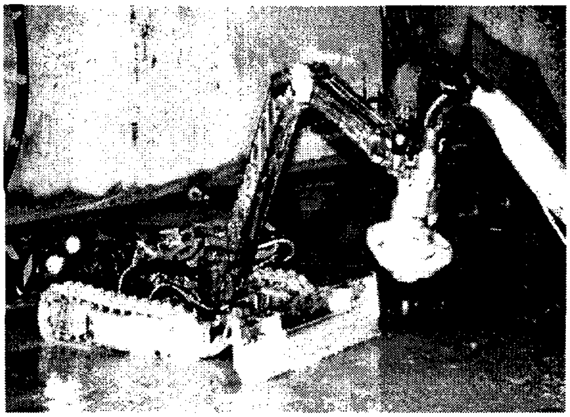

Figure 13. Houdini with the Confined Sluicing End-Effector.

Confined Sluicing End-Effector and support systems
The principal waste retrieval tool used by Houdini and the centerpiece of the Waste Dislodging and Conveyance system is the Confined Sluicing End-Effector (CSEE), based on a University of Missouri-Rolla prototype system with extensive modifications to improve reliability. (See Figure 13.) Operation of the CSEE is analogous to a high-performance carpet cleaner in which rotating water jets mobilize dirt and a vacuum then removes the dirty water. It weighs about 45 lb and has two grasp handles so it can be operated by or exchanged between the MLDUA and Houdini.

Grasp handles are oriented parallel and perpendicular to the waste surface, allowing positioning flexibility when cleaning tank floors and walls. The CSEE is equipped with three rotating cutting jets mounted 120° apart that can deliver up to 10,000 psi at about 10 gal/min. As the cutting jets rotate, hard waste material is dislodged. The CSEE has a several-inches-deep region of influence that varies from 4 to 6-in-wide depending on the hardness of the waste material. The CSEE can be positioned above or submerged in soft waste and then swept across the tank floor to remove sludge and supernate. The CSEE can also clean walls. At 10,000 psi operating water pressure, almost 0.1-in gunite is removed. A higher-pressure scarifying end-effector has been developed and tested that is very similar to the CSEE but able to operate at up to 30,000 psi for more effective surface removal.

CSEE's hose is managed by a motorized, four degree-of-freedom Hose Management Arm (HMA). Teleoperated HMA motions include mast vertical travel, shoulder pitch and rotate, and elbow yaw. The HMA consists of a vertical mast and two 8-ft pipes attached by swivel joints so that they can fold against the mast for deployment. Total horizontal reach is 25 ft, sufficient to cover all interior surfaces. A decontamination spray ring mounts below deck level under the containment box. As the HMA and the CSEE are raised out of the tank, eight water jets deliver a ring of spray at 2,100 psi. Contaminated water drains back into the tank.

Modified Light Duty Utility Arm
Working in conjunction with Houdini at the gunite tanks is the Modified Light Duty Utility Arm (MLDUA) See Figure 14. ORNL worked with SPAR, the system builder, and other users to redesign the Light Duty Utility Arm, another OST technology already in development, for a longer reach, higher payload capacity, and skid mounting rather than truck-based deployment. The MLDUA is capable of deploying up to 200-lb payloads through risers as small in diameter as 12 in with a vertical reach of nearly 50 ft and a horizontal reach of 15 ft. With a gripper and the CSEE attached, the effective reach is 17.5 ft.

Figure 14. The Modified Light Duty Utility Arm in cold test pit.

The MLDUA can be operated remotely, using joysticks, and in pre-programmed sequences. A tool interface provides utilities and communications to support multiple end-effectors. At ORNL, a 60-lb parallel-jaw gripper end-effector is usually attached to manipulate the CSEE or other tools. Because of its limited horizontal reach, the MLDUA must be re-deployed in four risers to reach all floor and wall surfaces in the 50-ft-diameter tanks.

The MLDUA has eight degrees-of-freedom: two telescoping vertical mast sections, mast rotate, shoulder pitch, two elbow yaws, and a three degree-of-freedom wrist with pitch, yaw, and roll. Arm tip speed ranges to 5 in/s. All joints, except the mast rotate and wrist roll, are hydraulically actuated. The system is designed for radioactive and high pH environments. A purge system keeps the arm, mast, and mast housing pressurized to prevent in-leakage of airborne and liquid contamination.

Operations
A graphical user interface allows a single operator to remotely control CSEE, HMA, and balance-of-plant systems. A controls trailer also houses operator consoles for Houdini and MLDUA, additional remote cameras, and video recording equipment.

Cold testing the waste retrieval system
To support the cold test program, a test facility was assembled from two unused underground experiment cells at ORNL. An observation deck was constructed in one of the cells. Above the other cell, which was established as the mock storage tank, a platform was constructed to support the tank waste retrieval system. Risers were placed at the same separations as those in GAAT. A surrogate waste mixture of kaolin clay, sand, gravel, and water was placed in the mock storage tank.

The Tanks Technology Cold Test Facility (TTCTF) was then ready for the retrieval systems to arrive. Redzone Robotics, the vendor, completed Houdini-I's production in summer 1996 and delivered the system to ORNL in September. Delivery followed extensive testing in a mock-up area at Redzone's Pittsburgh facility. This included evaluations specific to both ORNL and Fernald applications, durability runs, and final acceptance tests.

Figure 15. Houdini-1 operational checkout.

By November 1996, all equipment for the overall waste retrieval system had been delivered and installed at ORNL's TTCTF. Meanwhile, facility modifications to support waste removal in tanks W-3 and W-4 in NTF began October 1996. Modifications included adding seven 24-in tank access ports, erecting a 40 x 70-ft steel platform to support retrieval equipment, and installing a HEPA ventilation system and utilities. Individual subsystems were tested and integrated throughout the summer and fall with each new arrival. Figures 14 and 15 show the MLDUA and Houdini being checked out before their hot deployment.

The test program, lasting until the first quarter of 1997, focused on three objectives: functional checkout of all systems, validation of operating and maintenance procedures, and operator training. The tests were structured so operators could validate and/or debug new procedures while performing tasks as would be required during hot operations.

In the process of accomplishing these tests, many hours were logged, enabling the operators to become familiar with the equipment and procedures. These quality-controlled, structured tests, as well as equipment installation and maintenance and repair activities, were also used to develop and test contamination control procedures while still in the uncontaminated test area.

Houdini-I System Performance

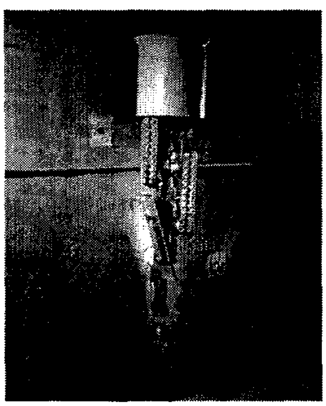

Figure 16. Houdini-I entering

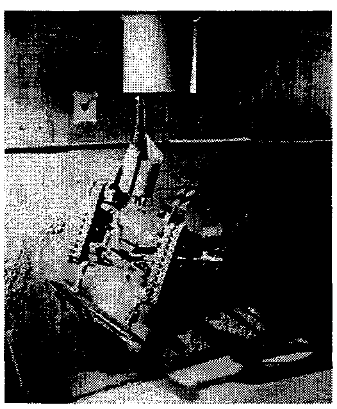

Figure 17. Houdini-I unfolding

In May 1997, Houdini was disconnected from TTCTF and moved to the North Tank Farm. The system was positioned over the north riser of Tank W-3 and was powered up for the first time on June 12 using the suitcase controller. Figures 16 and 17 illustrate Houdini's folding capability that allow it to enter tanks through 24-in-risers.

The system logged 150 hours of tank operations and was deployed in the tank on 27 workdays. It was used on numerous occasions to remove in-tank debris including tape, pipes, cord, hand tools, plastic bags,

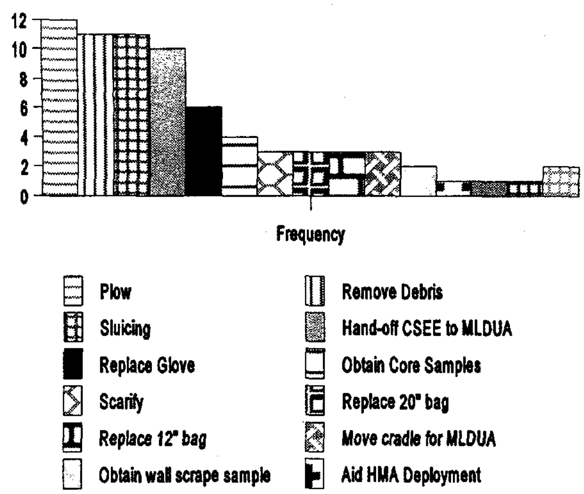

Figure 18. Frequency of various Houdini operations at W-3

and bottles. Houdini performed a variety of tasks as can be seen in Figure 18.

Over the course of the next four months, the vehicle was successfully deployed and retracted from W-3 24 times, sometimes remaining in the tank overnight. On-site operators called the system the "beast" because it was such a powerful workhouse.

On June 25, Houdini was the first piece of sludge-moving equipment to enter a GAAT tank. This occurred when the vehicle was lowered through the riser to just above supernate level to test the strength and flexibility of some pipes. These pipes were subsequently removed by Houdini using a Jaws-of-Life shear on July 24 while hanging by its tether in mid-air. There were no problems associated with use of the shear. Houdini completed its first full deployment into Tank W-3 on August 1, 1997. The system completed six hours of operation and performed very well overall.

Unexpected challenges were encountered during retrieval operations. For instance, sludge depth was 2 ft as opposed to the anticipated 8 in. The majority of the sludge was removed in a two-week period in August. References 1 and 10 provide additional information.

Overall review
Even though Houdini was still a prototype system during its GAAT demonstration at NTF, it proved its versatility: it has been used more frequently and tested in applications far beyond those originally planned.

- It deployed sluicing and characterization end-effectors.
- Plowed waste to the CSEE as the confined sluicer was being held by the MLDUA for maximum retrieval efficiency.
- Removed non-pumpable objects.
- Proved to be the only system capable of deploying such tools as the Jaws-of-Life, a mobile-hydraulic shear, and a Wall-Coring End-Effector for sampling gunite tank walls.

The system had significantly more downtime than anticipated. Such heavy-duty testing of a first-generation system resulted in numerous breakdowns that brought many design issues to light. Further discussion of maintenance issues is found in Section 7. The most consistent failure of the system was hydraulic leaks. The Titan-III manipulator wrist rotate joint performed erratically while Houdini took a bulk sludge sample from Tank W-3 on August 6. The erratic performance of the manipulator has continued to be a problem and will be addressed on Houdini-II. This problem will be repaired on Houdini-I during maintenance following completion of Tank W-4 operations in the spring of 1998.

Waste retrieval performance
Houdini and the MLDUA worked well both independently and together. Sluicing operations were most efficient when the plow on Houdini pushed sludge toward the MLDUA. The MLDUA worked best for wall cleaning, while Houdini was better on the floor surface.

Houdini was used on numerous occasions to assist the MLDUA by retrieving and handing off end-effectors that were either out of the arm's reach or not in the proper orientation for the MLDUA to pick up. Additional tools were quickly integrated and used by Houdini, based upon emerging situations encountered during the campaign. These tools included the shear tool, a wall scraper, and a small modified vacuum cleaner used for final cleaning.

Houdini obtained core samples that revealed that 90 percent of the wall contamination was in the first 1/8 in of depth. Walls were cleaned using the MLDUA and the CSEE to remove much of the scale and loose contamination. During wall cleaning, a dense fog limited visibility. A survey of the walls by characterization end-effectors showed that radioactivity in the walls was reduced by about 20 percent.

After water from the wall cleaning was pumped out, a small amount of grit remained on the tank floor. An attempt was made to plow the material into piles, but this was unsuccessful. A new end-effector was designed to link up to a vacuum system for final tank cleaning without adding any more water.

Success measures in tanks W-3 and W-4

- Approximately 7,200 gal of supernate, 5,500 gal of sludge, and various in-tank debris were removed.
- Tank W-3's radioactivity was reduced from 344 Ci to 13 Ci, a 96 percent reduction of inventory.
- Residual sludge was estimated at 100 gal.
- The state of Tennessee agreed that the goals had been achieved for Tank W-3.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

Past practice for tank waste retrieval is to use large volumes of water to mobilize the material. Although this approach has been found to be acceptable for bulk removal of some physical waste forms, it is not appropriate for hard or adhesive wastes and does not address residual quantities left afterwards (the heel) or the management and removal of in-tank debris.

Before remote systems became available for tank remediation projects, the only baseline alternatives were impractical:

- Manned entry through existing ports.
- Development and use of long-handled manual tools.
- Overburden and tank dome removal, construction of a containment building, and then manned entry.

Within the class of remote systems, two types of complementary and nonexclusive approaches have been considered:

- Long-reach arms, and
- Remotely Operated Vehicles (ROVs) like Houdini.

Different approaches and systems have been developed in both subcategories, and the marketplace is still growing in part due to successes noted in this Houdini program. For now, however, the focus is on those systems that have been demonstrated and deployed.

Long-reach arms

Long-reach arms are deployed into tanks through a single access port and then extend to much of the interior surface and volume of the tank. The MLDUA, used on the GAAT project and previously introduced in this report, is an example of this approach. The long extension of the arm results in lower payload capacity and gives it a tendency to vibration and tip location inaccuracy. Limitations of arm motions often result in surface and volume areas being unreachable in certain configurations, such as above the elbow. If headspace is limited, the arm may not be able to enter the tank.

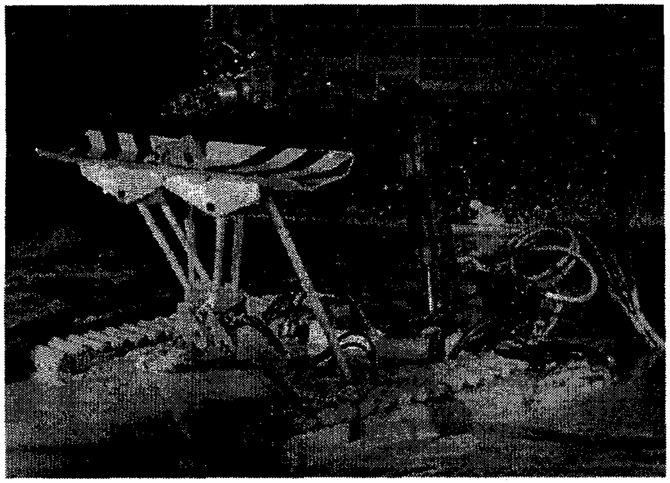

Figure 19. 1995 Houdini pre-prototype testing at ORNL.

Other ROV systems

Other ROV systems were also considered. In anticipation of the Treatability Study, the GAAT project funded a vehicle demonstration program in late 1995. An invitation to participate was placed in the *Commerce Business Daily*. Seven vendors expressed interest and three systems were pre-qualified. Of those machines that were evaluated, only the Houdini-I pre-prototype demonstrated sufficient functionality and strength to operate the CSEE while also being able to pick up objects and perform various tool deployment tasks. Figure 19 was taken during the vehicle demonstration program. Reference 4 provides additional details on the test program.

Technology Applicability

Houdini can be broadly applied to retrieve highly radioactive and/or hazardous waste stored in both underground and aboveground tanks. It is best used where access to tanks is limited through 24-in-diameter penetrations and in tanks where the waste is neither deep nor viscous. As shown in previous sections, Houdini deploys tools to support nearly all in-tank tasks ranging from waste removal to hardware disassembly and sizing. DOE remediation sites at Fernald, Hanford, Savannah River, INEEL and others have tanks where this technology could be used. Deployment opportunities beyond the DOE complex are also possible. Figure 20 illustrates the results of preliminary planning for applying Houdini at Fernald's K-65 silos.

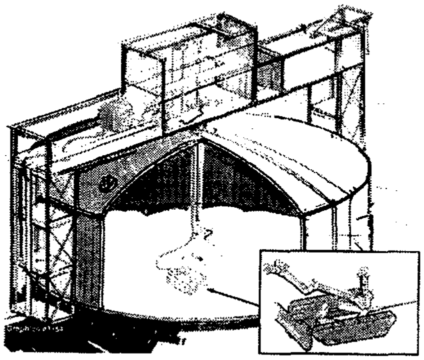

Figure 20. Potential Houdini application at Fernald.

Key considerations for a new application would be the size of the tank and its risers, physical space available around the riser selected, the physical properties and depth of the waste, any additional equipment that Houdini interfaces with, and space for mounting all subsystems. Tether length can be tailored to the application. Room must be provided for the TMADS and the PDCU, with respective footprints of 7 x 8 and 6 x 8 ft wide and respective weights of 5,500 lb and 8,000 lb. Additional requirements are determining the need for the TMADS stand and making accommodations for the height of the TMADS configured with the containment bezel. A location to house the controls console must also be selected.

Depending on waste constituents at a proposed deployment site, a Houdini unit could be re-used in subsequent tank campaigns. If a new unit is needed, at least six months lead time is required to produce and deliver a system. Once received, cold testing and training for system operators is strongly advised, as it was done at ORNL. This may take two to three additional months of effort. A spares list should be developed and procured to minimize downtime. Some interface hardware may need to be built, such as the riser interface, or mounting points if the TMADS is suspended. Installation can be made in a few days once the procedure and physical interfaces have been refined and checked out.

Although it is generally intended to be deployed from a suspended location, horizontal or inclined-ramp deployments can also be considered although tether management in these configurations is mostly untested. Houdini is not designed for high-volume waste removal or pre-programmed routines. Its reach is limited, and it cannot, therefore, access every tank surface. Traction is currently optimized with a counterweight, which may impact the vehicle's ability to locomote on weak waste surfaces. Sinkage could be minimized by reducing that weight or through other means. Houdini is not designed to be explosion-proof although this could be made available.

Commercialization and Sponsors

The original concept of a folding remote work platform was first proposed in 1992 at the Field Robotics Center of the Robotics Institute at Carnegie Mellon University. RedZone Robotics of Pittsburgh became a partner and committed to commercializing the system. RedZone proposed the project to the Federal Energy Technology Center (FETC) in Morgantown, West Virginia as a research opportunity in 1995. RedZone built Houdini-I and is currently building the second generation Houdini-II. Additional units are available through RedZone. Several major components are procured as off-the-shelf items, including the arm—a Schilling Titan-III manipulator. Other than a trademark on the Houdini name, there are no licensing or patent issues involved in obtaining this technology.

Houdini-I design and development was funded by DOE's Office of Science and Technology (OST) Industry Programs and managed by FETC. Robotics Technology Development Program (RTDP), Fernald, and ORNL representatives were involved from project inception to maintain relevance to the needs of deployment sites. Tanks Focus Area (TFA) began coordinating with ORNL as the GAAT project planning got under way. RTDP funded technical coordination efforts at ORNL and Fernald during Houdini-I activities and for the entire Houdini-II project. ORNL funded support equipment and provided resources for startup, operations, training, and maintenance.

SECTION 5

COST

Methodology

For Houdini, standard analysis of cost/benefits as compared to baseline budgets and technical approaches is not possible since Houdini was used in situations for which there are no other legitimate approaches for tackling waste retrieval tasks. However, significant savings and schedule acceleration can and have been quantified for the overall gunite tanks project at ORNL, where Houdini was one of the key enabling technologies contributing to the project's success. In the following subsection, three methods of approximating the cost savings attributable to Houdini are presented, using different bases of analysis and presented in increasing level of detail:

1. *Gunite tanks project baseline reduction*
2. Worker annual dose limits, productivity, and initial training costs
3. Radiation dosage reduction and comprehensive life-cycle costs

Because baseline data for the overall GAAT project is available, an estimate of Houdini's contribution can be made. However, it is impossible to accurately quantify the cost savings from each individual waste retrieval technology deployed at GAAT.

Another approach for estimating Houdini's contribution to cost reduction is to calculate a dollar value that represents workers' avoidance of radiation exposure. This value is based on the minimum number of workers required for manned entry, which is affected by annual radiation dosage limitations imposed by ALARA requirements. The occupational exposure limit varies by site across DOE but in practice is limited to 1,000 to 1,500 mR per year.

Costs avoided through reducing worker dosage can be estimated using a cost model developed by the radiation engineering organization at INEEL. (See Appendix B). Though the absolute accuracy of the model has not been extensively tested, it illustrates, at a greater level of detail, the many elements of cost that are inherent with work in high radiation environments—not only high levels of background and job-specific training, but also expensive consumerable personal protective equipment (PPE), such as suits and breathing apparatus that reduce productivity and eventually contribute to contaminated waste. This investigation of costs to mitigate the hazards of manned entry highlights the clear superiority of remote operations from the perspectives of cost, worker safety, and production efficiency.

All these results collectively and qualitatively demonstrate the elements of cost savings and how they combine to yield significant benefit. As is shown below, all three analyses indicate the same range of savings for the deployment of Houdini at the gunite tanks—in the range of $30 to $50 million. Comparing this savings to OST's investment of $4 to $5 million yields a return on investment as high as 10 to 1. Furthermore, these savings apply to Houdini's use at ORNL alone; this technology's use at other sites would yield additional cost savings.

Cost Analysis

First costing method: Gunite tanks project baseline reduction

Cost information contained in Reference 9, the ITSR for the waste retrieval project at the ORNL gunite tanks, supports the conclusion that waste retrieval equipment at the GAAT project, including Houdini, accelerated waste retrieval operations by 13 years and yielded $130 million in cost savings. Retrieval equipment reduced overall costs from $196 million to $66 million and shortened the projected completion date from 2015 to 2002. Assuming that 25 percent of the savings is attributable to Houdini (with the remainder being attributable to the other systems), puts Houdini's share of overall cost savings at about $30 million.

Second costing method: Worker annual dose limits, productivity, and initial training costs

Planning work in a highly radioactive environment involves many considerations. Foremost are the restrictions on worker radiation dose, with whole body occupational exposure limits ranging from 1,000 to 1,500 mR per year at various DOE sites. Generally, about twice as many workers are required to perform a task within a highly radioactive environment as compared to a standard industrial setting. For instance, suiting up and getting out of PPE is both costly and time consuming, resulting in lower than 50 percent actual productivity. Much PPE is consumable, such as outer gloves and suits, and becomes contaminated trash, compounding the problem of waste generation. Stay times are also limited, and frequent breaks are required, thus the total number of entries into the tank (and thus new PPE and generated waste) is typically at least four per day for an individual worker.

The objective in this section is to calculate the cost savings that accrue from workers avoiding being exposed to the radiation in tanks. Total dose that would be incurred if workers entered the tanks is based on the time it actually took for Houdini to perform inside the tanks since there are no similar tasks done outside the tanks. Using occupational dose restrictions that limit individual workers to 1,500 mR per year, the number of workers for manned entry is derived—the minimum number of workers that is required to avoid any worker exceeding the dose limitation. Finally, using a coarse and conservative estimate of the costs to train that many workers, a dollar value is estimated for the radiation dose avoided.

If this job were actually done with manned entry, every effort would be made by health physics and safety teams to design procedures and shielding to protect workers while still getting the essential work done. The cost of those activities and related equipment would certainly exceed any savings associated with the reduced worker dose.

For the purposes of this estimate, then, simplifying the basis to training costs alone is a reasonably conservative assumption. Training is the single greatest cost in preparing workers for the rigors of work in radioactive environments. At the least, initial training includes OSHA Hazardous Worker, Radiation Worker-II, and respirator training over three weeks. Annual refresher courses are needed thereafter and take a week to complete. In addition, job- and site-specific training are required. From the INEEL study (Appendix B, p.B-2), total initial training is reported to be about $4,000 per worker.

At ORNL, Houdini has seen 270 hours of service operating in Tanks W-3 and W-4 at the GAAT demonstration over four months. A two-man crew would be required to perform the same number of hours of activity due to the extensive work requirements. Average radioactivity inside the NTF tanks was 500 mR/h, and thus the crew would receive a total exposure of 270 man-rem as follows:

500 mR/h x 2 workers x 270 hours of service = 270 man-rem

Conservatively assuming the higher 1,500 mR/year limit, that amount of exposure would require at least 90 workers over which to spread the dose to avoid any one worker exceeding the dose restriction:

270 man-rem / 1,500 mR/yr = 90 workers

Activities at NTF have only removed about 600 Ci, or 0.95 percent of the total curie content in the GAAT OU of 63,000 Ci. The potential radiation exposure in man-rem saved for the overall gunite tanks project (and thus cost savings) is directly proportional to both the relative curie content and also dose as measured in Rads (R or mR).

If removal of 1 percent of the curie inventory takes 90 workers, then the entire job will take 100 times as many, or 9,000 workers—the population of a moderate-sized town. With each worker costing at least $4,000 to train (in 1995 dollars), the total cost avoided through the use of Houdini is $36 million (9,000 workers x $4K/each). If workers are re-used in subsequent years, retraining costs are reduced although the figure of $4K/worker significantly understates current year training costs. Given the conservative estimates in this analysis, the actual costs would probably be much higher.

Third costing method: Radiation dosage reduction and comprehensive life-cycle costs

This analysis compares Houdini and manned entry on the basis of life-cycle operations costs and is predicated on the referenced INEEL study that was completed in 1995. This analysis results in a value for the cost incurred per man-rem of worker occupational radiation exposure. As the INEEL study shows, life-cycle costs are dominated by worker training but also include many other elements, such as the cost of suits, respirator equipment, management of secondary waste, and pre-job briefings. In the following analysis, elements of cost from the INEEL model are combined with additional health physics (HP) support and the cost of the workers themselves, and adjusted for inflation. Starting with the lower figure of $3,795 (see the second table in Appendix B, p. B-2), the overall cost can be conservatively estimated at $5K per man-rem, as shown Table 1.

Table 1. Calculating the value of avoided radiation exposure

Description	Factor 1	Factor 2	Cost	Assumptions
Estimate plus 3 years' escalation (FY95–98)	$3,795	5%/yr = 15.7%	$4,393	- 5% escalation per year - 125 mR/h whole body exposure rate - Worker and HP costs in present dollars using ORNL-loaded rates - Full-time HP oversight required - 8 hours in-tank per man-rem - Full PPE required
HP support	10 h	$69/h	$ 690	
Worker	12 h	$51/h	$ 612	
	Total Cost		$5,695	
	Typical cost per man-rem			**$5,000**

As shown in the second analysis, a manned crew would receive a total exposure of 270 man-rem in the execution of NTF in-tank activities. Thus, at the conservative estimate of $5,000 per man-rem, $1,350,000 was saved in exposure costs just in the two tanks at NTF as follows:

$5,000 x 270 man-rem = $1,350,000

The overall GAAT project has had monthly operating costs of about $25,000 per day. Conservatively assuming that 25 percent of the operating costs, including maintenance, training, spares, and operator labor, are attributable to Houdini, a total of $760K in Houdini operating costs were incurred during the four-month-long campaign in both tanks:

$25K/day x 25% x 4/12 months x 365 days/year = $760,000

Thus, total cost savings are $590K ($1,350K-$760K) for Houdini's use at NTF alone. More operations and savings are expected in STF tanks with their much higher radioactivity levels. With 600 Ci, or 0.95 percent of the total curie inventory removed, a cost savings of $590K was achieved. Assuming that 95 percent of total curie inventory is also removed from contents of the remaining tanks (100%-~1%=99%), an additional 94 percent (95% x 99%) of the total potential man-rem dose savings will be accrued. With total savings proportional to relative dose, a total savings of $55 million is derived from the ratio of achieved and future avoided exposure as follows:

Savings = (94%/1%) x $590K = $55.4M

Clearly, some uncertainty exists as to the scaling of the cost model to various radiological hazard levels. Quite possibly, though, in the highest rad level cases, the value jumps disproportionately *higher* since those are the cases where there is really no other way to do the job.

Cost Conclusions

Three cost models, using data ranging from net savings over the baseline approach to rough worker burn-out estimates and conservative assumptions, have demonstrated cost savings between $32 million and $55 million. Deducting OST's $5 million investment in Houdini's development (both Houdini-I and Houdini-II), a return on investment as high as 10 to 1 can be achieved at ORNL's gunite tanks project alone.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

No special permits are required to operate Houdini. In radioactive tank cleanup, it would generally be used as part of a CERCLA or RCRA project with all necessary permitting and environmental impact issues considered. That was the case with the Houdini demonstration at ORNL, where the waste retrieval demonstration was in support of treatability studies that led to the definition of the retrieval approach for the remaining tanks in the Operable Unit. Because Houdini has only contributed to the overall remediation, information was not needed on the nine specific CERCLA criteria.

Houdini is far superior to baseline technologies in complying with ALARA (As Low As Reasonably Achievable) exposure goals because it dramatically reduces worker exposure.

Secondary waste streams generated during Houdini operations include expended parts, decontamination supplies, and ultimately disposal of the robot itself. Parts expended in operations will be contaminated and must be disposed of as waste. Expended decontamination supplies will be limited, however, if a water-based cleaning system can be used with runoff draining back into the tank. If this is not possible, other methods of decontamination may result in secondary waste. A minor amount of waste consists of contaminated glove bags that are used to pass objects for retrieval or maintenance.

The robot can be re-used at subsequent sites if the hazardous and radiologic constituents of the waste are compatible. Since it cannot be completely decontaminated, some material will remain in the vehicle and storage system, which could cross-contaminate a new site if the materials are incompatible (such as mixing hazardous and radioactive waste). At the end of its useful life, the robot will, therefore, have to be disposed of as waste.

Because of the regulatory complications that come along with creating mixed waste, the selection of working fluid for Houdini's hydraulic system should be carefully considered. Normal hydraulic fluid is petroleum based, and amounts over a certain threshold that leak into the tank from ruptured hoses and fittings could cause regulatory problems. The exact amount that would cause a problem depends on the type of waste and is subject to interpretation. Alternatives are available, however. Water/glycol-based fluids do not present regulatory difficulty but will reduce the life of the equipment through increased wear. (see Section 7 for more details). Mineral- and vegetable-oil-based fluids are also now being marketed that have better lubricity.

Safety, Risks, and Community Reaction

Houdini reduces the risks associated with high exposure to radiation while following good ALARA and industrial hygiene practices. As with any piece of heavy machinery, though, hazards exist that must be mitigated. The primary danger exists during equipment maintenance when workers may come into contact with contaminated material stuck to the robot in the TMADS. The steel panels help mitigate that potential, however. In the redesigned TMADS for Houdini-II, even more consideration has been given to improving ease of maintenance so as to lower exposures during repair.

During non-routine maintenance, the potential for contaminant release must be carefully controlled since temporary containment structures and glove bags have to be used to get the vehicle out of the TMADS for repair. HEPA-filtered negative pressure in the tank and the TMADS compartments can minimize the risk of these leaks.

Safety reviewers have questioned whether a Houdini collision into tank walls could affect waste confinement integrity. Assuming a failure in all speed limiting hardware and operation at the highest system pressure available, the vehicle would travel at only 3 ft/s, which would not affect any tank with at least minimally acceptable structural integrity.

The most significant physical hazards are those associated with hoisting, and precautions have been taken in the design to account for them. At cold test facilities, workers could conceivably be under the robot as it hangs in the TMADS. Safety chains have been included to give additional protection, supplementing fail-safe brakes on the tether drum drive motor. When reviewed at Fernald, the tether and its connections to the drum and vehicle were given the next highest hazard category beyond that for standard industrial hazards. The rationale for this hazard category is that losing Houdini in the tank could adversely affect the overall mission. In response, RedZone overdesigned these components and implemented destructive testing of a sample of the tether, with a minimum required proof load of 10,000 lb, 10 times the normal vehicle weight. This is also over 3 times the 3,000-lb maximum pull force developed by the tether drive motor.

Since, in the balance, Houdini is an important tool in lowering risks through successful waste retrieval where it would otherwise not be possible, the public's and community's perception of the system has been quite positive. Being a novel remote system, it's an object of the public's interest and curiosity. The only potential liability or risk to the community would be contaminant leakage during repairs. That risk can easily be mitigated through standard glove bagging, negative air pressure, and other radiological controls.

SECTION 7

LESSONS LEARNED

Implementation Considerations

Technical and regulatory constraints must be considered early in any proposed waste retrieval project, and adequate lead time for equipment design, integration, and most particularly operator training must be provided. This section describes technical deficiencies in Houdini-I and how they are being addressed in the Houdini-II design.

Houdini maintenance experience
Although Houdini-I has had the reliability of a prototype, ORNL operators report that no showstoppers have been found. Experience gained from maintenance activities, while unwelcome, have provided a wealth of data for system improvements for Houdini-II. Many of these design improvements are being incorporated into the next system to make it more reliable.

Some significant problems were brought to light and corrected while the Houdini-I system was still undergoing cold testing at ORNL. For instance, a water/glycol fluid initially used for the hydraulic system was found to cause an inordinate number of failures in the valves located on the vehicle and in the TMADS. The electrically conductive water/glycol fluid also caused electrical short circuits on the manipulator when a failed servo valve allowed the fluid to flood the arm's housing. The water/glycol fluid was replaced by Shell Tellus 32, a mineral-oil-based fluid before Houdini was moved to North Tank Farm.

The manipulator supplied with Houdini-I had to be replaced before deployment. The housing on the original Titan-II was open at the shoulder and allowed handfuls of sludge to collect inside the arm during mock retrieval and decontamination operations. These pockets of sludge could only be removed by disassembling the arm. Therefore, the Titan-II was replaced with a Titan-III since the housing on that version is sealed at the shoulder.

Leaking or damaged hydraulic hoses, electrical cables, and connectors have been the most persistent problems with the Houdini-I system. Many of the connectors were subject to damage or loosening when the vehicle was folded during retractions and deployments. The most common failure point was at the elbow fittings to the track drive manifolds. The connectors loosened and had to be tightened weekly. It was also during these operations that the hoses sometimes pinched. Fixes on the current system have been limited to controlling hose routing with wire ties, daily inspections of all hoses, and weekly tightening of all connectors. Loosening of fasteners has also been a frequent complaint. Following numerous in-service repairs accomplished through the glove ports on the TMADS during W-3 operations, the robot was refurbished before being relocated to Tank W-4. A maintenance tent was erected on the GAAT platform next to the TMADS. Using creative glove bag techniques, the TMADS was opened and Houdini lowered onto a table in the tent. Every fitting, connection, and fastener on the vehicle was tightened.

The relief valve for the manipulator (located on the azimuth) was damaged during a retraction of the vehicle from the tank. This valve was easily replaced while the vehicle was stored in the TMADS. Both vehicle-mounted cameras sustained damage during deployments and retractions. On the hand camera, power and signal cables got cut and had to be re-spliced in the containment bezel. This was an extremely difficult operation to perform through glove ports. A connector was added at the tether termination so that in the future the entire cable can be replaced if necessary. Mounting screws on the body camera loosened frequently. The unit is prone to damage during deployments and retractions and loosening of fasteners from vibration during normal tank operations.

The Houdini-I TMADS door is hydraulically actuated and occasionally has failed to open or close. This was traced to a faulty counterbalance valve system and leakage across valve ports. When the hydraulic valve that controlled the latch failed, there was no way to reach the valve without cutting a hole in the frame. This was done, and a bolt-on panel was added in case the need should arise to access the panel again in the future.

Lessons learned program
A formal lessons learned process was initiated when it was decided to develop a second generation unit. It started in December 1996 with the bulk of activities occurring in the first few months. ORNL operators and system leads were frequently interviewed, and potential users at Fernald reviewed system requirements. Input was also solicited from the system vendor, RedZone. The items were then compiled into a master list. As part of the funding provided by OST's Robotics Technology Development Program, conceptual redesign work was initiated at RedZone on a time and materials basis.

The list was subsequently ranked and reviewed, as RedZone gathered additional information. A number of items were briefly considered, such as increasing flotation with additional track width and respecifying the location of the body camera. These proposals were abandoned as unnecessary or cost prohibitive for near-term applications. The final configuration was selected, and detailed design work began in late summer 1997. The Houdini-II design was finalized and approved in late November 1997. The finished system is set to be delivered to ORNL in July 1998.

Houdini-II improvements
Because the TMADS is critical to operability and ease of usage, it has been the most extensively redesigned subsystem. Additions include interior lighting, a hoist to raise and lower tram buckets for item extraction, and pass-through ports to introduce small tools and parts without using glove bags. The robot compartment has been enlarged, which will simplify retrieval. Modular shielding slats will be available to cover full height Lexan panels on two opposing sides, giving potential for both complete shielding and ample views for repair and decontamination. The adjacent steel panels will be hinged, providing easy access to remove the vehicle. Tie-down points will be provided around the frames to connect to temporary containment tents for more extensive repairs when they cannot be done inside the TMADS.

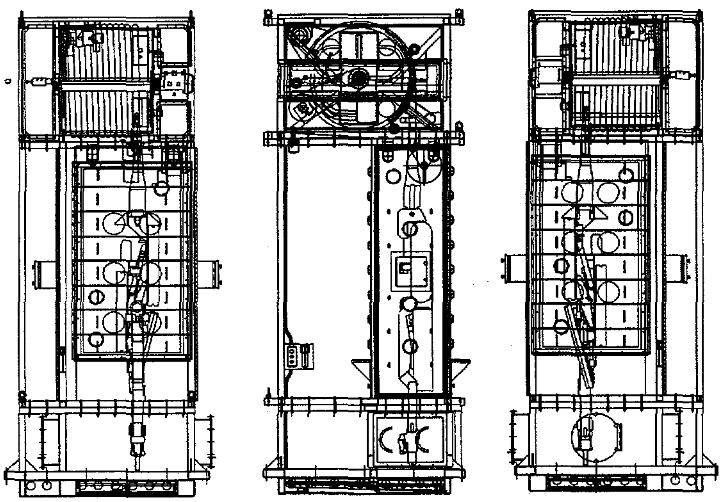

Figure 21. Houdini-II improves upon the Tether Management and Deployment System (TMADS).

The TMADS on Houdini-II will have a more rectangular profile so it can be free-standing although the heavy steel stand will still be used at ORNL as continued precaution against high winds. The sealed door at the bottom will now be closed with a linear motion across the opening. It will be integrated as a sealed module with electric motor, guides, and seals enclosed. The containment bezel will now be incorporated as an integrated part of the TMADS, giving extra height in the compartment to retract the robot without needing to furl its arm.

Bolt patterns on both the top and bottom of the containment bezel will be the same, with the door usually mating below it and the remainder of the TMADS above. To improve its usefulness at other deployment sites, the containment bezel may be optionally removed so that it can be reduced from its normal height of 19 ft to just over 16 ft, making it easier to fit into an interior space such as at Fernald.

The vehicle has been extensively redesigned for improved durability. Hydraulic hoses and loose electric wires have been eliminated in some cases and re-routed in others. Additional pinned and locking elements will be added to strengthen frame connections. The plow blade, hydraulic manifold and valves, and tether termination designs have been improved. The controller for the robot arm has been moved up to the TMADS, and better cameras have been selected. Due to the many revisions, the number and type of lines that pass through the tether have changed. Significant revisions have been made to the hydraulic pump in the PDCU as well as the overall hydraulic circuit. Many other improvements have been made.

Technology Commercialization

Houdini-II represents the final design revision that will be necessary to bring the technology from *demonstration* as defined in Gate 4 of OST's technology development model to *implementation* in Gate 5. The technology will soon be available from Redzone Robotics in Pittsburgh, and further OST development will not be necessary. Guidance and considerations for Houdini's application at other deployment sites was previously discussed in Section 4.

APPENDIX A

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APPENDIX B

COST MODEL

Algorithm to Justify Remote/Robotics Activities

In 1994, the radiation engineering organization at Idaho National Engineering and Environmental Laboratory developed an algorithm that associates the cost of remote/robotic activities with avoided radiation exposure. By quantifying robotic development costs in terms of a dollar cost per man-rem, the algorithm justifies the investment to develop and use remote systems.

The algorithm yielded a cost of $3,795 per man-rem and was based on several assumptions, which can change from job to job. The algorithm is presented below.

Dollar cost per man-rem

Worker cost	$38/h
Cost per double set anti-cs with airline	$500
Waste disposal cost	$50/ft^3
Training:	
Radiation worker	40 h
Hazardous materials worker	20 h

Assumptions:
1. Exposure limit—1,500 mrem
2. Contamination levels—greater than 20,000 disintegrations per minute
3. General body field—greater than 500 mrem/h
4. This calculation is based on 2 entries. An evaluation must be done prior to exceeding 1,000 mrem.
5. Pre-job briefing—3 man hours: 1 worker at $38/h + 1 radiological control technician at $38/h + 1 supervisor at $60/h.
6. Worker to gather PPE and PC (personal protective equipment, protective clothing) = .5 h or $19
7. 4 ft^3 of waste

Formula:

Training cost is calculated as follows:

60 h x $38/h (worker) = $2,280
\+ 60 h x $60/h (trainer) = $3,600

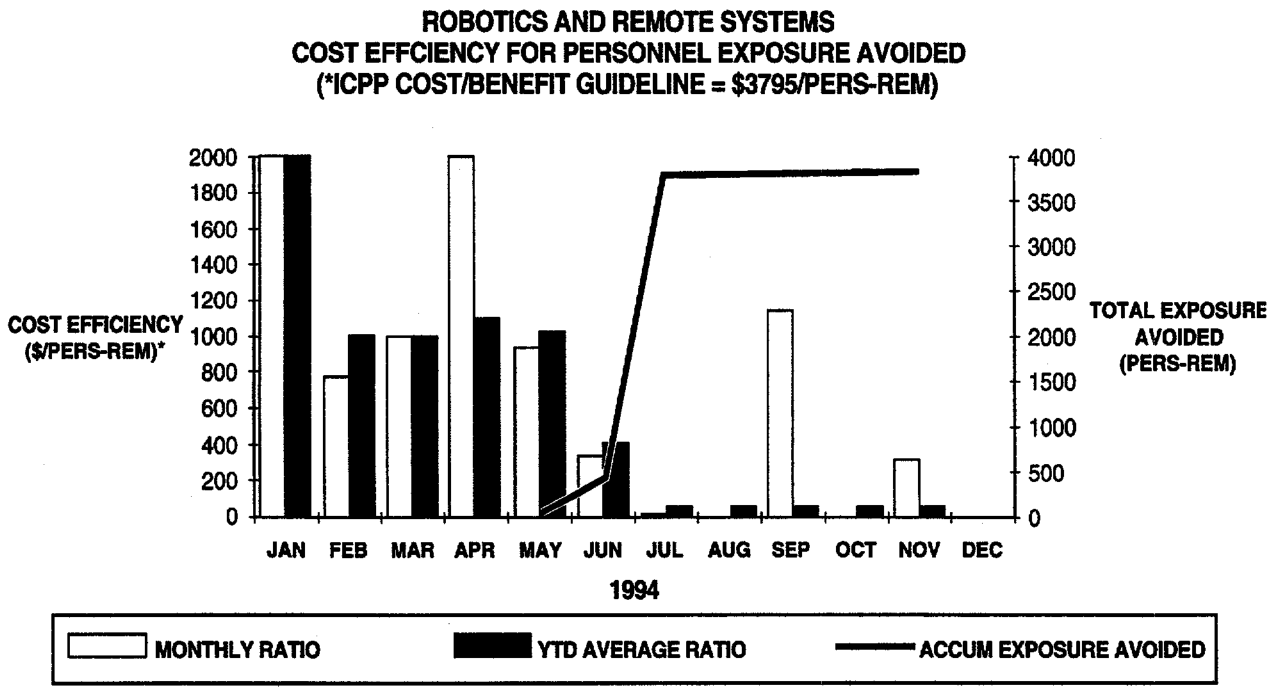
Costs are as depicted in the following table:

Type	Cost
Worker training	$2,280.00
Trainer	$3,600.00
Waste disposal	$200.00
Pre-job briefing	$136.00
Gather PPE and PC	$19.00
Double set anti-cs with airlines	$500.00
Total Cost	$6,735.00

Because the worker can be used to work in other areas, the training cost per man-rem is reduced to the amount indicated in the following table:

Type	Cost
Worker	$1,140.00
Trainer	$1,800.00
Waste disposal	$200.00
Pre-job briefing	$136.00
Gather PPE and PC	$19.00
Double set anti-cs with airlines	$500.00
Total Cost	$3,795.00

Note: The cost of anti-cs is based on one 50-ft of airline hose per entry. The cost will increase with additional airline hoses. Cost per airline hose is $200/50 ft.



APPENDIX C

ACRONYMS AND ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
Ci	curie(s)
CSEE	Confined Sluicing End-Effector
DOE	Department of Energy
EM	Office of Environmental Management
EM-40	Office of Environmental Restoration
EM-50	Office of Science and Technology
FETC	Federal Energy Technology Center
ft	foot (feet)
ft/s	foot (feet) per second
FY	fiscal year
GAAT	Gunite and Associated Tasks
gal	gallon(s)
gal/min	gallon(s) per minute
h	hour(s)
HEPA	High Efficiency Particulate Air Filters
HMA	Hose Management Arm
HP	health physics
in	inch(es)
in/s	inch(es) per second
INEEL	Idaho National Engineering and Environmental Laboratory
ITSR	Innovative Technology Summary Report
kg	kilogram
lb	pound(s)
LDUA	Light Duty Utility Arm
m	meter
man-rem	roentgen equivalent man
MLDUA	Modified Light Duty Utility Arm
mR	milli-roentgen
mrem	milli-roentgen equivalent man
NTF	North Tank Farm
ORNL	Oak Ridge National Laboratory
ORO	Oak Ridge Operations
OST	Office of Science and Technology
OU	Operable Unit
PC	protective clothing
POTS	Position and Orientation Tracking System
PDCU	Power Distribution and Control Unit
PPE	personal protective equipment
psi	pounds per square inch
R	roentgen
R/h	roentgen per hour
RCRA	Resource Conservation and Recovery Act
ROV	Remotely Operated Vehicle
RTDP	Robotics Technology Development Program
STF	South Tank Farm
TFA	Tanks Focus Area
TTCTF	Tanks Technology Cold Test Facility
TMADS	Tether Management and Deployment System