SYSTEM REVIEW OF THE MODIFIED LIGHT DUTY UTILITY ARM AFTER THE COMPLETION OF THE NUCLEAR WASTE REMOVAL FROM SEVEN UNDERGROUND STORAGE TANKS AT OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

The Modified Light Duty Utility Arm (MLDUA) is a custom seven-degree-of-freedom long-reach manipulator system developed, designed, and built by SPAR Aerospace, Ltd. The MLDUA was delivered to Oak Ridge National Laboratory (ORNL) in November 1996. After operational tests and training cold tests, the MLDUA was moved to the first underground tank (W-3) in May 1997. After the completion of tank W-3, the MLDUA was used in cleanup operations of six other underground tanks, in this order, tanks W-4, W-6, W-7, W-10, W-8, and finally on tank W-9. Tank W-9 was completed in September 2000. Tanks W-3 and W-4 are 25-foot diameter tanks and the other five tanks are 50-foot diameter tanks. The MLDUA was deployed only in one tank riser for the 25-foot tanks. For the 50-foot tanks, the MLDUA was deployed in either two or four tank risers. The MLDUA performed the following types of operations in support of the underground tank waste cleanup operations: grasping the sluicer to allow deployment of the Hose Management Arm (HMA) into the tanks, holding and maneuvering the sluicer to remove tank water and waste material, tank wall radiation surveys, tank wall material sample collection, tank wall cleaning operations with high-pressure water jets, vertical pipe cutting operations, pipe plugging operations and support for tank wall coring operations. The MLDUA performed exceptionally well considering it is a one-of-a-kind long-reach manipulator prototype design. The MLDUA operations included over 7400 hours of in-tank exposure to radiation fields with an estimated total dose of 77,000 rads. Total working time within the tanks was over 2250 hours. While the MLDUA performed exceptionally well, a relatively few problems developed during tank cleanup operations. The most serious problem that developed during operations was the loss of the manipulator's wrist roll operation. The wrist roll drive motor's power supply cable developed an internal short within the manipulator's umbilical cable during operations on tank W-6. The MLDUA operators compensated for operations without an operating wrist roll by pre-planning the MLDUA jobs and presetting the wrist position. The MLDUA was never a delay in tank operations. Also, many "lessons" were learned in both manipulator operations within the tanks and manipulator design. Many design modifications were identified that would have made the MLDUA a better machine. The design modifications include changes to make setup and take down of the MLDUA easier, to perform maintenance easier, reduce operator's radiation exposure during MLDUA support operations within the Tank Riser Interface Containment (TRIC), and the Operator's computer graphic interface. Overall, the MLDUA performed exceptionally well and has a proven track record.

1. INTRODUCTION

The Oak Ridge National Laboratory (ORNL) Gunite and Associated Tanks (GAAT) are being remediated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process. A CERCLA treatability study was conducted in the GAAT North Tank Farm (NTF) before commencing remediation of the larger tanks in the South Tank Farm (STF) [1]. A remotely operable tank waste retrieval system has been developed for the GAAT remediation campaign. A summary description of this retrieval system is provided in “A Remotely Operated Tank Waste Retrieval System for ORNL” [2]. To provide functional checkout of the system and operator training, a cold test program was conducted. The test program is described in *Treatability Study Operational Testing Program and Implementation Plan for the Gunite and Associated Tanks at Oak Ridge National Laboratory, Oak Ridge, Tennessee* [3].

The Modified Light Duty Utility Arm (MLDUA) is part of the retrieval system. The MLDUA has been used in the NTF to deploy a variety of end effectors in the process of removing waste from the tanks, cleaning the tank walls, and checking radiation levels inside the tanks. The MLDUA is equipped with a removable general-purpose gripper end effector (GEE). The MLDUA is user selectable for telerobotic or robotic operations and has eight degrees-of-freedom when the telescoping vertical mast is operated. In the 25 ft (7.62 m) diameter tanks in the NTF, the MLDUA can reach the walls from a central riser; however, in the 50 ft (15.24 m) diameter gunite tanks in the STF, the reach coverage area is restricted because of the location of the peripheral risers where the MLDUA is deployed. The Office of Science and Technology (EM-50) sponsored the development of the MLDUA to support Waste Management (EM-30) and Environmental Restoration (EM-40) missions for the remediation of underground storage tanks.

2. MODIFIED LIGHT DUTY UTILITY ARM SYSTEM

The MLDUA system was designed and built by Spar Aerospace Limited of Toronto, Canada. The system consists of the following major system components: mobile deployment system (MDS), vertical positioning mast housing (VPMH), vertical positioning mast (VPM), MLDUA (also called the utility arm), hydraulic power unit (HPU), operator control trailer (OCT) console, tank riser interface containment (TRIC), and decontamination spray ring (DSR). The MDS supports the VPMH on the tank platform.

The MDS is equipped with four hydraulic outrigger legs that are used to raise and level the VPMH above the TRIC. The MDS allows the VPMH five degrees-of-freedom: X, Y, Z, pitch, and roll. These degrees-of-freedom are hydraulically powered.

The VPMH contains the VPM tubes and the hydraulic winches used to vertically position the VPM tubes, which determine the working height of the utility arm inside the tank. A purge air system maintains a slight positive purge pressure in the VPMH. The VPM consists of two stainless steel tubes: outer VPM tube and inner VPM tube. Each VPM tube has an independent hydraulic winch equipped with a fail-safe hydraulic brake for vertical positioning of the tube. The outer VPM tube rides on and is guided by linear rails inside the VPMH. The inner VPM tube is guided inside the outer tube to prevent rotation of the inner VPM tube inside the outer VPM tube. The utility arm is attached to the end of the inner VPM tube. When fully retracted, the outer VPM tube is completely contained inside the VPMH and the inner VPM tube and utility arm are completely contained inside the outer VPM tube.

The utility arm is attached to the inner VPM tube. The utility arm has seven degrees-of-freedom: shoulder yaw, shoulder pitch, elbow 1 yaw, elbow 2 yaw, wrist pitch, wrist yaw, and wrist roll. Including the VPM vertical motion, the MLDUA has eight degrees-of-freedom. Except for shoulder yaw and wrist roll, which are electric motor driven, the other joints are hydraulically powered. The utility arm is equipped with a GEE for grasping tools equipped with a Spar-designed “X” handle. The X handle design provides a positive hold on the tool being held by the GEE. The utility arm, with the GEE, has a full reach of about 16.5 ft (5.03 m) and a 200 lb. (90.72 kg) payload based on a 24 in. (0.61 m) center of gravity from the end of the utility arm tool interface plate (TIP). The weight of the GEE is included in the 200-lb (90.72 kg) carrying payload of the utility arm.

The HPU is a portable unit that contains the hydraulic oil pumps (pressure and filter), hydraulic reservoir, hydraulic filters, hydraulic cooler, and the interconnecting hydraulic hoses and control cables. The HPU also contains the computer cabinet to house the control electronics for the MLDUA system operations.

The OCT contains the operator interface computer, video camera displays, and joysticks required to remotely control the MLDUA system.

The TRIC is the containment enclosure used to support the utility arm operations and maintenance. Southwest Research Institute designed the TRIC. The TRIC is located between the VPMH and the tank riser. The TRIC is used for installing and removing the GEE and for placing various tools into the GEE. Two deployable tools, the characterization end effector (CEE) and gunite scarifying end effector (GSEE) are equipped with large-diameter tether cables. The CEE is used to measure the radiation field at the tank wall, and the GSEE is used to scarify the tank wall. Tether operations for these end effectors are performed with two detachable tether-handling systems (THS). One THS at a time is attached to a port on the TRIC to allow the end effector and its tether to pass from the THS into the TRIC. The THS has a tether drum and feed guide to control the play out and take-up of the tether as the utility arm enters or leaves the tank with the CEE or GSEE.

3. REMOTELY OPERATED VEHICLE

The remotely operated vehicle (ROV) was designed and built by RedZone Robotics, Inc., and is known as the Houdini. The Houdini is a hydraulically powered, tracked vehicle equipped with a six-degree-of-freedom hydraulically powered Schilling arm. The vehicle is equipped with a hydraulically powered plow blade for pushing waste sludge. A separate paper describing the Houdini system has also been prepared for presentation at this conference [4].

4. HOSE MANAGEMENT ARM AND CONFINED SLUICING END EFFECTOR

The hose management arm (HMA) and confined sluicing end effector (CSEE) provide the sluicing equipment to remove the waste material or sludge from the tanks. The HMA consists of a vertical mast with a two-section pipe boom. A length of suction hose is connected to the end of the pipe boom that is away from the vertical mast. The CSEE is connected to this hose. The two boom sections plus the hose length provide a reach of approximately 28 ft (8.53 m). This configuration allows the CSEE to reach anywhere inside a 50 ft (15.24 m) diameter tank when the HMA is deployed in a central tank riser. A water-powered, 7000 psi (482.6 bars) jet pump located in the vertical mast provides the motive force to move the waste material into the CSEE, through the hose and pipe boom, and up the vertical mast and then discharges the material through a piping system to the waste holding tank. The HMA has four powered degrees-of-freedom: vertical mast height, vertical mast roll, shoulder pitch (boom section connected to the vertical mast), and elbow yaw (joint between the two boom sections). In normal operation, the elbow yaw joint is de-energized and can move freely to allow the second boom section to follow the CSEE operation. The CSEE is positioned inside the tank with either the utility arm or the Houdini. The CSEE has three high-pressure (100 psi (6.9 bars) to 7000 psi (482.6 bars)) cutting jets that nearly converge to a location about 5 in. (12.7 cm) below the suction port of the CSEE. The cutting jets are located on a rotating assembly on the bottom of the CSEE. When rotating, the cutting jets form a cone of high-pressure cutting water to cut and mix the waste sludge directly beneath the CSEE suction port. When the HMA and CSEE are being deployed into a tank, either the MLDUA or Houdini must grasp the CSEE, which dangles below the HMA, to keep the CSEE out of the tank waste until the HMA is fully deployed into the tank. For retraction of the HMA out of the tank, the CSEE must also be held until the HMA is high enough out of the tank to keep the CSEE out of the tank waste. For in-tank operations, the CSEE is stored in a "cradle" when the CSEE is not in use. The cradle is lowered by the utility arm from the TRIC and is placed on the tank floor. The HMA was designed by Jim Blank of The Providence Group of Oak Ridge, Tennessee and was built by Tennessee Tool and Engineering of Oak Ridge, Tennessee. The CSEE was based on a prototype designed by the University of Missouri-Rolla and Pacific Northwest National Laboratory (PNNL). WaterJet Technology of Seattle, Washington fabricated the fielded CSEE.

5. TANKS TECHNOLOGY COLD TEST FACILITY

Before the MLDUA, ROV, and HMA were deployed into the gunite tanks, the equipment was tested and personnel were trained at the Tanks Technology Cold Test Facility (TTCTF) at the Robotics and Process Systems complex at ORNL. An underground experiment cell, about the size of the 25 ft (7.62 m) diameter tank, from the abandoned Experimental Gas-Cooled Reactor Building was converted into a mock tank. The equipment control room was located in a service building about 75 ft (22.86 m) away from the work platform mounted above the "tank." The cold testing proved to be very beneficial for both the equipment and personnel [5]. Operation of the MLDUA at the TTCTF began on November 11, 1996, and ended on May 14, 1997, with the move to the NTF to begin hot operations. During the 25 weeks of TTCTF operations, the MLDUA computer was started 150 times for an operating period of 872 hours. The hydraulic pumps were started 354 times for an operating period of 328 hours. The utility arm was deployed into the test facility a total of 19 times for operations. The utility arm was stored inside the tank both in the vertical or horizontal orientation storage overnight and on weekends to determine if there were any undesirable effects of this type of storage on the MLDUA system.

During the TTCTF testing, the MLDUA system was interfaced with the TRIC. The TRIC was initially designed as a glove port box with six sets of gloves to allow the installation and removal of the GEE from the utility arm. A GEE handling system was supplied with the TRIC. This system was designed to allow the installation and removal of the GEE to and from the utility arm. During testing of the GEE handling system, many safety concerns became apparent, including the fact the TRIC had to be fully open to use the system. The original GEE handling system was abandoned, and a new GEE Handling System was designed and built. The new system is a small cart that travels on the TRIC floor. This GEE cart provides six degrees-of-freedom for installing or removing the GEE to and from the utility arm. The GEE cart also holds the GEE inside the TRIC when the GEE is not in use. With this system, the TRIC does not need to be open to use the cart to install or remove the GEE from the utility arm.

The functions and uses of the TRIC were greatly expanded from this initial TRIC design. The utility arm is covered with a silicon rubber boot to provide an isolation barrier and purge air containment for the utility arm. A set of tools was developed for use in the TRIC to allow replacement of this boot. Since this silicon rubber boot is easily damaged, a clear flexible plastic secondary boot was developed to cover the utility arm. This secondary boot covers the utility arm from the GEE to the cameras located inside the inner VPM mast. Because this boot is installed on the utility arm as the arm is deployed into the tank and the boot is removed as the utility arm is retracted from the tank, the TRIC was modified to support the secondary boot operations. Many other changes to the TRIC were made to support the utility arm operations. Including a camera being mounted inside the TRIC to allow the control room operators to view operations inside the TRIC. A small pass-through port was added to the TRIC door to allow tools and supplies to be passed into the TRIC without the TRIC door being open. Changes inside the TRIC included the addition of storage locations for tools and supplies. The TRIC was modified to accept the connection of the THS for either the CEE or the GSEE. The TRIC connection is a port approximately 2 ft (0.61 m) high by 3 ft (0.91 m) wide on the side of the TRIC that faces the MDS. The port is covered with a Lexan plate when the THS is not in use.

During the TTCTF testing, Spar personnel spent two weeks installing and testing software options purchased by ORNL. These software options are used to support function based shared control algorithms (FBSC) developed by Professor T. J. Tarn and associates at Washington University [6]. This is a hybrid controller combining teleoperation with robotic control. The control algorithm allows a path plan for the utility arm to sweep an area of the tank floor but allows the MLDUA operator to modify the path in real time with a joystick to avoid an object in the sweep path. When the operator releases the joystick, the algorithm returns the utility arm to the path point nearest to the point of the joystick release. The FBSC testing was conducted at the TTCTF, but FBSC use has been limited to tank W-3 operations only.

During TTCTF testing, the MLDUA system was tested with the HMA, CSEE, and ROV systems. The testing included grasping of the CSEE with the utility arm when the CSEE was hanging from the HMA hose in mid air, using the CSEE for cleaning the tank floors, and working with the HMA operator to avoid the HMA boom sections when positioning the CSEE with the utility arm. Additional testing was performed using the CSEE and the utility arm for wall scarifying. The GSEE was not available during TTCTF operations. Testing and training were completed for ROV and MLDUA combined operations. For example, testing included passing the CSEE back and forth between the utility arm and the ROV's manipulator and sludge removal using the ROV to plow material to within reach of the utility arm holding the CSEE.

6. NORTH TANK FARM OPERATIONS

The NTF operations consisted of cleaning two (W-3 and W-4) 25-ft (7.62 m) diameter gunite underground storage tanks. The NTF was categorized as a radiological facility rather than a nuclear facility, like the STF. The cleaning of tanks W-3 and W-4 allowed operator training and equipment shakedown in field conditions before moving the equipment to the STF, where radiological hazards were more severe. Therefore, operations at the NTF were conducted as a CERCLA treatability study to demonstrate and evaluate the effectiveness of the tank waste retrieval technology. Operations began in tank W-3 in June 1997 and then proceeded to Tank W-4 in October 1997. An estimated 20,000 gallons (75708 l) of sludge was contained in the two tanks. For both tanks, the MLDUA was deployed into the 24 in. (0.61 m) center tank riser. The HMA was deployed in the east riser for tank W-3 and in the west riser for tank W-4. The ROV was always deployed in the north tank riser.

6.1 Tank W-3

MLDUA operations at tank W-3 began on June 18, 1997, with the initial power up of the equipment. The first utility arm deployment into tank W-3 was performed on June 26. The last utility arm deployment into the tank was performed on September 18. The MLDUA equipment was shut down on September 23 in preparation for the move to tank W-4. The total work time at tank W-3 was 15 weeks. During tank W-3 operations, the MLDUA computer was started 87 times for an operating period of 455 hours. The hydraulic pumps were started 133 times for an operating period of 238 hours. The utility arm was deployed into tank W-3 a total of 20 times with an in-tank-operating period of 686 hours. The utility arm was stored in the vertical orientation overnight or on weekends to reduce operator exposure time to the tank's radiation field. The initial operations inside the tank were for the development and testing of the utility arm deployment and retraction auto joint sequences. The auto joint sequences allow the computer to deploy and retract the utility arm into or out of the tank without operator action.

The CEE THS was attached to the TRIC. The utility arm and GEE, holding the CEE, were deployed into the tank to survey the radiation emission from the wall. The survey was conducted at the following survey points around the perimeter of the tank: 0, 45, 90, 135, 180, 225, 270, and 315 degrees. The 0-degree point was north. The survey was conducted at three elevations within the tank at each survey point: near the floor, mid tank, and near the ceiling. The survey with the CEE was performed before and after the tank wall was scarified. The wall material was sampled with a scraping tool held by the GEE. The wall was sampled before and after it was scarified. The scraping tool consisted of a sharp steel blade with collection cavities to hold the material that was scraped off the wall

The depth of the waste sludge in tank W-3 came into question when the tank level sensors did not agree with the earlier manual surveys. The manual surveys predicted a sludge depth of 4 to 6 in. (10.16 to 15.24 cm). A folding tape ruler, folded out to 36 in. (0.91 m), was attached to the GEE, and the utility arm was deployed vertically into the tank to insert the ruler into the sludge. The utility arm deployment continued until the ruler began to bend under the deployment force. The sludge depth was measured at 24 in. (61 cm). This sludge depth was far too deep for the ROV to be deployed into the tank. The ROV is designed for this sludge depth but due to a flaw in the manufacturing of the ROV tether cable termination seal, the ROV is limited to sludge depths of 6 to 8 in. (15.24 to 20.32 cm). The deployment of the ROV was delayed until the MLDUA, using the CSEE, had removed enough sludge to partially clear a landing zone beneath the ROV tank riser location.

Before the tank wall scarifying began, the tank wall was tested to see if it was vertical. A probe consisting of two parallel 8 in. long flexible fingers was held by the GEE near the tank floor. The probe was pushed against the lower wall until the fingers were bent down about 45 degrees. The VPM was moved vertically upward to drag the bent probe along the wall. As the probe was moved along the wall, the finger angles were checked with the cameras to see if the angles changed. The variation in wall verticality appeared to be less than 0.5 in. (1.27 cm), based on the flexing of the probe. This process was repeated several times at various places on the tank walls.

The tank wall was scarified using the CSEE water cutting jets operating at 6500 psi (448 bars). The CSEE was held in a horizontal orientation, cutting jets toward the wall, about 6 to 12 in. (15.24 to 30.48 cm) from the wall. Using the utility arm auto joint sequence, a scarifying path was programmed for the utility arm to follow. Because the utility arm was deployed in the center tank riser, a path for the CSEE to follow was easily programmed using only the VPM and shoulder yaw joint. The other utility arm joints were kept fixed to keep the CSEE a fixed distance from the wall. The auto joint sequence program consisted of repeating vertical paths that covered 10 to 20 degrees around the tank wall. To ensure that the utility arm would not make contact with the HMA components, the four corners of the wall area to be cleaned were tested for utility arm-HMA collisions. The auto joint sequence was the only safe way to operate the utility arm. Within minutes after starting the scarifying operation, the tank would become so foggy from the aerosol created by the CSEE cutting jets that none of the cameras could be used to view

The MLDUA with the Confined Sluicing End Effector (CSEE) removing sludge from a tank.

the HMA or utility arm. The utility arm held the CSEE for scarifying about 76.5 hours, with about 75% of this time being used to actually scarify the wall.

Using the CSEE, the utility arm attempted to remove just the volume of sludge around the ROV tank riser location. During this sludge removal, it became clear that the sludge depth was in fact 24 in. (61 cm). During the waste removal, the sludge would "flow" back into the volume that needed to be cleaned for the ROV deployment; therefore the utility arm had to remove approximately 80 % of the tank sludge to get the depth to an acceptable level for ROV deployment and operation. The final tank sludge waste was removed by the ROV. It is estimated that approximately 100 gallons (378.5 l) of material, liquid, and sludge was left in tank W-3 after completion of MLDUA and ROV operations.

Two problems developed in the MLDUA system during operations in W-3. The first problem was a hydraulic oil leak within the utility arm. The second was a failed position sensor for the inner VPM tube.

The wrist pitch hydraulic servo control manifold developed an oil leak in one of the fittings to the hydraulic piston. The first indication of a hydraulic oil leak was that the wrist pitch joint drifted when the joint was locked. The second indication was the presence of hydraulic oil inside the clear secondary boot. The utility arm was immediately removed from tank operations. The utility arm was deployed inside a contamination control bag on the W-3 platform outside the TRIC. The utility arm was decontaminated, and repairs proceeded outside the contamination bag. The cause of the leak was a bad "O" ring, which was replaced. After a hydraulic pressure test, the utility arm was returned to service. Within a few days of operation, the same hydraulic oil leak returned. Utility arm operations continued for about a week before the utility arm was again removed from tank operations for repairs. The cause of the oil leak was found to be in the same hydraulic fitting in which the "O" ring failed. Further investigation determined that the hydraulic fitting components were incompatible with each other. The hose end fitting was modified to accept the "O" ring and form a seal. Since the second repair, this hydraulic fitting has not leaked. Approximately five gallons of hydraulic oil leaked from the fitting during the week of utility arm operations. All of the hydraulic oil except approximately one-quart was captured inside the secondary boot. The

GEE camera was found to be damaged during the first leak and the camera was replaced during the second leak repair. The MLDUA system was out of service for a total of two weeks to perform all repairs.

Also during tank W-3 operations, the inner VPM tube reel position sensor tracking cable jumped out of its guide pulleys. The reel position sensor works like a retractable tape measure. When the tracking cable jumped out of its pulleys, the tracking cable became jammed in the pulleys. The inner VPM tube position information needed by the computer was lost. Repairs consisted of returning the tracking cable to the guide pulleys. The camera cable for the VPM mast cameras was attached to the outside of the umbilical cable. This cable formed a loop outside the boundary of the umbilical cable because of umbilical cable motion. This loop had knocked the sensor tracking cable off the pulleys. The loose cable was fastened back to the umbilical cable, and no further problems with the pulleys have been observed.

6.2 Tank W-4

MLDUA operations at tank W-4 began on October 10, 1997, with the initial power up of the equipment. The first utility arm deployment into tank W-4 was performed on October 20. The last utility arm deployment into the tank was performed on February 26, 1998. The MLDUA equipment was shut down on March 5 to prepare for the move to tank W-6. The total work time at tank W-4 was 19 weeks. During tank W-4 operations, the MLDUA computer was started 72 times for an operating period of 445 hours. The hydraulic pumps were started 67 times for an operating period of 304 hours. The utility arm was deployed into tank W-4 a total of 15 times with an in tank operating period of 834 hours. The utility arm was stored in the vertical orientation overnight or on weekends to reduce operator exposure time to the tank's radiation field. Again, the initial operations with the MLDUA were for development and testing of the utility arm deployment and retraction auto joint sequences. The CEE THS was attached to the TRIC. The utility arm and GEE, holding the CEE, were deployed into the tank to survey the radiation emission from the wall. The survey was conducted at the following survey points around the perimeter of the tank: 0, 45, 90, 135, 180, 225, 270, and 315 degrees. The 0 degree point was north. The survey was conducted at three elevations within the tank at each survey point: near the floor, mid tank, and near the ceiling. The survey with the CEE was performed before and after the tank wall was scarified. The wall material was sampled in the same manner as in tank W-3. The tank wall was scarified using the CSEE water cutting jets operating at 6500 psi (448.1 l). The same method used to scarify the walls in tank W-3 was used in W-4. It took about 47% more time to scarify the walls in tank W-4 than it took in tank W-3 (112 hours vs. 76 hours). The additional time needed in W-4 was caused by the problems of the utility arm and HMA working in the same volume and the number of conflicts encountered.

The original depth of the waste sludge in tank W-4 was also in question. The sludge from tank W-3 was consolidated in tank W-4, but before the contents of W-3 were added, the estimated depth of the sludge in tank W-4 was about 12 in. (30.48 cm). After the MLDUA and HMA began operations in tank W-4, an effort was made to clean an area to get to the tank floor to determine the true sludge depth. About 24 to 30 in. (61.0 to 76.2 cm) of sludge was removed when a hard surface was encountered, which was thought to be the tank floor until the surface cracked open. The hard surface turned out to be a hard, crystallized layer of sludge. The true depth of waste sludge in tank W-4 was about 48 in. (122 cm). The utility arm was deployed with a scoop to recover samples of the sludge and hard crystal layer for analysis. Using the CSEE, the utility arm attempted to remove just the volume of sludge around the ROV tank riser location. During waste removal, the sludge would “flow” back into the volume that needed to be cleaned for the ROV deployment; therefore the utility arm and the CSEE were used to remove approximately 90 % of the tank sludge to get the depth to an acceptable level for ROV deployment and operation. The remaining tank sludge waste was removed by the ROV.

It is estimated that approximately 100 gallons (378.5 l) of material, liquid and sludge, was left in tank W-4 after completion of MLDUA and ROV operations.

The MLDUA performed in tank W-4 without any major maintenance or operating problems. One major change was implemented on the MLDUA system. The hydraulic cylinders used for the VPMH X, Y, and roll positioning were changed to mechanical push-pull jacks. This was done because the VPMH would drift from its initial deployment position. The VPMH drift was not noticed during the cold testing, but became noticeable during tank W-3 operations. Because the drifting of the VPMH is not acceptable, the push-pull jacks were installed to keep the VPMH in a fixed position during operations.

7. SOUTH TANK FARM OPERATIONS

The STF operation consisted of cleaning six (W-5, W-6, W-7, W-8, W-9, and W-10) 50-ft (15.24 m) diameter gunite underground storage tanks. The STF is classified as a category 3 nuclear facility. An estimated 8,000 ci in 80,000 gallons (302832 l) of sludge are contained inside the six tanks. Operations began in tank W-6 in April 1998 and proceeded to tanks W-7, W-10, W-8, and finally tank W-9. Tank W-5 was cleaned without the MLDUA system. For all tanks except W-6, W-8, and W-9, the MLDUA was deployed sequentially in each of the four perimeter tank risers that surround a center tank riser. In tanks W-8 and W-9 to reduce the project schedule, the MLDUA was deployed in only the north and south risers. With this two-riser deployment sequence, the wall scarifying by the MLDUA was abandoned.

The HMA was always deployed in the central tank riser. The ROV was installed in the first tank riser in which the MLDUA completed operations. This gave the MLDUA and HMA a chance to clean an area under this first riser to allow the ROV to enter the tank. The MLDUA was moved four times on each platform (except W-8 and W-9) to reach all areas of the tank wall. The other major operations for the MLDUA in the STF were to collect wall scrape samples and to scarify the tank wall and to support the ROV in sludge waste removal. Other MLDUA operations include the tank wall radiation surveys, tank wall material sampling, pipe cutting, and pipe plugging.

Tank W-9 was the collection tank for all solid waste material removed from the NTF and the other five STF tanks. Tank W-9 was the last tank cleaned.

7.1 Tank W-6 Operations

Tank W-6 received an acid waste discharge during its years of waste storage operations. As a result, the walls of tank W-6 showed significant damage to the internal wall surfaces. A decision was made not to clean the tank wall using high-pressure water in the GSEE for fear of causing more wall damage. Only a low-pressure rinse with the GSEE was performed on the walls. For this reason, the MLDUA system was deployed into the north and south risers only.

7.1.1 Tank W-6 North Riser

MLDUA operations at the tank W-6 north riser began on April 9, 1998, with the initial power up of the equipment. The first utility arm deployment into the tank W-6 north riser was performed on April 20. The last utility arm deployment into the tank W-6 north riser was performed on June 2. The MLDUA equipment was shut down on June 8 to prepare for the move to tank W-6 south riser. The total work time at the tank W-6 north riser was ten weeks. During tank W-6 north riser operations, the MLDUA computer was started 43 times for an operating period of 190 hours. The hydraulic pumps were started 54 times for an operating period of 102 hours. The utility arm was deployed into the tank W-6 north riser a total of 16 times with an in-tank operating period of 489 hours. As in past operations, the utility arm was stored in the vertical orientation overnight or on weekends to help reduce operator exposure time to the tank's radiation field. The first operation in tank W-6 with the utility arm was to perform the radiation survey of the tank wall with the CEE. Then, samples of loose wall material were collected using the wall-sampling tool held by the utility arm. The samples were sent to an ORNL analytical laboratory for analysis. A 4 ft long probe was deployed into the tank by the utility arm to probe, pick, and test the strength of the wall material, especially in the areas that showed the most damage from the acid waste. GSEE testing began at high pressures in limited wall areas to determine whether the wall was solid. The GSEE was used to rinse off the wall in all other areas. After the wall was rinsed, the CEE was deployed to survey the tank wall to determine the effectiveness of the wall cleaning. The utility arm was deployed into the tank with the long probe equipped with a rake head to test for any hidden objects under the riser that the ROV will use for its deployment. This check was to ensure that the ROV tracks would not become entangled with wires or pipes. The MLDUA was also used in support of the testing of the HMA and CSEE. This testing continued for about a week, which required the MLDUA to hold the CSEE in mid air. No tank waste was removed at this time.

The utility arm was used to install an ORNL designed pipe plug onto the end of the 3-in. overflow pipe between tanks W-5 and W-6. The pipe was known for leaking water into the tank after a rain. No leakage into the tank has been observed since the pipe plug was installed on the pipe.

The MLDUA system was used to test the wall-coring end effector (WCEE). The WCEE is designed to drill and recover wall core samples from the tank walls. The WCEE is a custom tool that uses a commercial coring tool modified to include a water pressure chamber to push the coring drill bit into the wall. When the water pressure is removed, springs compressed by the water pressure chamber are relieved and force the coring drill bit out of the wall. The wall core sample is captured inside the coring drill bit. Testing of the WCEE with the utility arm demonstrated that the arm was not stiff enough for core sampling. The VPM is a flexible structure, and the WCEE deflects the VPM away from the wall instead of moving the coring drill bit into the wall. The utility arm is used to insert the WCEE into the tank for the ROV to grasp and use. The utility arm is also used to remove the WCEE from the tank.

The MLDUA system had a major failure during operation at this riser. A stepper motor drives the utility arm's wrist roll joint. The motor amplifier that drives the wrist roll joint is located in the HPU computer cabinet. During utility arm deployment and retraction operations into and out of the tank riser, the motor amplifier would fault because of a short in the motor drive cabling. Testing determined that the fault was from a motor drive power conductor shorting to the shield surrounding the power conductors. It was also determined that the fault occurred at a specific location in the umbilical cable as the cable travels over the cable guide pulley at the top of the VPMH. Once the umbilical cable passed this location on the pulley, the wrist roll joint operated normally.

Operation of the MLDUA system continued even though the wrist roll joint was out of service. A control circuit was wired between the OCT and the HPU to allow the MLDUA operator to turn on or off the wrist roll amplifier as required to support utility arm operations during deployment and retraction operations. Once inside the tank, the utility arm performed normally. Operations of the wrist roll joint degraded during tank W-6 south riser operations and failed during early tank W-7 operations. The loss of the wrist roll has not stopped the MLDUA system from performing its required tasks. The MLDUA operating tasks were still performed, but required advance planning by the MLDUA operators for the desired operating location of the wrist roll joint, which was adjusted manually inside the TRIC prior to deployment.

7.1.2 Tank W-6 South Riser

MLDUA operations at the tank W-6 south riser began on June 15, 1998, with the initial power up of the equipment. The first utility arm deployment into the tank W-6 south riser was performed on June 16. The last utility arm deployment into the tank W-6 south riser was performed on August 21. The MLDUA equipment was shut down on August 24 to prepare for the move to the tank W-7 south riser. The total work time at the tank W-6 south riser was eleven weeks. During tank W-6 south riser operations, the MLDUA computer was started 50 times for an operating period of 301 hours. The hydraulic pumps were started 81 times for an operating period of 199 hours. The utility arm was deployed into the tank W-6 south riser a total of 20 times with an in-tank-operating period of 664 hours. As in the north riser, the utility arm was stored in the vertical orientation overnight or on weekends. Operations in the south riser were basically the same as those in the north riser. The only change was that sluicing began to remove the waste from the tank. Thus, the MLDUA, HMA, CSEE, and ROV were all operating. The utility arm held the CSEE and let the ROV push the sludge waste to the CSEE.

7.2 Tank W-7 Operations

Unlike the tank W-6 walls, the tank W-7 walls showed no damage from contact with the waste material. The MLDUA system was deployed at each tank riser starting in the south riser.

7.2.1 Tank W-7 South Riser

MLDUA operations at the tank W-7 south riser began on September 15, 1998, with the initial power up of the equipment. The first utility arm deployment into the tank W-7 south riser was performed on September 18. The last utility arm deployment into the tank W-7 south riser was performed on November 6. The MLDUA equipment was shut down on November 6 to prepare for the move to the tank W-7 west riser. The total work time at the tank W-7 south riser was eight weeks. During tank W-7 south riser operations, the MLDUA computer was started 30 times for an operating period of 143 hours. The hydraulic pumps were started 35 times for an operating period of 98 hours. The utility arm was deployed into the tank W-7 south riser a total of 22 times with an in tank operating period of 195 hours. As in tank W-6, the utility arm was stored in the vertical orientation overnight or on weekends. Operations in this riser were routine. The tank wall radiation levels were surveyed with the CEE, the wall-scraping tool was used to collect wall material for analysis, and the GSEE was used at 6500 psi (448.1 bars) to clean the wall surface. After the wall was cleaned, the CEE was again used to survey the wall to see if the wall radiation levels had decreased. A pipe-cutting end effector (PCEE) was deployed and used for the first time on a vertical pipe near the riser. The PCEE is a modified portable bandsaw and worked well cutting the pipe into smaller sections. After cutting this pipe, the pipe fell from the ceiling and into the bandsaw blade loop, which trapped the PCEE inside the tank. The utility arm was used to break the blade to free the PCEE. Before moving to the next tank riser, waste sludge was removed using the utility arm, CSEE, and HMA to create a path in the sludge from the south riser to the HMA located in the tank center riser. The ROV can not operate in deep levels of sludge, and this path was used by the ROV to travel to and grasp the CSEE hanging from the HMA.

7.2.2 Tank W-7 West Riser

MLDUA operations at the tank W-7 west riser began on November 13, 1998, with the initial power up of the equipment. The first utility arm deployment into the tank W-7 west riser was performed on November 17. The last utility arm deployment into the tank W-7 west riser was performed on December 3. The MLDUA equipment was shut down on December 4 to prepare for the move to the tank W-7 north riser. The total work time at the tank W-7 west riser was four weeks. During tank W-7 west riser operations, the MLDUA computer was started 15 times for an operating period of 77 hours. The hydraulic pumps were started 33 times for an operating period of 50 hours. The utility arm was deployed into the tank W-7 west riser a total of 13 times with an in-tank-operating period of 170 hours. As in tank W-6, the utility arm was stored in the vertical orientation overnight or on weekends.

Operations in the west riser followed almost exactly the operations in the south riser except that no waste sludge was removed. Only tank wall cleaning and pipe cutting were performed. The PCEE was used successfully to cut another pipe.

7.2.3 Tank W-7 North Riser

MLDUA operations at the tank W-7 north riser began on December 11, 1998 with the initial power up of the equipment. The first utility arm deployment into the tank W-7 north riser was performed on December 15. The last utility arm deployment into the tank W-7 north riser was performed on February 11. The MLDUA equipment was shut down on February 23 to prepare for the move to the tank W-7 east riser. The total work time at the tank W-7 north riser was eleven weeks. During tank W-7 north riser operations, the MLDUA computer was started 47 times for an operating period of 223.7 hours. The hydraulic pumps were started 66 times for an operating period of 165 hours. The utility arm was deployed into the tank W-7 north riser a total of 19 times with an in-tank-operating period of 768 hours. As in tank W-6, the utility arm was stored in the vertical orientation overnight or on weekends. Operations in the north riser followed almost exactly the operations in the south riser including waste sludge removal.

7.2.4 Tank W-7 East Riser

MLDUA operations at the tank W-7 east riser began on March 1, 1999 with the initial power up of the equipment. The first utility arm deployment into the tank W-7 east riser was performed on March 2. The last utility arm deployment into the tank W-7 east riser was performed on March 26. The MLDUA equipment was shut down on March 30 to prepare for the move to the tank W-10 northwest riser. The total work time at the tank W-7 east riser was four weeks. During tank W-7 east riser operations, the MLDUA computer was started 25 times for an operating period of 147.63 hours. The hydraulic pumps were started 39 times for an operating period of 102 hours. The utility arm was deployed into the tank W-7 east riser a total of 19 times with an in-tank-operating period of 303 hours. As in previous risers, the utility arm was stored in the vertical orientation overnight or on weekends.

Operations in the east riser followed almost exactly the operations in the south riser including wall cleaning and waste sludge removal.

7.3 Tank W-10 Operations

Tank W-10 contained a large volume of sludge with a large concentration of radioactive material. The walls showed no damage from contact with the waste material. Tank W-10 was initially thought to be a challenging tank to clean due to the volume and the activity of the sludge but once the sludge removal began it was discovered that the sludge flowed freely and easily. The MLDUA system was deployed at each tank riser starting in the southwest riser.

A major modification was made to the MLDUA system during the shutdown from Tank W-7 to W-10. A separate hydraulic pump was added to the system to provide hydraulic pressure for the Gripper End Effector (GEE Pump or GEEP). The two horsepower motor-powered constant-pressure variable flow hydraulic pump supplied 2500 psi fluid to the GEE gripper to hold the gripper closed. This pump allowed the GEE to hold a tool without the need for the main hydraulic pump or the computer system to be operating. The GEEP allowed the holding of a tool (i.e. CSEE or GSEE) overnight and over the weekends. The longest period of time for holding a tool was on tank W-9 when the GEE held the CSEE for 21 days. No tool was ever dropped due to a failure of the GEEP.

7.3.1 Tank W-10 Northwest Riser

MLDUA operations at the tank W-10 northwest riser began on May 11, 1999, with the initial power up of the equipment. The first utility arm deployment into the tank W-10 northwest riser was performed on May 13. The last utility arm deployment into the tank W-10 northwest riser was performed on June 21. The MLDUA equipment was shut down on June 23 to prepare for the move to the tank W-10 northeast riser. The total work time at the tank W-10 northwest riser was six weeks. During tank W-10 northwest riser operations, the MLDUA computer was started 31 times for an operating period of 415 hours. The hydraulic pumps were started 54 times for an operating period of 83 hours. The utility arm was deployed into the tank W-10 northwest riser a total of 17 times with an in tank operating period of 473 hours. The GEEP was started a total of 12 times with an operating period of 236 hours.

As in previous tanks, the utility arm was stored in the vertical orientation overnight or on weekends when the GEE was not holding a tool. Operations in this riser were routine in nature. The tank wall radiation levels were surveyed with the CEE, the wall-scraping tool was used to collect wall material for analysis, and the GSEE was used at 6500 psi (448.1 bars) to clean the wall surface.

7.3.2 Tank W-10 Northeast Riser

MLDUA operations at the tank W-10 northeast riser began on July 1, 1999, with the initial power up of the equipment. The first utility arm deployment into the tank W-10 northeast riser was performed on July 9. The last utility arm deployment into the tank W-10 northeast riser was performed on July 27. The MLDUA equipment was shut down on July 28 to prepare for the move to the tank W-10 southeast riser. The total work time at the tank W-10 northeast riser was four weeks. During tank W-10 northeast riser operations, the MLDUA computer was started 9 times for an operating period of 261 hours. The hydraulic pumps were started 30 times for an operating period of 54.5 hours. The utility arm was deployed into the tank W-10 northeast riser a total of 9 times with an in-tank-operating period of 179 hours. The GEEP was started a total of 11 times with an operating period of 191.5 hours. As in previous tanks, the utility arm was stored in the vertical orientation overnight or on weekends. Operations in the northeast riser followed almost exactly the operations in the northwest riser.

7.3.3 Tank W-10 Southeast Riser

MLDUA operations at the tank W-10 southeast riser began on August 4, 1999, with the initial power up of the equipment. The first utility arm deployment into the tank W-10 southeast riser was performed on August 10. The last utility arm deployment into the tank W-10 southeast riser was performed on August 20. The MLDUA equipment was shut down on August 20 to prepare for the move to the tank W-10 southwest riser. The total work time at the tank W-10 southeast riser was two weeks. During tank W-10 southeast riser operations, the MLDUA computer was started 13 times for an operating period of 169 hours. The hydraulic pumps were started 20 times for an operating period of 41 hours. The utility arm was deployed into the tank W-10 southeast riser a total of 7 times with an in-tank-operating period of 135 hours. The GEEP was started a total of 7 times with an operating period of

141 hours. As in previous tanks, the utility arm was stored in the vertical orientation overnight or on weekends. Operations in the southeast riser followed almost exactly the operations in the northwest riser.

7.3.4 Tank W-10 Southwest Riser

MLDUA operations at the tank W-10 southwest riser began on August 30, 1999, with the initial power up of the equipment. The first utility arm deployment into the tank W-10 southwest riser was performed on August 31. The last utility arm deployment into the tank W-10 southwest riser was performed on October 27. The MLDUA equipment was shut down on October 28 to prepare for the move to the tank W-8 south riser. The total work time at the tank W-10 southwest riser was nine weeks. During tank W-10 southwest riser operations, the MLDUA computer was started 18 times for an operating period of 322 hours. The hydraulic pumps were started 37 times for an operating period of 79 hours. The utility arm was deployed into the tank W-10 southwest riser a total of 18 times with an in-tank-operating period of 309 hours. The GEEP was started a total of 19 times with an operating period of 261 hours. As in previous tanks, the utility arm was stored in the vertical orientation overnight or on weekends. Operations in the southwest riser followed almost exactly the operations in the northwest riser.

7.4 Tank W-8 Operations

The tank W-8 was the tank that contained a volume of sludge with large a concentration of radioactive material. The tank W-8 walls showed no damage from contact with the waste material.

After the MLDUA was deployed into the south riser, a decision was made not to deploy the MLDUA into the east and west risers to push the project schedule forward. Even though the walls of this tank were considered the highest in embedded contamination, the decision was made not to clean the tank walls using the MLDUA. An alternative approach was developed using a Linear Scarifying End-Effector (LSEE). A separate paper describes the LSEE [7].

7.4.1 Tank W-8 South Riser

MLDUA operations at the tank W-8 south riser began on November 8, 1999, with the initial power up of the equipment. The first utility arm deployment into the tank W-8 south riser was performed on November 18. The last utility arm deployment into the tank W-8 south riser was performed on December 16. The MLDUA equipment was shut down on December 17 to prepare for the move to the tank W-8 north riser. The total work time at the tank W-8 south riser was five weeks. During tank W-8 south riser operations, the MLDUA computer was started 21 times for an operating period of 347 hours. The hydraulic pumps were started 36 times for an operating period of 53 hours. The utility arm was deployed into the tank W-8 south riser a total of 10 times with an in tank operating period of 338 hours. The GEEP was started a total of 10 times with an operating period of 294 hours.

As in previous tanks, the utility arm was stored in the vertical orientation overnight or on weekends when the GEE was not holding a tool. Operations in this riser were routine except wall cleaning was not performed. The tank wall radiation levels were surveyed with the CEE and the wall-scraping tool was used to collect wall material for analysis. The CEE survey did confirm that the tank walls did contain high concentrations of embedded contamination.

7.4.2 Tank W-8 North Riser

MLDUA operations at the tank W-8 north riser began on January 3, 2000, with the initial power up of the equipment. The first utility arm deployment into the tank W-8 north riser was performed on January 6. The last utility arm deployment into the tank W-8 north riser was performed on March 23. The MLDUA equipment was shut down on March 24 to prepare for the move to the tank W-9 south riser. The total work time at the tank W-8 north riser was twelve weeks. During tank W-8 north riser operations, the MLDUA computer was started 24 times for an operating period of 532 hours. The hydraulic pumps were started 42 times for an operating period of 77 hours. The utility arm was deployed into the tank W-8 north riser a total of 16 times with an in-tank-operating period of 512 hours. The GEEP was started a total of 11 times with an operating period of 496 hours. As in previous tanks, the utility arm was stored in the vertical orientation overnight or on weekends when the GEE was free of tools. Operations in the north riser followed almost exactly the operations in the south riser.

7.5 Tank W-9 Operations

The tank W-9 was the collection tank for tanks W-3, W-4, W-5, W-6, W-7, W-8, and W-10. Some of the material in W-9 was earlier transferred to the treatment and storage facility at Melton Valley. The sludge material was mixed with flight mixer pumps and pumped with a disk-flow pump to Melton Valley. The estimated amount of remaining sludge in tank W-9 was about 36 to 48 inches deep.

Following the reasoning as used on tank W-8, the decision was made not to deploy the MLDUA into the east and west risers to push the project schedule forward. The decision was made not to clean the tank walls with the MLDUA.

7.5.1 Tank W-9 South Riser

MLDUA operations at the tank W-9 south riser began on May 22, 2000, with the initial power up of the equipment. The first utility arm deployment into the tank W-9 south riser was performed on June 13. The last utility arm deployment into the tank W-9 south riser was performed on August 3. The MLDUA equipment was shut down on August 4 to prepare for the move to the tank W-9 north riser. The total work time at the tank W-9 south riser was eleven weeks. During tank W-9 south riser operations, the MLDUA computer was started 24 times for an operating period of 866 hours. The hydraulic pumps were started 50 times for an operating period of 102 hours. The utility arm was deployed into the tank W-9 south riser a total of 15 times with an in tank operating period of 901 hours. The GEEP was started a total of 14 times with an operating period of 778 hours.

As in previous tanks, the utility arm was stored in the vertical orientation overnight or on weekends when the GEE was not holding a tool. Operations in this riser were routine except wall cleaning was not performed. The tank wall radiation levels were not surveyed with the CEE. The in tank camera system could not see the CEE radiation LCD display.

7.5.2 Tank W-9 North Riser

MLDUA operations at the tank W-9 north riser began on August 10, 2000, with the initial power up of the equipment. The first utility arm deployment into the tank W-9 north riser was performed on August 11. The last utility arm deployment into the tank W-9 north riser was performed on September 13. The MLDUA equipment was shut down on September 14 to prepare for equipment removal from the tank farm. The total work time at the tank W-9 north riser was five weeks. During tank W-9 north riser operations, the MLDUA computer was started 6 times for an operating period of 531 hours. The hydraulic pumps were started 28 times for an operating period of 83 hours. The utility arm was deployed into the tank W-9 north riser a total of 14 times with an in-tank-operating period of 533 hours. The GEEP was started a total of 10 times with an operating period of 529 hours. As in previous tanks, the utility arm was stored in the vertical orientation overnight or on weekends when the GEE was free of tools. Operations in the north riser followed almost exactly the operations in the south riser.

8. MLDUA SYSTEM PERFORMANCE

The MLDUA system performed very well for the time period required to clean the underground tanks W-3, W-4, W-6, W-7, W-10, W-8, and W-9, especially considering the environment in which the utility arm was operated.

At final equipment shutdown, the final operating statistics included the following operating information. The MLDUA computer was started 665 times with operating times of more than 6387 hours. The hydraulic system was started 1159 times with operating times of more than 2256 hours. The GEE pump was started 94 times with operating times of more than 3225 hours. The VPM Housing was raised a total of 43 times with a total of 44 VPM deployments off the storage limit switches. The GEE was attached to the robot arm Tool Interface Plate (TIP) a total of 20 times. The robot arm was deployed into a tank a total of 250 times with an in-tank operating time of 7418 hours. The GEE grasped the CSEE 127 times with holding times of more than 2865 hours. The GEE grasped the GSEE 52 times with holding times of more than 1159 hours. The GEE grasped the CEE or other tools 98 times with holding times of more than 1045 hours. The GEE held a tool of some sort for a total of 5069 hours. The Decon Spray Ring was turned on 131 times for a spray down time of 7.8 hours. The estimated dose of radiation received by the MLDUA (as measured with a dosimeter located inside the outer clear boot) was 77,000 R shallow dose and 32,000 R deep dose.

Considering that the MLDUA system is a one-of-a-kind machine, the MLDUA system performed remarkably well for a fielded machine performing radioactive cleanup work.

Three similar systems, the light duty utility arm (LDUA) systems were delivered to PNNL and Idaho National Energy and Engineering Laboratory. The MLDUA system did benefit in the design and fabrication process from being the third system delivered by Spar Aerospace. This allowed Spar Aerospace to benefit from a steep learning curve before delivering the MLDUA system to ORNL. The major differences between the MLDUA and LDUA systems are an extended reach, higher payload, and different wrist kinematics. The MLDUA and one of the LDUA systems are mounted on outriggers for craning into position rather than mounted on the bed of a truck.

The MLDUA system was used successfully in operations with the following tools: CSEE, GSEE, CEE, PCEE, pipe plugs, wall-sampling tools, waste sludge sampling tools, wall probes, and sludge-depth probes. The MLDUA system also supported operations with the ROV using the WCEE and with the HMA and ROV in sludge sluicing and wall-scarifying operations.

The MLDUA system robotic operating mode was used mostly for tank deployment and retraction operations, wall-scarifying operations, and some CEE operations. The system telerobotic operating mode was used for general motion operations inside the tank, which includes sluicing operations, pipe plugging and cutting operations, and sampling operations.

The MLDUA system is capable of returning the utility arm and the tool the arm is holding to a known point in space inside the tank to a degree of repeatability which approaches ± 0.25 in. (0.63 cm). This repeatability is required for reliability of the CEE and wall material sampling operations. Although the MLDUA system failed to operate the WCEE because the VPM was not stiff enough to allow the WCEE to work, that same lack of stiffness protected the utility arm from damage when the utility arm collided with the HMA or the tank wall and floor. Upon collisions, the flexibility of the utility arm and VPM allows the collision force to deflect the utility arm in a new direction. No utility arm damage was observed.

9. DESIGN LESSONS

The following lessons were learned during the operation of the MLDUA system.

The TRIC was not optimally designed. A full understanding of the TRIC tasks and frequency of tasks was not fully clear when the TRIC design started. Many tasks were retrofitted into the TRIC, whereas, if the tasks were fully understood up front a much better and supportive TRIC could have been designed. The TRIC had to support GEE installation and removal from the robot arm, robot arm primary boot replacement, secondary boot handling, wall coring tool, THS interface, GSEE operations, and decon operations.

The VPM Housing as designed by SPAR had some design shortcomings. While the VPM Housing operated very well, the following design oversights caused operating problems. Changing the oil in the two VPM winches should have been designed to be performed without breaking containment. Internal instrumentation should have been accessible, where practical, without breaking containment. The base of the VPM housing (in vertical orientation) should have been designed to collect loose hydraulic oil and prevent the oil from leaking though the VPM Housing deployment port. The umbilical cable should not have the hydraulic hoses in contact with the electrical cables.

The GEE would have been much more useful if the gripper had a variable closing and opening position control. The GEE gripper operated either fully open or fully closed. Lack of variable gripper position control was a tradeoff made during preliminary design to save on development cost.

The HMI display screens were too complex and busy. For example, to start the hydraulic pumps and unlock the robot arm required the operator to visit four HMI screens. The warning system although very useful could be improved. Once announcing its presence on the HMI, there was not a time blocking feature to prevent the warning from continuously alarming at the HMI.

The HPU required modifications to the hydraulic oil reservoir heater control with the addition of a stand-alone temperature controller for the heaters. The E-stop system was modified to ensure that an E-stop would stop the hydraulic pumps, not including the separate GEE pump.

Currently, the MLDUA is searching for a new home within the DOE complex.

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