

**PERFORMANCE ASSESSMENT OF THE WASTE DISLODGING AND CONVEYANCE
SYSTEM DURING THE GUNITE AND ASSOCIATED TANKS REMEDIATION PROJECT*†**

P. D. Lloyd Oak Ridge National Laboratory P. O. Box 2008 Oak Ridge, TN 37831-6426 Lloydpd@ornl.gov 865-574-6329	C. L. Fitzgerald Oak Ridge National Laboratory P. O. Box 2008 Oak Ridge, TN 37831-6304 Fitzgeraldcl1@ornl.gov 865-574-7160	H. Toy Oak Ridge National Laboratory P. O. Box 2008 Oak Ridge, TN 37831-6426 Toyh@ornl.gov 865-574-5710	J. D. Randolph Oak Ridge National Laboratory P. O. Box 2008 Oak Ridge, TN 37831-6305 Randolphjd@ornl.gov 865-574-6591
--	---	--	--

R. E. DePew The Providence Group 10330 Technology Drive Knoxville, TN 37932 Depewre@providence-group.com 865-218-8711	D. D. Falter The Providence Group 10330 Technology Drive Knoxville, TN 37932 Dfalter@providence-group.com 865-218-8711	J. A. Blank The Providence Group 10330 Technology Drive Knoxville, TN 37932 Jblank@providence-group.com 865-218-8711
--	---	---

ABSTRACT

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 underground storage tanks (USTs) in which radiation levels and access limitations make traditional waste retrieval methods impractical. Specifically, these systems were developed for cleanup of the Gunite and Associated Tanks (GAAT) Operable Unit (OU) at the Oak Ridge National Laboratory (ORNL). The WD&CS is comprised of a number of different components. The three primary hardware subsystems are the Hose Management System (HMS), the Confined Sluicing End-Effector (CSEE), and the Flow Control Equipment and Containment Box (FCE/CB). In addition, a Decontamination Spray Ring (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 remotely operated vehicle system such as the Houdini .

The HMS was designed to act as a pipeline for the transfer of dislodged waste; as a hose-positioning and tether-management system; and as a housing for process equipment such as the water-powered jet pump that provides the necessary suction to vacuum slurried waste from the UST. The HMS was designed to facilitate positioning of an end-effector at any point within the 25-ft- or 50-ft-diameter USTs in the GAAT OU.

*Oak Ridge National Laboratory, managed by UT-Battelle, LLC, (formerly Lockheed Martin Energy Research) for the U.S. Department of Energy under contract DE-AC05-00OR-22725

†The Providence Group, Inc.

The CSEE is equipped with three rotating cutting jets mounted 120° apart. The jets, capable of delivering water at pressures of up to 10,000 psig, nearly converge at a point about 5 in. below the conveyance line intake on the end-effector. As the jets rotate, hard waste is dislodged and vacuumed up through the center of the CSEE and into a 2-in.-inside-diameter hose by the suction provided by the jet pump mounted in the mast of the HMS. A higher-pressure (30,000 psig) variation of this end-effector, the Gunitite Scarifying End-Effector (GSEE), was also developed to scour the tank walls after the bulk sludge was removed from the tank floor.

The FCE/CB attaches to the HMS and is equipped with process piping, instrumentation, and equipment that includes valves for flow control, flushing, and automatic sampling of the waste stream. Instrumentation in the FCE/CB was incorporated to facilitate monitoring of the waste stream flow rate and density. The FCE/CB also provides secondary containment for the waste stream and the interface to the destination tank and/or distant process piping and equipment.

After undergoing extensive cold testing in the ORNL Tanks Technology Cold Test Facility, the WD&CS system was placed in service in the GAAT OU North Tank Farm (NTF) in July 1997. After completing the cleanup of two 25-ft-diameter waste storage tanks in the NTF, the WD&CS was re-deployed to the South Tank Farm (STF) where it was subsequently used with other components of the TWRS to complete cleanup of five additional 50-ft-diameter USTs. The initial waste inventory of the tanks was estimated at approximately 88,000 gal of radioactive sludge and solids and about 250,000 gal of supernatant. Sludge radioactivity was estimated at 63,000 Curies (Ci) of various isotopes. The supernatant and tank walls were estimated to contain an additional 15,000 Ci. In approximately 900 hr of operation since its deployment in 1997, the WD&CS has proven to be reliable and effective. It has been used successfully as part of the TWRS to remove approximately 95% of the curie content and 99% of the sludge waste from these tanks.

This paper addresses the performance of the WD&CS during its deployments in the GAAT OU. Overall, the system performed quite reliably; system strengths as well as weaknesses will be discussed. In addition, a number of innovations and improvements, which were made by the GAAT team as it gained experience with the system, will also be presented.

1. INTRODUCTION

The U.S. Department of Energy (DOE) is responsible for cleanup and closure of 273 large, aging, USTs that have been used to store tens of millions of gallons of high- and low-level radioactive and mixed waste. The hazardous nature of the waste precludes humans from working in the tanks. Therefore, remotely controlled retrieval equipment and methods must be developed.

Among the tanks that require closure are a number of tanks at ORNL including several tanks in the NTF and STF of ORNL's GAAT complex. Previously, an 18-month sluicing operation conducted at ORNL from 1982 through January 1984 was successful in removing over 90% of the waste then present in the GAAT STF.¹ At the end of the sluicing operations in 1984, however, a waste heel of mixed waste sludge that varied in depth from 6-36 in. remained in the tanks. The total volume of the sludge heel was approximately 88,000 gal. The sludge was estimated to contain approximately 63,000 Ci of various isotopes. In addition, in-leakage during subsequent years had created an additional volume of approximately 250,000 gal of wastewater. Radioactivity in this supernatant and in the tank walls was estimated at approximately 15,000 Ci.

Since June 1997, the TWRS² has been used successfully by members of the GAAT Remediation Project Team to complete the clean out and closure of the two 25-ft- and the six 50-ft-diameter tanks in the GAAT complex. A key component of the TWRS, the WD&CS, was designed and constructed to

address specific requirements associated with waste retrieval and final cleaning of USTs. The WD&CS is not a stand-alone unit; rather, it is designed for deployment with either a long-reach manipulator such as the MLDUA or a remotely operated vehicle system such as the Houdini™.

2. GUNITE AND ASSOCIATED TANKS WASTE REMEDIATION SYSTEMS OVERVIEW

During GAAT operations, waste was removed from the UST by the TWRS and pumped by the WD&CS jet pump to a destination tank for consolidation or further processing. Major systems of the TWRS include the WD&CS, MLDUA, Houdini and a collection of process equipment and instrumentation referred to as the Balance of Plant (BOP). Figure 1 is a photograph of the major TWRS components—MLDUA, Houdini™, and the WD&CS—during cold testing at the Tanks Technology Cold test Facility in Oak Ridge.

The MLDUA is an eight-degree-of-freedom (DOF) robotic arm with a 200-lb payload and 15-ft horizontal reach, capable of deployment through a 12-in.-diameter riser. It is a modified version of the Light Duty Utility Arm and was manufactured by SPAR Aerospace.³

Houdini is a remotely operated, tethered vehicle, which weighs approximately 1000 lb and is capable of entering through a 24-in.-diameter riser. Houdini-II is a second-generation vehicle. Both systems were manufactured by RedZone Robotics, Inc., and have an integral six-DOF manipulator arm with a 240-lb capacity at full extension, an on-board camera system, and a plow blade. DOE/EM-0495⁴ provides a summary of the Houdini and Houdini-II capabilities.



Fig. 1. The Houdini plows sludge to the Modified Light Duty Utility Arm as the arm sluices with the CSEE in the Cold Test Facility. The Hose Management Arm is almost fully extended in the photo.

3. WASTE DISLODGING AND CONVEYANCE SYSTEM DESCRIPTION

The WD&CS is a suite of sub-systems capable of deploying waste retrieval end-effectors through a 24-in.-diameter riser to clean a tank floor located approximately 25 ft below grade. It can be used to dislodge, mobilize, and remove waste to aboveground treatment or transportation systems. It can accurately be described as a “system of systems” and consists of a HMS, a CSEE, a FCE/CB, a DSR, and a control system. The WD&CS is utilized in conjunction with other BOP systems such as utility skids and high-pressure pumps. Generally speaking, these BOP systems were integrated with the WD&CS and remotely controlled from the WD&CS operator control station. Following is a brief description of the design criteria used to develop these components and the resulting hardware. Randolph et al.⁵ provides additional detail.

3.1. Required Functionality

The WD&CS was designed to provide certain specific functionality. Specifically it was intended to

- Provide a means of:
 - managing cables and hoses required for operation and control of the end-effectors used to dislodge the waste,
 - pumping the waste out of the tank,
 - monitoring waste stream volume flow rate,
 - deploying and retracting waste removal equipment into the storage tank, and
 - maintaining environmental containment for in-tank equipment during deployment and transportation between deployments; and
- Provide appropriate interfaces with other GAAT systems such as:
 - waste storage tank,
 - destination tank or process piping and equipment,
 - end-effector positioning systems (i.e., MLDUA and Houdini), and
 - process piping and equipment (i.e., BOP).

It is important to recognize that the WD&CS was intentionally not designed to accomplish certain specific tasks, such as positioning the end-effectors within the tank or pumping the waste stream long distances after it was removed from the UST.

3.2. Component Description

3.2.1. Hose Management System

The HMS was designed to act both as a pipeline for the transfer of dislodged waste and as a hose-positioning system. Staff from ORNL and The Providence Group designed the HMS to provide access to all points within either the 25-ft- or the 50-ft-diameter tanks in the ORNL GAAT complex.

The HMS is comprised of several subassemblies: a Hose Management Arm (HMA), Storage Tube (ST), Confinement Box (CB), and Mast Elevation Table (MET). In addition, most of the required process and waste stream piping and equipment was integrated directly into the HMS. The rigid members of the HMS provide four DOF for deployment of the end-effector, and management of the cables and hoses. The HMS also provides the required waste removal and process water conduits.

Two of the HMS’s four DOF, mast vertical travel and mast rotate, are provided by a MET that is mounted aboveground in a CB. The other two DOF, shoulder pitch and elbow yaw, are provided by a

two-link arm constructed of Schedule 80 carbon steel pipe. The inner link of the arm is connected to the mast via a shoulder swivel joint, while the inner and outer links are connected to an in-line swivel by two 90° elbows, as shown in Fig. 2. This two-link pipe arm and the mast to which it attaches make up the HMA. The mast, which is supported in its deployed position by the MET, is constructed of a half-section of 20-in.-diameter, carbon steel pipe with a flat plate welded across the half-section. The mast houses a variety of pipes and instrument cables, a jet pump, process piping for the motive water to the CSEE and the jet pump, and the waste conveyance line. The jet pump is an axial-flow, water-powered eductor that utilizes 7,000-psig motive water to produce a vacuum that is used to remove the waste from the tank. Design and testing of a jet pump are described in Mann 1998.⁶

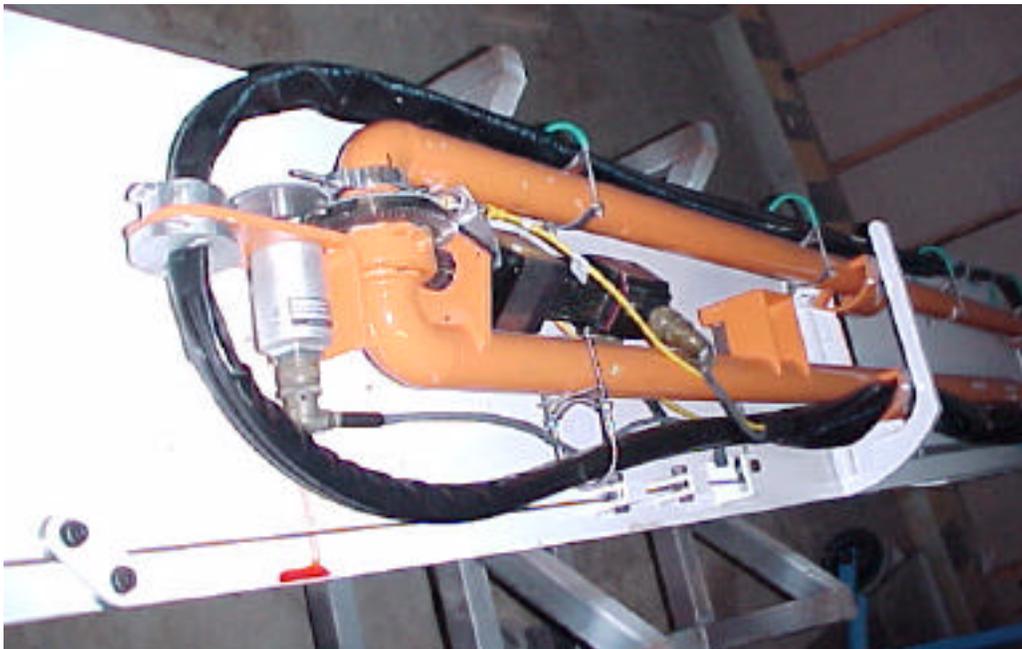


Fig. 2. The arm-links of the HMA-II shown in the stowed position on the lower half of the mast. The HMA-II is a slightly modified version of the first generation arm and was built as a spare.

The high-pressure water jet pump is mounted internally to the HMA mast. The pump is an off-the-shelf, relatively low-cost (less than \$2K) item. The pump design incorporates six water jets placed radially around the throat of the pump's mixing zone. The high-pressure water jets create a vacuum that is used to pull waste in through the CSEE inlet. In addition to vacuum, the high velocity jets provide excellent mixing and can also reduce particle size of solids in the waste stream. The jet pump used in the WD&CS was capable of a maximum suction lift of ~15 ft and a discharge head of 20-25 ft. The design maximum available working pressure for the pump was 10 ksi but was limited to 7 ksi. The unit was capable of two phase (solids and liquids) pumping at ~120 gpm (for specific gravities of 1.0-1.2). Air entrainment in the waste stream resulted in significant reductions in the flow rates. For maintenance purposes, the jet pump could be accessed via a cover plate in the HMA mast.

The CB provides the required interfaces to the storage tank, the BOP process equipment and piping, and the FCE/CB. It facilitates making the electrical and process connections required during deployment (or retraction) of the arm into (or from) the storage tank. It also provides a facility for minor maintenance and repair of the arm and end-effectors.

The ST is mounted to the CB and provides the required isolation of the HMA from the environment once it is withdrawn from the tank. When fully assembled, the top of the ST stands ~35 ft

above the support platform. The combined weight of the CB & ST is ~18,000 lb. For maintenance purposes, the ST can be separated from the CB for access to the HMA. An electrically operated hoist at the top of the ST provides the means of deployment and retraction of the arm. A 1-in.-diameter bolt can be inserted into the ST when the HMA is retracted to serve as a safety hard stop that will prevent the HMA from accidentally being lowered into the CB when operators are using the glove-ports.

3.2.2. Confined Sluicing End-Effector

The CSEE was designed by Pacific Northwest National Laboratory, ORNL, and Waterjet Technology Inc. (WTI) and built by WTI. The CSEE is equipped with three rotating cutting jets mounted 120° apart, as shown in Fig. 3. The jets, which are capable of delivering water at pressures of up to 10,000 psig, nearly converge at a point about five in. below the end-effector intake to the conveyance line and can be rotated at 0–500 rpm. As the jets rotate, hard waste is dislodged, and a slurry is created that can then be vacuumed up through the center of the CSEE and into the 2-in.-diameter hose that connects the CSEE to the HMA. Suction at the CSEE inlet is provided by the jet pump, which as previously mentioned, is mounted up the waste stream in the HMA mast. DOE/EM-0372 provides a summary of the CSEE capabilities.⁷



Fig. 3. The CSEE has three rotating water jets that are used to break up and suspend waste material in the gunite tanks.

3.2.3. Flow Control Equipment and Containment Box

The FCE/CB attaches to the HMS and is equipped with process piping and equipment that includes valves for flow control, flushing, and automatic sampling of the waste stream. Instrumentation in the FCE/CB was incorporated to facilitate monitoring of the waste stream flow rate and density. The FCE/CB also provides a secondary containment for the waste stream and the interface with the destination tank and/or distant process piping and equipment.

3.2.4. Decontamination Spray Ring

The DSR provides the required interface between the CB and the waste storage tank. Additionally, it facilitates the remote gross decontamination of in-tank portions of the HMA and CSEE when the equipment is being removed from the tank. A ring of spray nozzles is used to direct high-pressure water jets onto the equipment as it is being withdrawn from the tank. The DSR was designed and built by Southwest Research Institute.

3.2.5. Control System

A control system, developed at ORNL, provides a graphical user interface (GUI) to operators in the operator control trailer. The GUI provides the operators with a high-level interface to the low-level controllers for the WD&CS as well as with the pumps, valves, and process instrumentation of the BOP. It provides a safe, effective, and efficient method of monitoring and controlling sluicing, flushing, and decontamination activities remotely.

4. PERFORMANCE

4.1. Retrieval Operations

The various components of the WD&CS were delivered to ORNL during the summer of 1996 and integrated into a complete system by September 1996. Several months of cold testing ensued, during which time the equipment was integrated with the other remote retrieval systems of the TWRS—that is, Houdini and the MLDUA. Relocation of the WD&CS to the GAAT site was initiated in June 1997.

As soon as the initial sampling operations were completed in each tank, the HMA and CSEE were deployed. Either the MLDUA or the Houdini had to be deployed first so that the CSEE could be grasped as the HMA was deployed, preventing premature submersion of the CSEE in the sludge. Cold testing had revealed that if this procedure were not followed, waste material in the tank would often plug the end-effector nozzles. Low-pressure flushing of the nozzles during deployment was not possible because the water lines for flushing the nozzles could not be connected at the masthead until the mast was fully deployed into the tank.

Normally, the first one or two days of sluicing in each tank were spent dewatering it. During this process, the CSEE cutting jets were operated at low pressures (~150 psig) to prevent nozzle plugging while the supernatant was drawn off using the jet pump.

Once the sludge layer was revealed, pressure to the cutting jets was increased as necessary to break up and suspend the waste material for sluicing. Typical cutting jet pressures required during sludge removal ranged from 1000 to 4500 psig. Higher pressures were generally found to be unnecessary and tended to cause the end-effector to bounce around enough to cause position control alarms and faults for the MLDUA controller. Only occasionally were these control faults significant enough to shut down the MLDUA. The Houdini did not encounter any problems handling the CSEE or its reaction forces. The WD&CS was most efficient at removing sludge when the waste material was deep enough to partially submerge the CSEE, thus avoiding three-phase (solid, liquid, gas) pumping. For the last 1-3 in. of tank waste, the most productive method of operation was to have the Houdini collect and plow “waves” of waste to the end-effector as it was held by the MLDUA, as shown in Fig. 1.

Generally, once sluicing operations were completed, wall scarifying was initiated. In tanks W-3 and W-4, the CSEE was used to scarify the tank walls at pressures of ~6500 psig. The GSEE was used in tank W-4 at the same pressure. A higher-pressure pump was later obtained and the GSEE was used in

conjunction with that pump to clean the walls of the remaining tanks. Although pressures of up to 36 ksi were possible with the new pump, the MLDUA was unable to handle the reaction forces at pressures of greater than 20 ksi.

At project completion in September 2000, the WD&CS, as part of the TWRS, had succeeded in removing approximately 95% of the radiation sources and 99% of the sludge waste from seven of the eight gunite tanks in the NTF and STF of the GAAT OU (See Table 1). The eighth tank, which contained relatively little sludge, was cleaned using different technologies. During this time, the WD&CS was operated for over 900 hr.

Table 1. Gunite Tank Sludge Removal Performance Summary

	W-3	W-4	W-6	W-7	W-8	W-9	W-10	Total
Sludge Gallons (Initial)	5,500	13,500	12,880	10,000	10,300	9,200	24,400	85,780
Sludge Gallons (Final)	100	100	1567	476	238	500	393	3374
Curies (Initial)	340	924	2,255	4,581	7284	3,873	58,481	77,738
Curies (Final)	12	11	564	208	844	616	1,064	3,319
Water Used (Gal)	41,800	92,300	52,000	62,000	42,200	65,000	65,280	420,580
% Volume Removed	99.7	99.7	99.1	99.7	99.1	99.4	99.7	99.5
% Curies Removed	96.5	98.8	75.0	95.5	88.4	84.1	98.2	95.7

Notes:

1. W-3 sludge and curies are included in W-4 and not included again in totals. W-9 values reflect "native" waste only and do not include removal of "consolidated" waste.
2. Estimates reflect sludge volumes and curies for all tanks based on "best" current estimates. Curie values include sludge, water, wall scale, and gunite.
3. Removal performance is based on actual values achieved for W-3, W-4, W-6, W-7, W-8 and W-10. W-9 performance is based on estimates from ORNL/ER/SUB/87-99053/79.⁸
4. Data for W-5 is not included in this table, as the WD&CS was not deployed in that tank.

4.2. System Strengths

Overall reliability of the system was very high. There were only a limited number of actual failures during the 39 months of operation of this highly prototypic system. By almost any standard, the system performed well. Of significance, the job was completed safely and well ahead of schedule. There were no injuries, and with the exception of one very small leak in the CB, there were no failures of the primary or secondary containment systems. Beyond that, there are other strengths and weaknesses of the system that are outlined below.

The success of the system was a direct result of many factors that include, but are not limited to the following:

- establishment of a solid understanding of the requirements prior to design;
- a thorough and systematic design process;
- good communication and teamwork throughout the design, fabrication, and testing process;
- a systematic evaluation and testing process that included cold testing of all systems prior to deployment;
- consistent attention to detail, resolution of discrepancies, and validation of assumptions; and
- a skilled, well-trained, and proactive team.

Fabrication costs for the WD&CS were relatively low (less than \$750K). Despite the unique and prototypic nature of the system, designers maximized the use of readily available commercial grade products wherever possible. For example, the outer links of the HMA were constructed of Schedule 80

pipe and commercial grade pipe fittings. Similarly, the use of identical hardware wherever possible limited the number and variety of spare parts that had to be kept on-hand.

Lightning protection and electrical surge protection were integrated into the system and were effective in preventing any damage to the system throughout the life of the project. Lightning is known to have damaged a portion of an adjacent system that was in the process of being installed on the platform when a lightning storm hit.

Flexibility was designed into the system. With the assistance of the MLDUA or the Houdini, the HMS can be effectively used to position the CSEE at any point in any of the GAAT complex 25-ft- or 50-ft-diameter tanks. Servo controlled joints on the HMS allow the operator to accurately and remotely reconfigure the HMA within the tank. However, back-drivable joints on the arm also allow the operator to disable the arm so that the MLDUA or Houdini can “drag” the CSEE. This feature reduces operator fatigue because it reduces the requirement for very close coordination between the operators. Most of the equipment could be operated in multiple modes (e.g., Local vs. Remote and Manual vs. Automatic) to facilitate varying operational requirements, alternate configurations, maintenance, and testing.

System design placed a high degree of importance on reliability, but maintenance issues were also given high priority. For example, the design facilitated ready removal of the ST from the CB, which means that deployment of the HMA in the maintenance facility can be performed while

- minimizing hoisting and rigging requirements,
- minimizing the space required for the maintenance laydown areas,
- minimizing potential for spread of contamination, and
- facilitating complete HMA replacement under full containment, should a catastrophic failure occur.

Decontamination issues were effectively addressed during the design and fabrication phases of the project. In addition to the remotely operable DSR, a portable, hand-held, pressure washer wand was available in the CB for spot decontamination of hard-to-reach contamination traps. While this feature was useful prior to maintenance operations, the remote decontamination provided by the DSR was generally sufficient during routine deployment and retraction operations and further decontamination was not generally required. In addition, the forward and reverse waste stream flushing capabilities that were integrated into the WD&CS, combined with the “end-of-shift” flushing requirements included in the operating procedures, proved to be very effective at reducing the residual contamination in the waste transfer lines.

4.3. System Weaknesses

Despite the generally favorable performance of the WD&CS during GAAT operations in the North and South Tanks Farms at ORNL, operators identified a number of weaknesses in the system. Among these were ergonomic deficiencies, maintenance-related issues, instrumentation deficiencies, and control system faults. It should be noted that many of the “weaknesses identified by the operators” were not unanticipated by the designers; rather, they were result of conscious trade-off decisions made during the design and fabrication phases of the system’s development.

The location of the CB glove-ports was cumbersome. The ports were positioned so that the average operator was required to squat or bend at the waist in order to insert his arms fully into the gloves. Operators who were slightly smaller than average had difficulty using the gloves because the horizontal distances between the glove-ports were too great for their shoulders. It was relatively difficult to access all parts of the CB; and it was difficult to pass items such as tools from one side of the CB to the other, making deployment, retraction, and maintenance operations more difficult. System designers

recognized some of these discrepancies during the design phase and attempted to mitigate them by including a maintenance hoist inside the CB. This hoist was useful in performing maintenance on the end-effectors and other heavy or cumbersome items in the CB.

Deployment and retraction of the HMA were lengthy and demanding processes that required operators in the control room and on the platform. Deployment of the HMA into the tank generally took an hour or so; retracting the arm from the tank took slightly less time but still took longer than desired. There are several reasons for the relatively long deployment/retraction cycle. Among them was the fact that, during deployment, the end-effector needed to be grasped by one of the other systems (i.e., MLDUA or Houdini) to prevent premature submersion in the sludge. The limited number of camera views available to the MLDUA/Houdini operators and the fact that the HMA operators could not control the exact location of the CSEE handle made this operation very difficult.

Additional delay in the deployment and retraction operations resulted from having to disconnect all of the cables and hoses (10 cables and 3 hoses) from the upper portion of the HMA mast prior to retracting the arm into the ST. To increase reliability (and at the same time reduce complexity and cost), system designers opted for this approach over one that would have allowed all of the cables and hoses to remain connected. Despite the use of quick connect fittings and quarter-turn electrical connectors, this portion of the operation was both physically demanding and time consuming.

Another result of the simplified approach to cable and hose management within the CB was the fact that the range of motion for the shoulder roll was limited to approximately $\pm 90^\circ$ after the hoses and cables had been connected. In general, rotating beyond 90° in either direction after the hoses and cables had been connected would put undue stress on one or more of the cables or hoses. As a safety precaution, limit switches were installed 90° apart, and a movable "target" was inserted between them after the hoses and cables were connected so that travel was effectively limited to $\pm 45^\circ$. In addition to impacts on deployment procedures, the limited range of motion for the mast roll joint limited the workspace of the CSEE: to move to another quadrant, hoses and cables had to be disconnected, the mast rotated, cables and hoses reconnected, and the limit pin repositioned. This approach, while flexible, effective and reliable, was somewhat time consuming and cumbersome for the operators.

The actual number of maintenance-related problems with the WD&CS was quite low when compared to the other systems in service during the GAAT remediation project. The HMA was relocated to a maintenance facility for repair (replacement of a damaged signal cable from the load cell on the shoulder pitch cable) on only one occasion and the repair task was accomplished in parallel with a scheduled inspection conducted during the relocation of equipment from the NTF to the STF. As a result, the impact on operations and schedule was minimized. The damaged cable had previously been repaired in the CB, but damage to the cable shield had been so severe that the low-voltage signal was rendered useless. The repair consisted of simply replacing the cable; but since this task required simultaneous access to both the top and the bottom of the HMA mast, it could not be performed without relocating the HMA to the maintenance facility. Repair was facilitated by the existence of a spare conduit that had been included in the design for just such a requirement. The required repair highlighted previous concerns about the susceptibility of the cables and hoses to damage, especially at the top of the mast and in the vicinity of the shoulder joint at the bottom of the mast. Careful cable routing and attention to detailed procedures prevented any other significant damage to the cables.

For the most part, the instrumentation provided as part of the WD&CS was adequate and provided the operators with a sufficiently detailed indication of the systems performance. One notable exception was the Coriolis flow meter (FE-204), a Micro Motion DL200S, which was installed in the FCE/CB. Based on manufacturers sales information for the flow meter and the expectation that the CSEE-jet pump combination would be able to deliver a reasonably consistent flow with minimal (i.e., less than

10%) air entrainment, it had been anticipated that FE-204 would be able to provide reasonably accurate data on flow rates, and densities of the waste stream. However, the highly dynamic three-phase nature of the waste stream, which was typically interspersed with significant “slugs” of air, rendered the flow meter almost completely ineffective. Because the presence of the flow meter did not interfere with operations, it was not removed from the waste stream piping; but the data from the instrument was only accurate during full pipe pumping (e.g., during supernatant removal). The Coriolis flow meter was sometimes useful to operators in helping to discern when blockages of the CSEE were developing. Other instrumentation was used effectively to monitor waste transfer and water balances.

A few mechanical design and fabrication issues were noted as well. Among them was a problem that was identified during cold testing of the system. To provide reasonable access to the HMA for maintenance and/or inspection when it was retracted into the ST, the design specified that a 24-ft-long section of a 27-ft-long 26-in.-diameter Schedule 20 pipe was to be split in half, welded to flanges, and reassembled by bolting the flanges together. The cutting, welding, and reassembly resulted in deflection of the ST that made movement of the arm within the ST impossible. Grinding and cutting modifications were made to the arm and the ST during cold testing so that no additional impact was realized.

A second issue was not identified until the system was deployed in the NTF. The CSEE effectively performed the task for which it was designed (i.e., dislodge, slurry, and vacuum up clay-like waste). It was less effective when it encountered debris in the tank, such as lengths of discarded tape, heavy plastic bags and gloves, and pieces of string or wire. The CSEE generally failed to cut this type of debris when it encountered it, and the debris usually clogged the screen on the waste inlet. As a general rule, back-flushing the end-effector inlet dislodged the obstruction effectively; however, at times the blockage was severe enough that the arm had to be withdrawn from the tank so that the blockage could be removed by operators working through the gloves in the CB. On the positive side, the screen on the CSEE inlet prevented any serious blockages (i.e., blockages that couldn't be easily removed by back flushing) in the upstream waste piping. During the later portion of the project, blockages became more problematic. As a result, a nozzle-cleaning tool was developed for deployment with the HMA. The tool facilitated remote removal of most blockages without retracting the arm into the CB.

The floor of the confinement box was designed with a lip that protruded slightly above floor level. The lip was included to minimize the risk of small objects, which might be dropped during maintenance activities, falling into the tanks. While this feature did prevent some objects from falling into the tanks, it also created a contamination trap that made decontamination activities more difficult. A drain hole in the lip allowed water used for decontamination to drain back into the tanks, but small amounts of contaminants became trapped by the lip. A smooth transition into the tank riser combined with a lightweight maintenance cover would have been a better solution.

Late in the design process it was postulated that a plug in the HMS waste lines might result in pressurization of the system by the jet pump motive water (up to 7000 psig). To prevent damage to the waste transfer piping, a 2-in.-diameter rupture disk was added. Due to design and schedule constraints, the disk was placed behind an access panel in the HMA mast with the realization that the disk would be impossible to replace using the CB glove-ports. The extremely abrasive nature of the surrogate used during cold testing resulted in one failure of the rupture disk prior to deployment in the NTF. The disk failed twice more during early-NTF operations. After the second disk failure in the NTF, the disk was relocated to the FCE-CB, reduced to 1in.-diameter, and increased to a higher failure rating (still within the safe working pressure of the WD&CS). One subsequent disk failure occurred near the end of the project. The CSEE inlet had become completely plugged with debris and sludge. The rupture disk failed when a back flush was performed and no waste was dislodged. A combination of rupture disk wear and water hammer from the back flush is thought to have caused the failure.

The mechanically abrasive nature of the waste created another design challenge related to the CSEE. A seal for the rotating portion of the CSEE cutting jets was subjected to a pressure drop created by the vacuum from the jet pump. The pressure drop tended to draw waste into the seal whenever it was positioned below the waste surface. Even with the seal positioned above the waste surface, the splash created by the cutting jets resulted in some exposure. Seal wear was undesirable because as the seal wore, the vacuum at the CSEE inlet was reduced and pumping efficiency dropped. The original design of the seal was a simple “V” seal with a clearance of approximately 0.005 in. and utilized a hard plastic (Delrin®) seal. These seals had to be replaced between every couple of tanks to prevent serious degradation in pumping efficiency. A second design, a steel/ bronze single stage labyrinth type arrangement, again with a clearance of only a few thousandths of an inch, was implemented and tested with limited success. The seal provided by the second design was very effective; in a sense, it was too effective. Rather than wearing when exposed to sludge as the plastic seals had done, the metal seals trapped the sludge resulting in a high-friction bearing surface that quickly generated over-torque faults of the CSEE rotate motor amplifier. Although not appropriate for general sludge removal, a CSEE built with the second type of seal was used to effectively and efficiently retrieve the last few inches of sludge from several tanks.

Another issue was the relatively complex hoisting and rigging required to move the HMS from tank to tank. Unless it was being moved to an immediately adjacent riser, safe relocation of the HMS generally required the entire arm to be lifted as a complete assembly from one tank riser, laid on its side on a flat-bed truck for transport, relocated, re-lifted and re-oriented to a vertical position before final positioning and insertion in the next riser. Although the HMS could easily be lifted by a single crane, re-orienting it from horizontal to vertical or vice versa was a relatively difficult and complex task that required a second crane and a skilled rigging crew.

A couple of deficiencies with the control system were also noted. The most serious of these was the inability of the system to automatically detect the presence of a disconnected cable. While this may not be required for all types of systems it certainly should be incorporated in a system such as the WD&CS where disconnecting and reconnecting cables is a routine field requirement for a remotely operated system. One accident with the HMA highlighted this problem; the servomotor for the shoulder pitch joint on the HMA was energized and enabled while the position feedback cable was disconnected. System designers initially thought that this feature had been implemented for the most important of the sensors, the resolvers at each joint on the HMA. However, they subsequently realized that the manufacturers data for the resolver-to-digital board had been misinterpreted and that it was effectively impossible (at that point in the project) to implement such a feature. Startup algorithms and operational procedures were revised so that administrative controls would reduce the likelihood of another similar incident.

A second deficiency with the control system was the presence of nuisance alarms. Initially, some of the alarm logic was incorrectly reasoned, and some of the alarm thresholds were set too low. Only minor software modifications were required to correct these discrepancies.

One persistent problem with the control system, a discontinuity in the mast roll resolver signal at $\pm 180^\circ$, was not identified until the system was deployed in the STF. The discontinuity and the closed-loop nature of the control system effectively limited the usable HMA configurations to ones where the discontinuity was outside the workspace defined by the mast roll limit switch. Recall that this is an operator selectable region of $\pm 45^\circ$ and is determined by the location of the limit-switch-pin. Hardware modifications to resolve the problem were possible but were not pursued due to schedule constraints.

4.4. Enhancements

In addition to the software modifications just mentioned, and the ST grinding and CSEE seal modifications described earlier, several other modifications were made to the WD&CS to enhance its functionality. Some, like the addition of Lexan panels on the mast hoist housing and the addition of temporary AC power in the CB, were relatively minor but deserve mention. Others, such as the addition of the Waste Removal and Transfer System (WaRTS) and the development of additional end-effectors like the GSEE and the Linear Scarifying End-Effector (LSEE) were more complex and expensive.

During the scheduled inspection of the HMA between operations in the NTF and the STF, Lexan panels were installed in place of the existing painted steel panels surrounding the mast hoist located at the top of the ST. The modification was made to facilitate periodic inspections of the hoist. When the steel panels were removed, small pools of condensate were observed in the mast hoist housing. The condensate, a consequence of the high humidity in the UST, was highly undesirable for contamination control and corrosion control reasons. Accordingly, a pair of additional modifications were approved and implemented. The first was the addition of a drain line from a low point in the mast hoist housing into the CB, where the condensate would easily return to the tank. Secondly, an air purge was added to the mast hoist housing. The air purge used a small flow of dried plant air to minimize the amount of condensation in the housing.

In general, sources of AC power for maintenance and incidental activities were initially inadequate on most of the support equipment platforms. While AC outlets were provided on the exterior of the HMS CB for maintenance, they were not initially provided inside the CB. After the system was deployed to the NTF, the need for AC power inside the CB was identified and a set of power distribution cables was developed for short-term maintenance activities inside the CB. Although not directly related to the WD&CS, a similar problem was experienced with other pieces of TWRS equipment. A mobile, modular power distribution system was developed to reduce work restrictions in the field.

Cold testing of the CSEE revealed that modification of the water jet geometry offered the potential for significant improvement in the efficiency of wall washing operations. Re-orienting the jets so that they diverged instead of converging could increase coverage from about 4 in. to about 14 in. per pass. As this end-effector would be used only for wall scarifying, no waste removal vacuum would be required. Accordingly, a second version of the CSEE, the GSEE, was designed, fabricated, tested, and eventually deployed as part of the GAAT remediation project. Originally the intent of the wall scarifying was to remove up to 0.25 in. of gunite from the tank walls. Testing indicated that doing so would generally require pressures in excess of 20 ksi. As a result of the tank geometry and the kinematics of the MLDUA, this was feasible in the NTF. However, these same factors limited the maximum operating pressure of the water jets during operations in the STF, where the thrust from the water jets and the long moment arm which resulted from the MLDUA positioning the GSEE for wall scarification generated significant torque at the MLDUA shoulder rotate joint. The actuator for that joint was not designed to withstand the resulting torque and repeated motor faults necessitated a reduction in the GSEE cutting jet supply pressure to a maximum of approximately 13 ksi. Over the life of the project, it became evident that increasing the pressure above 7 ksi produced little advantage with respect to the amount of waste removed in a single pass. At the same time, reducing the pressure to 7 ksi significantly limited the generation of mist during wall washing (a significant problem), thus increasing operational efficiency.

One of the most physically demanding tasks of the project was the deployment and retraction of the GSEE and its umbilical. Umbilical management, as it was implemented for the GSEE, left much room for improvement. The Tether Management System (TMS), developed for deployment and retraction of the GSEE tether, proved difficult and cumbersome for the operators. Decontamination of the GSEE tether by the DSR on the MLDUA riser proved to be ineffective. As a result, hand decontamination

with cheesecloth and a hand-held pressure washer, similar to the one in the HMA, was required. This task required manually positioning and holding the umbilical during decontamination operations, which was extremely difficult because of the stiff nature of the cable and less than optimal ergonomic design of the TMS. In addition, because the TMS also experienced periodic slack cable types of failures during deployment of the GSEE, operators were required to manually tension and monitor the tether during deployment. The TMS typified and highlighted the kinds of problems that may often result from a rapid design and development cycle.

In an effort to increase efficiency and flexibility, GAAT team members also developed another concept for washing the tank walls. Another wall-washing end-effector, the LSEE, was designed, constructed, tested, and placed in service in the STF. The LSEE has two water jets; each mounted on a separate linear positioning stage. The linear positioning devices are two 5-ft-long opposing-pitch acme thread lead screws actuated by a single bi-directional pneumatic motor. If the two jets are positioned so that they are always on opposite sides of, and the same distance from, the center of the end-effector, the torque generated by one jet cancels the torque from the other. Thus the LSEE could be positioned by the Houdini's Schilling Titan III arm, and a 10-ft-high by 1-ft-wide section of tank wall could be scarified with 7 ksi water jets in a single pass. Development, testing, and performance of the LSEE is described in Fitzgerald et al. 2001.⁹

The general approach taken by the GAAT remediation project was to consolidate all of the waste from the NTF and the STF into a single tank, W-9, in the STF. As the waste volume in W-9 increased, several additional waste removal systems were developed and placed into service. A description of those systems is beyond the scope of this paper. However, as the time approached for the final clean out of W-9, it became evident that the WD&CS and other TWRS components were inadequate for the final cleanup task without some additional enhancements. The existing systems were principally limited by two factors. The intermittent nature of the waste stream from the jet pump and the limited discharge pressure precluded the use of the jet pump alone to move the waste over the distance required to remove it from the site. In addition, because the WD&CS was not designed to control the solids content of its discharge (i.e., particle size and density), it could not be used without modification to meet the waste acceptance criteria of the destination storage facility, the Melton Valley Storage Tanks. Accordingly, ORNL developed an additional system, WaRTS, to augment the existing TWRS. The WaRTS took advantage of existing system capabilities and added the following:

- a Waste Stream Consolidation System, comprised of
 - a surge tank, T1,
 - a remote viewing camera and adjustable lighting,
 - secondary containment, and
 - associated piping and valving;
- a Supernatant Pumping System, consisting of
 - a supernatant reservoir, T2
 - a positive displacement pump, P2,
 - secondary containment, and
 - associated piping and valving;
- a positive displacement pump, P1; and
- a control system that provides for safe efficient remote operation of the additional hardware and features:
 - a distributed network architecture,
 - interlocks with existing systems, and
 - a graphical user interface.

The addition of the WaRTS to the TWRS provided an effective, reliable, and efficient system for final clean out of ORNL's GAAT USTs. The *Heavy Waste Retrieval System Innovative Technology Summary Report*¹⁰ provides a good summary of the development and operation of the enhanced system.

5. CONCLUSIONS

The WD&CS was used successfully as part of the TWRS to effectively and efficiently complete final clean out of eight USTs in the GAAT OU at ORNL. Prior to deployment of the WD&CS system, these eight tanks had contained over 88,000 gal of radioactive sludge and solids and 250,000 gal of supernatant that held an estimated total of 78,000 Ci of various isotopes. In approximately 900 hr of operation, the WD&CS mobilized and removed approximately 95% of the radiation sources and 99% of the waste volume from the tanks.

Among the most noteworthy strengths of the system was its reliability. No other system in the GAAT TWRS performed as reliably as the WD&CS. While minor maintenance was required from time-to-time on various portions of the system, there were no prolonged delays due to equipment breakdown or maintenance difficulties. The HMA was relocated to a maintenance facility for repair on only one occasion, and that task was accomplished in parallel with a scheduled inspection, thus minimizing the impact on operation and schedule.

In addition to its reliability, the WD&CS is an extremely versatile and relatively low-cost system. A number of innovations and modifications were made as operators gained experience with the system. These innovations further enhanced an already effective tool.

The interested reader is referred to a detailed report¹¹ prepared at the completion of operations in the NTF for additional information on the performance of the WD&CS system and other components of the TWRS.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of our families and the assistance of our fellow GAAT team members, who not only made the project a success, but also made it an enjoyable and rewarding experience.

REFERENCES

1. H. O. Weeren, *Sluicing Operations at Gunite Waste Storage Tanks*, ORNL/NFW-84/42, September 1984.
2. B. L. Burks, D. D. Falter, R. L. Glassell, S. D. Van Hoesen, M. A. Johnson, P. D. Lloyd, J. D. Randolph, "Development and Demonstration of a Remotely Operated Tank Waste Retrieval System for the Oak Ridge National Laboratory," *Rad Waste Magazine*, 4(2):10-16 (1997).
3. *Light Duty Utility Arm Innovative Technology Summary Report*, DOE/EM-0406, December 1998.
4. *Houdini™-II Innovative Technology Summary Report*, DOE/EM-0495, December 1999.
5. J. D. Randolph, P. D. Lloyd, M. A. Johnson, B. L. Burks, J. Blank, D. Summers, M. W. Rinker, D. Mullen, and D. Alberts, "Development of a Waste Dislodging and Retrieval System for Use in the Oak Ridge National Laboratory Gunite Tanks," pp. 894-906 in *Proc. ANS Seventh Topical Meeting on Robotics and Remote Systems*, Augusta, Georgia, April 27-May 1, 1997.
6. M. D. Mann, *High Pressure Jet Pump Conveyance Optimization*, Thesis T7486, University of Missouri-Rolla, 1998.
7. *Confined Sluicing End-Effector Innovative Technology Summary Report*, DOE/EM-0372, September 1998.

8. *Results of 1995 Characterization of Gunite and Associated Tanks at Oak Ridge National Laboratory, Oak Ridge, Tennessee*, ORNL/ER/SUB/87-99053/79, June 1996.
9. C. L. Fitzgerald, Jr., D. D. Falter, R. E. Depew, "Linear Scarifying End-Effector Developed for Wall Cleaning in Underground Storage Tanks," to be published in *Proc. ANS Ninth Topical Meeting on Robotics and Remote Systems*, Seattle, Washington, March 4–9, 2001.
10. *Heavy Waste Retrieval System Innovative Technology Summary Report*, DOE/EM-xxxx, to be published.
11. V. A. Rule, B. L. Burks, S. D. Van Hoesen, *North Tank Farm Data Report for the Gunite™ and Associated Tanks at the Oak Ridge National Laboratory, Oak Ridge, Tennessee*, ORNL/TM-13630, May 1998.