

Development and Deployment of the Mobile Arm Retrieval System (MARS) - 12187

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC27-08RV14800



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Development and Deployment of the Mobile Arm Retrieval System (MARS) - 12187

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ABSTRACT

Washington River Protection Solutions (WRPS) is developing and deploying Mobile Arm Retrieval System (MARS) technologies solutions to support retrieval of radioactive and chemical waste from underground single shell storage tanks (SST) located at the Hanford Site, which is near Richland, Washington. WRPS has developed the MARS using a standardized platform that is capable of deploying multiple retrieval technologies. To date, WRPS, working with their mentor-protégé company, Columbia Energy and Environmental Services (CEES), has developed two retrieval mechanisms, MARS-Sluicing (MARS-S) and MARS-Vacuum (MARS-V). MARS-S uses pressurized fluids routed through spray nozzles to mobilize waste materials to a centrally located slurry pump (deployed in 2011). MARS-V uses pressurized fluids routed through an eductor nozzle. The eductor nozzle allows a vacuum to be drawn on the waste materials. The vacuum allows the waste materials to be moved to an in-tank vessel, then extracted from the SST and subsequently pumped to newer and safer double shell tanks (DST) for storage until the waste is treated for disposal. The MARS-S system is targeted for sound SSTs (i.e., non leaking tanks). The MARS-V is targeted for assumed leaking tanks or those tanks that are of questionable integrity. Both versions of MARS are being/have been developed in compliance with WRPS's TFC-PLN-90, *Technology Development Management Plan* [1]. TFC-PLN-90 includes a phased approach to design, testing, and ultimate deployment of new technologies. The MARS-V is scheduled to be deployed in tank 241-C-105 in late 2012.

INTRODUCTION/BACKGROUND

Since 1999, thirteen (C-103, C-104, C-106, C-108, C-109, C-110, C-111, C-201, C-202, C-203, C-204, S-102, and S-112) Hanford Site SSTs have undergone retrieval operations. Hanford's 149 SSTs range in size from 55 thousand to 1 million gallons (208,198 to 3,785,411 liters) in capacity. Seven tanks have been emptied and six others have been partially emptied. The retrieval technology deployed in those tanks left residual volumes greater than are allowed in order to declare the tanks ready for closure.

The MARS was conceived by WRPS to retrieve all waste types from the Hanford Site SSTs with a single technology to below the residual volume requirements per the *Hanford Federal Facility Agreement and Consent Order* (HFFACO) (Ecology et al. 1989) [2]. The HFFACO requires that the residual volume be equal to or less than 360 cubic feet (approximately 2,700 gallons, or 10,220 liters).

The MARS-S has been deployed in tank 241-C-107 (C-107). To deploy the MARS-S, a new 47-inch (119-cm) riser was designed and installed into the dome of C-107. This required the cutting of a 55-inch (140-cm) diameter hole in the tank dome, making it the largest hole ever cut into an active U.S. Department of Energy radioactive waste storage tank. MARS-S is unique as the system is installed in specific sequence and subassembly by subassembly. Normal tank installations are usually simpler, and can be completed with single actions. The MARS-S installation required multiple installation activities, and a puzzle-like assembly process. After the successful installation and system checks, MARS became operational in September 2011.

Phase 2 Qualification Testing, per TFC-PLN-90, was completed on the MARS-V in September 2010. The purpose of Phase 2 Qualification Testing was to verify that the system meets the intended performance and functional criteria. Ultimately, the MARS-V will be deployed in Tank 241-C-105.

The presentation includes discussion of the design and development of the MARS-S Unit, design and installation of the 47-inch (119-cm) riser in C-107, the unique installation sequence for MARS, the operational experience gained in C-107, and the current development status of the MARS-V.

NEW LARGE RISER

The tank selected for the initial deployment (C-107), required a minimum access of a 42-inch riser (107-cm) located in the center of the tank. This required removal of an existing caisson and 12-inch (30.5-cm) riser, followed by the remote control cutting of a larger opening in the dome and installing a new large riser.

Tank Analysis and Riser Design

The key design activities for the new riser installation included an analysis of the tank modification to add a new larger penetration and the large riser assembly itself.

The analysis of the tank was performed with support from Pacific Northwest National Laboratory (PNNL) and is documented in RPP-CALC-43416, *An Evaluation of Single-Shell Tank 241-C-107 for the Addition of a Large Penetration in the Tank Dome* [3]. The focus of the analysis was evaluation of the dome condition after installation of a new 55-inch (140-cm) penetration.

This was achieved by using existing ANSYS structural models of an SST and DST. Key considerations included analyzing for the changes in stress levels in the dome with the new penetration and an operational moment that could potentially be introduced during the operation of the MARS. The stress analysis concluded that hoop stress does increase near the location of the penetration; however, the overall configuration of the dome was not significantly impacted by installation of the new penetration nor the new riser. The operational moment that could potentially be introduced by the operating equipment was also reviewed and found to have a negligible effect on the forces and moments in the tank dome.

Design of the riser required special considerations. Due to the radiation and industrial hazards, the riser had to be capable of being remotely installed. This was achieved by developing an installation assembly that allowed for majority of the back fill to be completed prior to cutting the hole and installing the riser. A caisson installed on

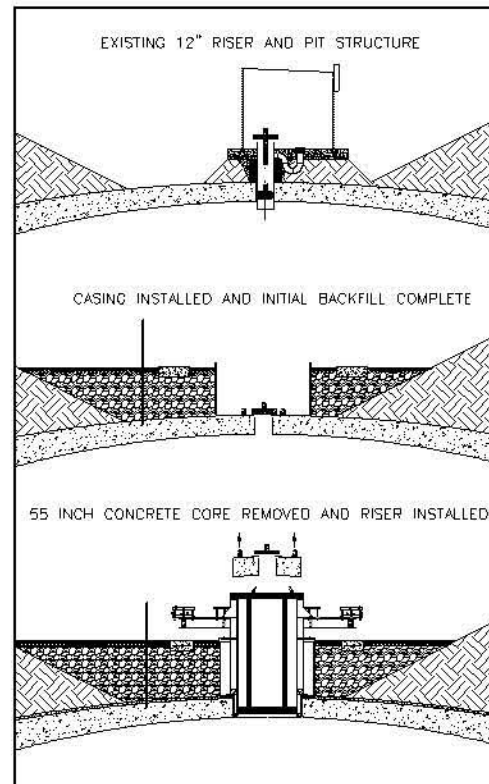


Fig. 1. Partial Riser Installation Sequence.

the dome would allow for the backfilling of the surrounding area prior to cutting the hole. The riser was designed with an I-Beam structure (coupled with mechanical jacks) to allow the assembly to be supported by the soil and not directly point load the dome. A partial installation sequence that illustrates the above description is shown in Fig. 1. In the figure, a 42-inch (107-cm) tall casing is shown located on the tank dome and is maintained with a separation distance of approximately 1 inch (2.54 cm) from the riser structure. This separation distance prevents direct loading of the dome through the casing and allows the loading to be distributed to the soil. Included in the assembly are steel embeds at eight specific locations to support the bearing points of the MARS containment box. All of the embeds and the riser position was set at specific elevations to maintain needed clearance. The overall assembly when set into place on the dome provided immediate shielding from the tank contents. Fig. 2 shows a cross section of the installed riser in the tank dome and a photo of the riser.

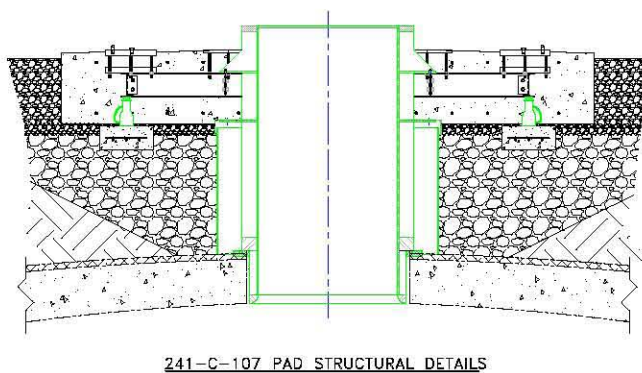


Fig. 2. Cross section of the installed riser in the tank dome.

Tank Cutting Technique

Installation of a new large riser required a new penetration to be added to the tank. A construction method study for the installation of a large riser was performed to select the best approach for cutting a larger opening in an SST. The process for evaluation was performed in a two stage approach. The first stage identified commercially available cutting technologies. The identified technologies were pre-screened to determine whether or not the technology would be considered for further evaluation. Key considerations during the pre-screening included:

- Commercially available
- Existing industry experience
- Expected cutting performance
- Adaptability to a nuclear environment.

During this first stage, some of the technologies were qualitatively dismissed for reasons related to cutting effectiveness, practicality associated with remote operations, worker safety, and contamination control or process control. The second stage took the remaining technologies through a ranking process with established criteria. Abrasive waterjet cutting was ultimately selected for the cutting technology.

The abrasive water jet utilizes a mixture of high pressure water and abrasive to cut through reinforced concrete. Common industry pressures and flow rates used for large scale cutting activities range from 30,000 to 50,000 pounds per square inch (207 to 345 megapascal) and 3 to 5 gallons per minute (11.4 to 18.9 liters/min). The process includes pressurizing the water

with a positive displacement pump and passing the water through a jewel orifice into a mixing chamber where garnet is introduced. The mixture of garnet and water is then expelled through a focusing tube to atmosphere and impacts the surface to be cut. The high velocity mixture removes material creating a kerf. The process for performing an abrasive water jet cutting can be summarized as installing a cutting track to guide the cutting head along the path desired, preparing a pilot (starter) hole, and moving the cutting head steadily around the track cutting all the way through the reinforced concrete in a single pass.

The application of the abrasive water jet to the top of the tank dome required special considerations and adaptations. The tool needed to have the capability of being remotely installed and have redundancy in the cutting heads to prevent the need for entry into the cutting area after the cut was initiated. This was accomplished by mounting multiple cutting heads on a large circular ring driven by a pneumatic motor. The large ring was precision machined to provide a round cut in the reinforced concrete. Air cylinders were also employed to aid in leveling the unit and holding it in place during the cutting activity. The multiple head design allowed for changing of the cutting heads without needing to access the area and the ring design allowed the tool to be deployed remotely. A photo of the cutting tool utilized to cut the tank dome is shown in Fig. 3. During the cutting activity, both the water and garnet flow into the SST and become part of the waste inventory.



Fig. 3. Cutting tool utilized to cut the tank dome.

Mockups

During the process of developing the equipment and preparing for the field activities, several mockups were conducted to optimize operating parameters and practice the installation techniques. The mockup activities that played the biggest role in the project were optimization of the cutting technology, field demolition, and riser installation.

During the process of the development of the cutting technology, several mockups were performed to refine the drive mechanism and to determine the optimum cutting parameters for the water jet. These mockups were critical for determining the maximum cutting speed required to ensure all of the concrete and reinforcing material was cut. Key resulting parameters included pump pressure of 48,000 pounds per square inch gauge (331 megapascal), use of Barton 36 CG garnet at 1.4 pounds per minute (635 gm/min), and a cutting head advance rate of 8 inches per hour (20.3 cm/hr). For each of the test cuts, a simulated dome section was created which closely matched the expected tank dome configuration. As a result of the refinements and up front work, a tool was created that would cut a near perfect circle (at a steady rate) while controlled from a remote location while minimizing the use of the abrasive.

Prior to accessing the dome, the existing equipment located on the tank required removal. This removal involved an existing pit containing old equipment and residual waste. To support this

effort, a replica of the expected pit configuration was fabricated (from existing drawings) in a clean area. This provided the opportunity to test different tools and develop the strategy for demolition that would remove the abandoned equipment while protecting the tank integrity.

As described previously, the installation of the riser involved setting a caisson performing backfilling, cutting the tank dome, removing the concrete plug, and installing the riser. This process was practiced using mockups in a clean area which allowed completion of each step. This provided the field crew real time practice with the equipment that would be utilized in the field. A key part of the installation of the riser involved the use of a GPS positioning system to guide the riser into the new tank penetration. This tooling allowed personnel to be located away from the hole during the placement of the riser.

Field Installation

The actual tank cut and installation of the large riser was performed in December 2010. The time required for the cut was approximately 21 hours to cut the 55-inch (140-cm) diameter plug from the 15-inch (38.1 cm) thick reinforced concrete dome. This was accomplished using approximately 2,530 lbs (1148 kg) of garnet material and approximately 3,800 gallons (14,385 liters) of water. After bagging and removal of the concrete plug, the large riser was installed and leveled (Fig. 4). This installation was followed by the placement and finishing of the reinforced concrete pad and surrounding backfill, restoring the grade. The overall process of cutting and installation of the riser went as planned. As a result of the field installation, potential improvements were identified by the project. Two key improvements are moisture control in the compressed air system and hose management of the cutting device. During the cut, ambient temperatures fell below freezing causing moisture problems in the compressed air stream. Increasing the capabilities of the moisture removal system on the compressors is expected to significantly reduce this problem for future activities. It was also noted that the water and garnet supply hoses for the cutting head could benefit from being longer and possible pre-wrapped to reduce the chances for restricting the cutting head movement.

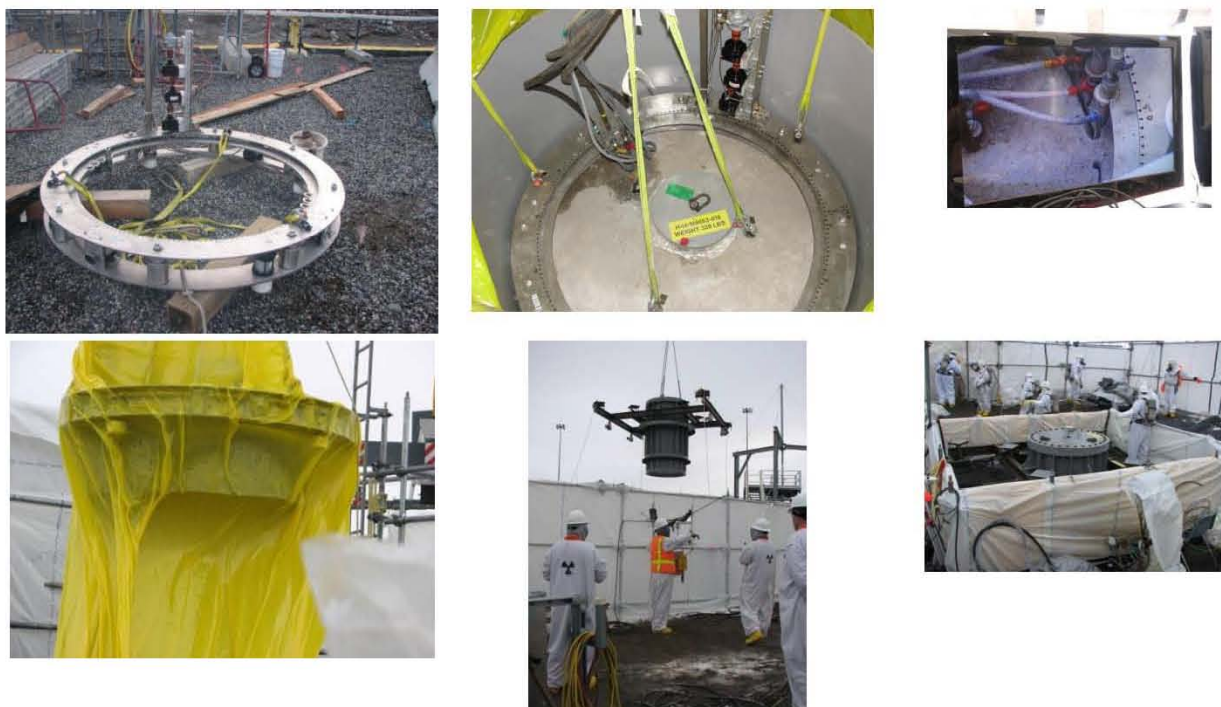


Fig. 4. Visual timeline of the field installation.

Mobile Arm Retrieval System-Sluice Mode (MARS-S)

The MARS is a telerobotic arm-based retrieval system. The MARS-S is made up of the following major subsystems:

- A containment box
- A vertical mast
- A telescoping arm, carriage and wrist/end effector
- A slurry transfer
- Pump backstop
- A portable instrument and valve box
- Two high-pressure water skids (trailers)
- In-tank viewing system
- Electrical /arm hydraulic power unit (HPU) skid and slurry transfer pump HPU
- In-tank hose management.

The MARS-S can be deployed in nearly any sound Hanford Site SST with a large diameter central riser. The MARS-S is designed to accomplish retrieval to the limits required by regulatory agreements. The MARS-S mobilizes and retrieves SST waste using spray nozzles on an end-effector at the end of a telescoping arm and a centrally located centrifugal slurry transfer pump. The waste mobilization is achieved with either recycled supernatant or high-pressure water. These spray nozzles direct the resulting waste slurry stream toward the center of the SST where the adjustable height slurry transfer pump is located. The waste is then pumped to the DST using this pump. Initially, the pump is planned to operate using a pump intake configuration similar to that used in past practice sluicing retrieval operations. Later, during hard heel retrieval operations, a pump backstop assembly will be lowered to a position around and under the slurry pump. In this position the backstop assembly will support

solid particle size reduction and enhance fluid velocities into the pump intake to improve heavy solids entrainment and transport to the DST.

The MARS-S mast will be installed in the large diameter riser in the center of the selected retrieval tank. Fig. 5 shows the configuration of the MARS-S.

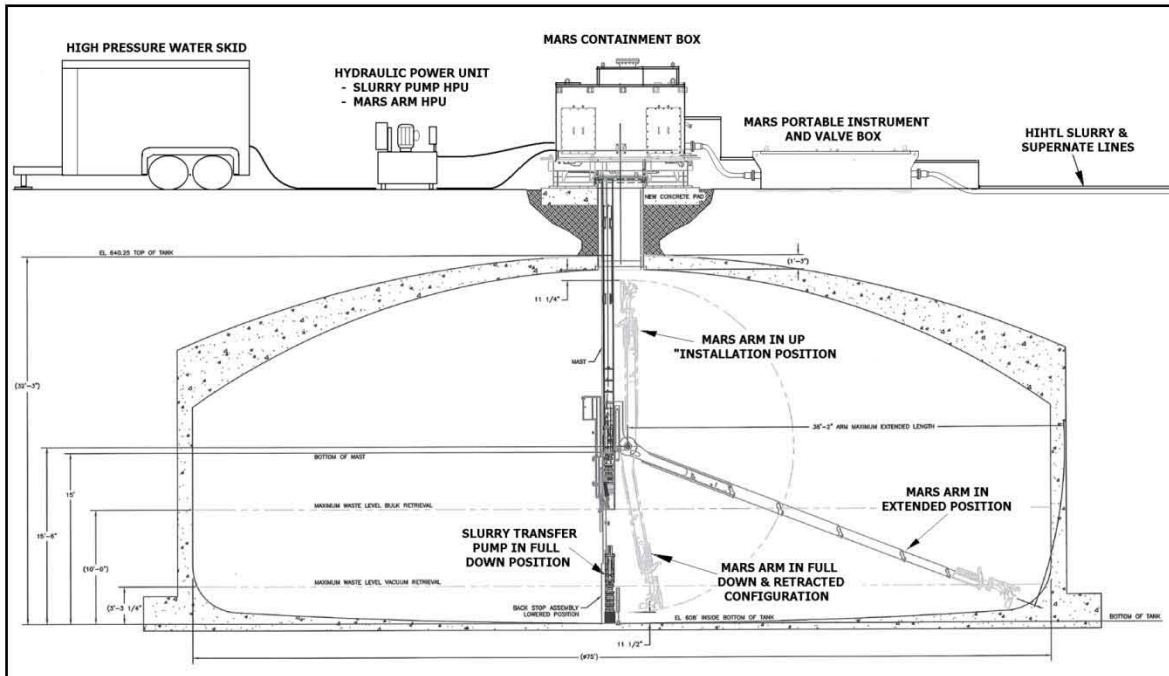


Fig. 5. MARS-Sluicing (MARS-S) Diagram

The MARS containment box, located above grade at the top of the mast system, houses:

- The MARS turntable and slew drive system
- All the hydraulic, water and process liquid interface connections
- The rotary union and the upper hose management tray
- The upper portion of the hose management strongback and its constant tension hoist
- The top of the adjustable height slurry transfer pump and its hoist system
- The pressure relief valve assembly
- Redundant leak detector assemblies (2).

It is a shielded secondary containment box with walls made of varying thicknesses of carbon steel for shielding. The shielding wall is split between a 10-inch (25.4 cm) tall stub wall on top of the containment box support structure and the balance of the shielding wall which is installed separately (after other assembly tasks are completed) inside the box. It provides containment for any process leakage which might occur in the box and shielding for personnel working near the box both during and after operations. It includes drains which empty back into the SST through the large diameter installation riser, and leak detectors located at an engineered low point in the support platform that alarm if liquid collects there.

The waste transfer system hose-in-hose transfer lines for slurry transfer to and recycled supernatant return from the DST receiver tank will interface with the portable instrument and valve box which is located next to the containment box. The containment box also supports minor end effector maintenance (i.e., cleaning nozzles, replacing nozzles, etc).

The containment box includes a heater for freeze protection.

VERTICAL MAST SYSTEM

The MARS-S mast system is suspended from the MARS-S turntable and hangs down into the tank through a new large diameter riser to a point of 15.5 feet (4.7 Meters) above the tank floor. The system supports all of the in-tank MARS-S retrieval. The main structural member of the mast is an approximately 12.25-inch square tube which supports the MARS-S carriage and telerobotic arm system (Fig. 5). The mast includes provisions to insert the adjustable height slurry transfer pump through the mast and into the SST. The mast also supports the slurry pump backstop assembly which mounts on a mast extension. The extension is the mounting point for the slurry pump backstop assembly actuation system used to deploy and retract the backstop assembly from its stored position on the back side of the mast.

TELESCOPING ARM, CARRIAGE WRIST AND END EFFECTOR

The arm carriage is the interface between the mast system and the arm system. It is installed with the telerobotic arm onto the mast after the mast has been inserted in the tank (Fig. 5). A set of hydraulic cylinders mounted on the carriage provide the actuation of the arm pivot point to raise and lower the arm as required to support the MARS retrieval activities, and end-effector change-outs activities.

The arm system is made-up of one fixed and four telescoping sections. This arrangement allows the arm to be installed in the tank in a shortened configuration approximately 11 feet long. It can then be lengthened by extending hydraulic cylinders to any position between its short length, 11 feet (3.4 meters), and its fully extended length of approximately 38 feet (11.6 meters). Adding the approximate 4 foot (1.2 meters) length of the wrist/end effector, the arm reach is approximately 42 feet (12.8 meters). The full arm extension is not required in C Farm SSTs.

The MARS arm wrist provides the capability to flex the end-effector 102 degrees in the vertical plane (90° upward, 12° downward), and 45° both to the left and right in the horizontal plane.

The MARS-S end-effector includes two types of recycled supernatant spray nozzles. One is for mobilizing waste at a distance and the other is for mobilizing waste in close proximity to the end-effector. The at-a-distance nozzle would be needed in a high solids SST where the solids level in the tank initially prevents the vertical pointing down orientation of the retracted arm and end-effector due to interference between the arm/end-effector and the waste surface. In this case, the initial retrieval operations would be conducted using the "At a Distance" spray nozzle mobilizing the interfering tank waste until the interfering material has been removed. The other recycled supernatant nozzles would be used during retrieval activities where the end-effector could be moved to close proximity of the waste to be mobilized.

SLURRY TRANSFER PUMP AND BACKSTOP

The MARS-S slurry pump system is an AGI Engineering (AGI) hydraulically driven slurry pump similar to the pumps used in previous retrievals. For the MARS-S version of this slurry transfer pump, the upper end of the pump design was modified to fit in the MARS containment box and the lower section was modified to fit down and interface with the MARS mast and backstop assemblies. Other changes to the MARS slurry pump include a higher torque hydraulic motor, hardened chrome plated pump shaft, and stuffer rings around the impellers.

This pump is a variable speed, hydraulically driven centrifugal slurry pump capable of pumping between approximately 60 and 130 gpm (127 and 492 liters/minute).

The slurry pump backstop assembly when deployed is located around the bottom of the slurry pump intake to catch waste slurry being driven to the pump from the end-effector by either the recycled supernatant mobilization nozzle stream or the high-pressure water size reduction stream and direct them through the pump intake screen and up into the slurry pump intake. The backstop will include a system of high-pressure water nozzles for breaking up (size reducing) solids and a recycled supernatant nozzle system driving the solids into the slurry pump inlet at sufficient velocity to be suspended in the flow stream until the pumps impellers can pick them up and pump them to the DST receiver tank. These high-pressure water and recycled supernatant nozzles will be fed by the same systems that supplies high-pressure water and recycled supernatant to the end-effector.

PORTABLE INSTRUMENT AND VALVE BOX

The MARS portable instrument and valve box is similar in design to other portable diversion boxes used in prior C Farm retrieval operations. It is located immediately adjacent to the MARS containment box. It contains both instrumentation and valves required to support MARS retrieval operations (Fig. 6).

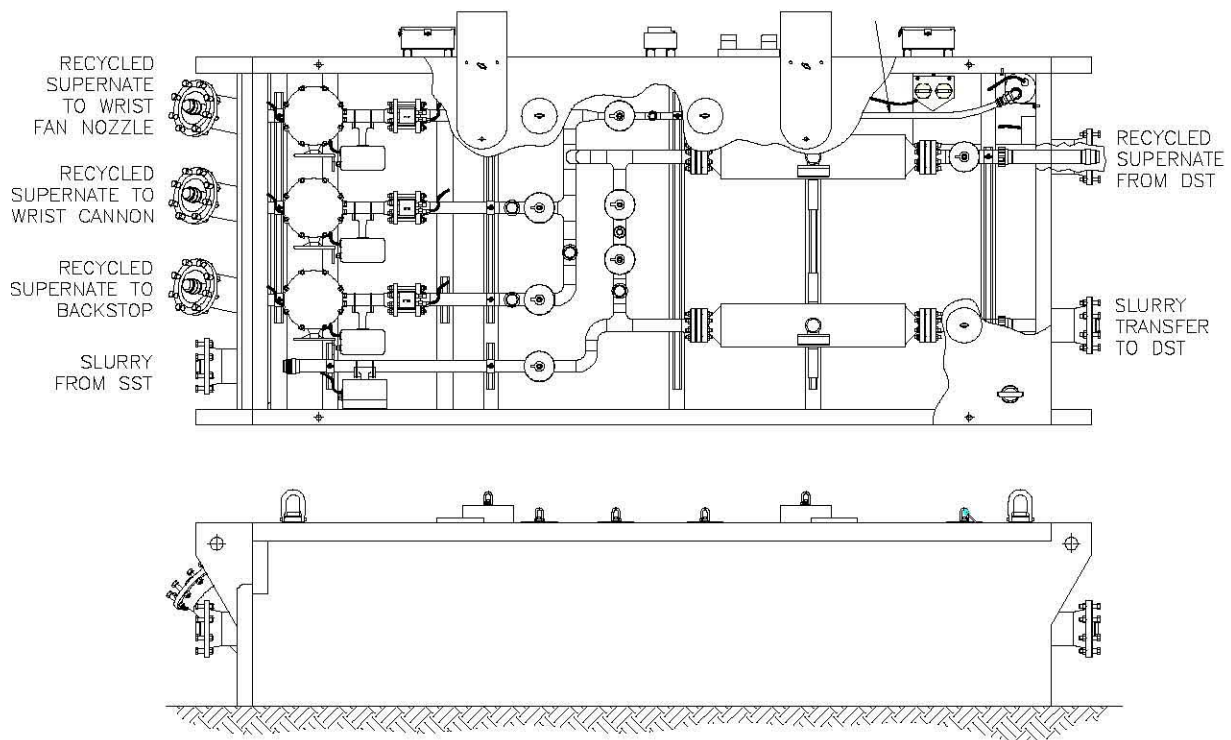


Fig. 6. Portable Instrument and Valve Box.

HIGH PRESSURE WATER TRAILERS

The MARS high-pressure water trailers will be located above ground near the selected retrieval SST. It will provide high-pressure water to the MARS via hoses to the portable instrument and valve box.

Each high-pressure water trailer provides up to 20 gallons per minute (75.7 liters/min) of water at up to 4,950 psig (34,129 kilopascal).

IN-TANK VIEWING SYSTEM

A color closed-circuit television (CCTV) system will be provided as part of the MARS. It will be mounted on the extension arm of the strongback hose management system to provide an enhanced view of the central portion of the SST during retrieval operations.

HYDRAULIC POWER UNITS

The MARS will include two HPUs. One will support the operation of the MARS arm, backstop assembly deployment cylinders, in-tank hose management constant tension reel, and end-effector subsystems. The second HPU will power the slurry transfer pump system. Both of these HPUs will be located above grade on or adjacent to the tank dome.

HOSE MANAGEMENT SYSTEMS

Because of the large number of MARS process and support services hoses, there are a number of subsystems which handle the routing of these hoses to their intended destinations.

These subsystems include the following systems:

- Containment Box Hose Management
- Strongback In-Tank Hose Management
- Mast Supporting Piping.

MARS-S Testing

Testing was conducted on the MARS-S in phases. Phase 1 Qualification testing was considered “proof of principle” testing. Numerous components were tested in this phase. Phase 1 Qualification testing utilized full-sized components so that performance characteristics could be measured to assess application towards detailed design.

Phase 2 Qualification testing was successfully completed at Hanford's Cold Test Facility (CTF) on the MARS-S in late September 2009 (Fig. 7). The following is a summary of the results of this testing:

The results show the MARS unit operated acceptably and met the criteria set in the test procedure. The retrieval rates were estimated at 750 to 970 gph (2839 to 3672 liters/hr) for bulk retrieval simulant #1, 85 to 140 gph (322 to 530 liters/hr) for dense heel simulant #2, and 150 to 300 gph (568 to 1136 liters/hr) for hard heel simulant #3. The goals for each simulant type were 900 gph (3407 l/hr), 100 gph (379 liters/hr) and 100 gph (379 liters/hr) respectively. The conditions tested for the bulk retrieval were conservative and equivalent to those for a tank during heel retrieval, not bulk retrieval. The system mobilized and transferred waste to the removal pump for all waste simulants extremely well.

The MARS demonstrated an effective capability for waste retrieval. The MARS was able to reach and clean the tank wall, while the wrist function allowed the sluicing action to reach around items. The arm functions of the elbow joint movement, arm “in and out” movement, wrist multi-axis movement, and the rotational movement of the mast/carriage/arm all worked smoothly together. The ability to hydraulically “rake” material from the outer reaches of the tank, into the influence of the pump is a capability that is not currently available with Hanford tank waste retrieval technology. The deployment of MARS will provide the ability to both complete bulk waste retrieval and perform the residual waste cleanup necessary to meet retrieval goals with use of a single technology.



Fig. 7. Photograph of the MARS testing.

A final set of tests were performed at the Columbia Energy Test Facility (CTC), in north Richland, in the summer of 2010. This testing proved that the final design configuration of the MARS-S was acceptable to proceed to the field installation process.

As part of final acceptance, the MARS-S was put through a five-volume acceptance test procedure to evaluate the entire range of MARS functionality in order to qualify MARS for deployment in tank 241-C-107. All aspects of the MARS that were tested as part of this acceptance testing met/passed the Acceptance Criteria. Testing included operating all the equipment of the MARS individually or as part of functional units as they will perform in the field.

In meeting all Acceptance Criteria the MARS has passed this Acceptance Test and has qualified for field deployment to tank 241-C-107.

MARS-S INSTALLATION

The installation of the MARS-S on Hanford's SST 241-C-107 (C-107) began in April, 2011. The installation process, including Construction Acceptance Testing, and Operational Acceptance testing was completed on September 25, 2011, with the completion/sign-off of the Readiness Acceptance documentation.

MARS-S Operation

For the first time in history a large robotic arm (MARS-S) was used to remove waste from one of Hanford's single-shell radioactive waste storage tanks. Operators brought the MARS-S to life inside tank C-107 in early October, 2011, and began transferring waste to nearby DST AN-106.

An image inside tank C-107 is provided as Fig. 8. The waste will eventually be delivered to the nearby Waste Treatment Plant where it will be immobilized in glass.



Fig. 8. In-Tank Camera Image of MARS-S Operating in C-107 (Circa 10/15/11)

As of October 20, 2011, approximately 22% of the waste has been retrieved from C-107 and transferred to DST AN-106. This equates to approximately 56,000 gallons (211,983 liters). There are an estimated 197,000 gallons (745,726 liters) of waste remaining in C-107 to be retrieved.

Mobile Arm Retrieval System-Vacuum Mode (MARS-V)

The MARS-V can be deployed in nearly any leaking or potentially leaking Hanford Site SST with a large diameter central riser. The MARS-V is designed to accomplish retrieval per regulatory requirements in leaking tanks, potentially leaking tanks and tanks of questionable integrity. The MARS-V retrieval platform uses many components which are similar to those used in the MARS-S, but there are a number of unique components. The unique systems/components will be described here.

The MARS-V mobilizes and retrieves SST waste using a fluid driven eductor system in an end-effector at the end of a telescoping arm and a slurry transfer pump located in a tank at the bottom of the MARS-V mast. The mobilization fluid used is supernatant from the DST. The waste mobilization is achieved with the vacuum effects of the eductor.

The end-effector is equipped with a pair of fluidization nozzles that liquefy the waste immediately surrounding the suction nozzle to make retrieval more efficient. The end-effector is also equipped with four high pressure nozzles. Two of the nozzles are used for back flushing the screen on the suction end of the end-effector and the other two are used to break up the heel or any other hard waste for retrieval using the eductor.

The vacuum retrieval version mast will be installed in the large diameter riser in the center of the selected retrieval tank. Fig. 9 shows the configuration of the MARS-V.

The waste is retrieved to a waste transfer tank located at the bottom of the MARS-V mast located inside the SST being retrieved. The tank is equipped with a centrifugal slurry transfer

pump. This pump supplies the end-effector eductor, as well as, a secondary eductor on the waste retrieval line. Additionally, this pump discharges a slurry stream to the DST.

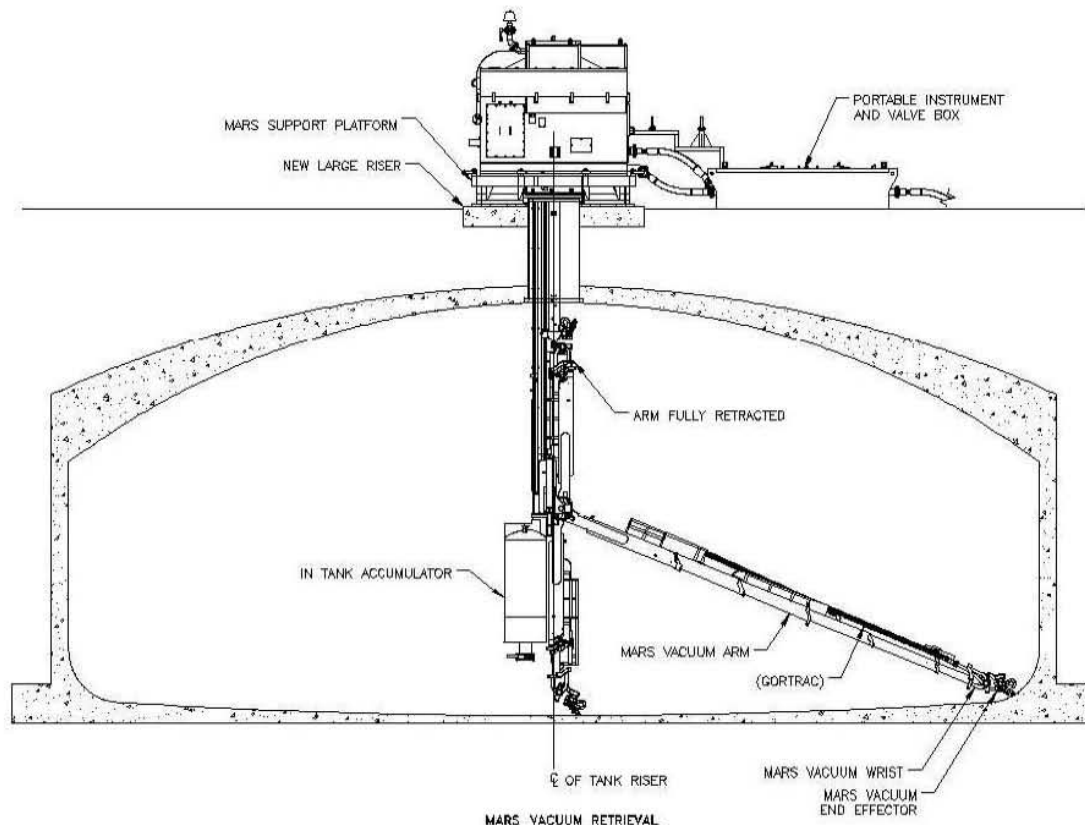


Fig. 9. MARS-V Diagram

The following MARS-V components are significantly different from MARS-S, and are therefore included in this section for information:

Vacuum Retrieval Mast System

The MARS-V mast system is suspended from the MARS-V turntable and hangs down into the tank through a new large diameter riser to a point 15.5 feet, (4.7 meters) above the tank floor.

It supports all of the in-tank MARS-V retrieval equipment. The main structural member of the mast is an approximately 12.25-inch (31.1 centimeters) square tube which supports the MARS-V carriage and telerobotic arm system (Fig. 9). The mast also supports the waste accumulator tank (WAT) mounted at the bottom end of the mast. The WAT contains the slurry transfer pump.

Vacuum Retrieval End-Effector

The MARS-V end-effector includes a pair of recycled supernatant spray nozzles used for fluidizing waste in close proximity to the end-effector. The end-effector is also equipped with two pairs of high pressure nozzles. One pair of high pressure nozzles is used to break up solid

sections or oversized pieces of tank waste for retrieval by the eductor. The other pair is used in the event the eductor screen becomes plugged to back flush the screen. A diagram of the MARS-V end-effector is provided in Fig. 10.

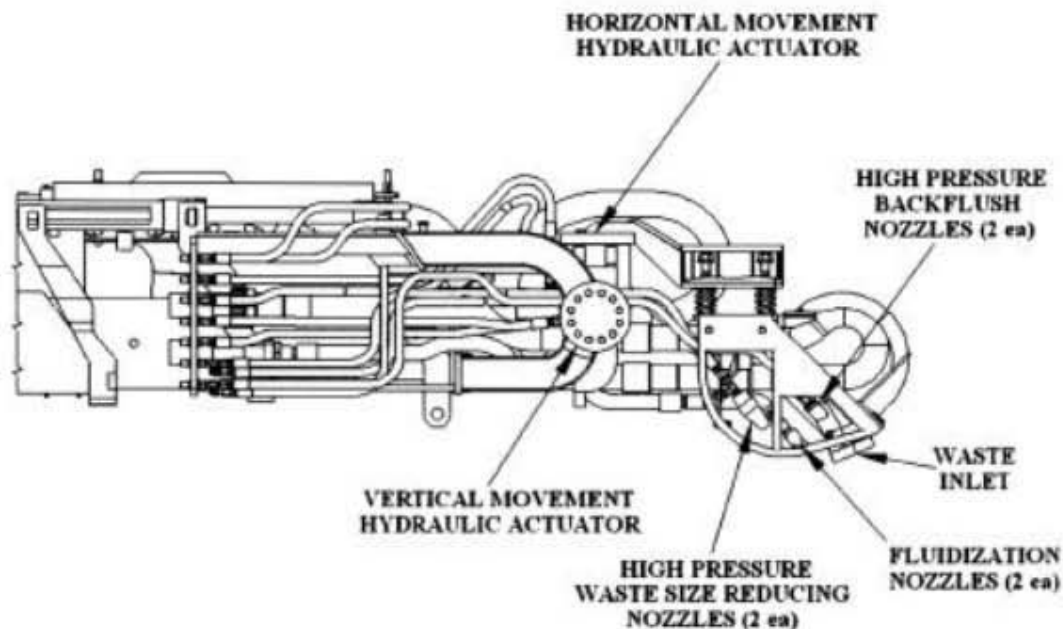


Fig. 10. MARS-V Retrieval End Effector

Arm Carriage

The arm carriage is the interface between the mast system and the arm system. It is installed with the telerobotic arm onto the mast after the mast has been inserted in the tank. A set of hydraulic cylinders mounted on the carriage provide the actuation of the arm pivot point to raise and lower the arm as required to support the MARS-V retrieval activities, and end-effector change-out activities.

Telescoping Arm System

The arm system is made up of one fixed and five telescoping sections. This arrangement allows the arm to be installed in the tank in a shortened configuration approximately 14.5 feet (4.4 meters) long.

It can then be lengthened by extending hydraulic cylinders on the first four sections to any position between its short length and its fully extended length of approximately 41 feet (12.5 meters). The fifth section on the arm is independently operated with its own hydraulic cylinders. Adding the approximate 4-foot (1.22 meters) length of the wrist/end-effector, the arm's full reach is approximately 41 feet (12.5 meters).

Arm Wrist

The MARS-V arm wrist provides the capability to flex the end-effector 90 degrees in the vertical Plane (67 degrees upward; 23 degrees downward), and 45 degrees both to the left and right in horizontal plane.

MARS-V Retrieval Slurry Transfer Pump

The bulk retrieval slurry pump system will be a submersible hydraulically driven centrifugal slurry pump model HSI I10HH manufactured by Godwin Pumps of America (Godwin).

The slurry pump is mounted inside the WAT.

This pump will be a variable speed, hydraulically driven centrifugal slurry pump capable of pumping between approximately 60 and 600 gpm (227 and 2271 liters/hour). The pump will be driven by an electric HPU located outside the SST being retrieved. The pump has also been modified to include a number of parts that have been hardened using 25 percent cast chromium. These parts include the pump volute, impellers, and wear plates. The pump is equipped with a manifold that breaks the discharge stream from the pump into three smaller streams. These streams are two recirculation streams that supply the eductor in the end-effector and the supplementary eductor in the WAT. The third stream is the return slurry stream to the AN tank farm. These streams all have flow rates of between 60 and 180 gpm (227 and 681 liters per minute).

MARS-V Testing

Similar to the MARS-S, the MARS-V has been, and will continue to be subjected to a battery of testing. The original concept for the MARS-V was based on an earlier vacuum system design provided by Non-Entry Systems Limited (NESL), which was used at Hanford to retrieve the small C-200 tanks. During the proof of principle testing it was determined that the NESL system would not perform to the expectations/requirements necessary to support retrieval efforts.

Examples cited include:

- The vacuum system resulted in choked flow if less than a 3 inch (7.6 cm) line was used. This created a space and handling issues.
- The in-tank separator had to run at a partial vacuum to work which greatly impacted the pump curve of any slurry pump. In addition, slugging created vacuum pulses in the tank resulting in additional flow control challenges.
- Vapor carryover in excess of 2 gallons per minute (7.6 liters per minute) was being experienced even with trying several Venturi configurations.
- Control of the NESL skid was difficult to integrate with the MARS system control and it appeared that the two systems would have to be operated independently.
- *A review of the vacuum skid confirmed that it was non-compliant with current safety requirements and either a major rebuild or new build would be required.*

At that time, limited testing was performed on an eductor based vacuum system. The testing indicated that the eductor based system would meet the requirements necessary to support retrieval efforts.

Based on Phase 1 Testing results, the project made the decision to transition to an eductor based vacuum system.

The following is from the MARS-V Phase 1 Testing Report Executive Summary:

The eductor MARS system (MARS-V) is being developed to be capable of cleaning out suspected leaking tanks using limited liquid addition and maintaining a minimum liquid inventory in the tank at all times. This concept is a variation of the direct vacuum removal system to provide a more robust system. Eductor systems are commonly used throughout North America to do private mining for precious metals or semi-precious stones. The eductor style end-effector system simplifies the original vacuum design by reducing the overall complexity of the system, including removing pressure vessel requirements and simplifying lifting/installation by reducing the number of cranes needed. The eductor system design also makes the pumping system

more efficient and controllable, allowing the system to run in a stable manner during both active retrieval and during waste pump out.

The retrieval test was run for over two hours maintaining a stable level in the in-tank separator tank. During the test approximately 10,400 pounds (4717 kilograms) of a waste simulant mixture consisting of Simulant #1 (kaolin mix) and Simulant #2 (hematite/sand mix) were retrieved. Assuming an average density for the two simulants over the test, the average overall waste retrieval rate was approximately 350 gph (1325 liters/hr). The efficiency of retrieval by the operator averaged 70% giving the MARS eductor system a retrieval rate averaging 500 gph (1893 liters/hr).

In addition to the waste retrieval, pump operation within a smaller tank in tank was examined. The pump was shown to be capable of self starting at a prescribed level, stopping a prescribed level, and operating within a stable range during various retrieval scenarios for over two hours.

This testing verified:

- An eductor style head is effective for moving heavy (high specific gravity) simulants,*
- A cable tray system can manage the in tank hoses and supply lines, and*
- An in tank style system for pumping out waste can be easily operated and controlled.*

A number of areas were also identified during testing to be included in further design and optimization testing. This includes potential equipment and operations modifications of: the end effector, the separator tank, the in tank hose management system, and pumps.

As the Design of the MARS-V progressed, two key tests were conducted on the MARS-V:

- Phase 2 Qualification Testing, and*
- Extended Wear and System Reliability Testing.*

Both of these tests were completed in September 2011. Important information was attained from each of these, including:

Phase 2 Qualification Testing

Phase 2 Qualification testing of the MARS-V was conducted at the Columbia Energy Test Center on August 22 and 23, 2011. The results show the MARS-V unit operated acceptably and met the Acceptance Criteria in the test procedure:

- The overall minimum waste transfer rate was observed to be 74.9 gallons per minute (284 liters per minute). This value is well above the acceptance criteria 60 gallons per minute (227 liters per minute) per RPP-SPEC-47363 [4]*
- The overall average waste transfer rate was calculated to be 96.7 gallons per minute (336 liters per minute). This value is in the target range of 80-100 gallons per minute (303 to 379 liters per minute).*
- The overall average specific gravity of waste transferred was calculated to be 1.66 and the maximum was calculated for Simulant 2 to be 2. 1. Both these values are well above the acceptance criteria specific gravity values of 1.45.*
- The overall average density of waste transferred was calculated to be 1.66 and the maximum was calculated to be 2. 1. Both these values are well above the acceptance criteria bulk (average) density of 1.55 grams/milliliter.*

The conditions tested were conservative and equivalent to those for tank during the final stages of retrieval. The system retrieved each of the waste simulants extremely well. The MARS-V demonstrated an effective capability for waste retrieval. The MARS-V was able to thoroughly clean the "tank bottom" during testing. The wrist function allows the eductor to reach around items. The arm functions of the elbow joint movement, arm extension/retraction movement,

wrist multi-axis movement, and the rotational movement of the mast/carriage/arm all worked smoothly together. The ability to 'vacuum' material directly out of the tank is a capability not currently available with Hanford tank waste retrieval technology. The MARS-V has the solid potential to be deployed to provide the ability to complete bulk waste retrieval and to perform the residual waste cleanup necessary to meet retrieval goals in leaking and potentially leaking tanks using a single technology. This potential will be demonstrated by the successful completion of this Phase 2 test, and addressing specific issues identified in this report, including potential moderate re-design of the system. This technology may even be considered as a single-use technology for use on sound tanks, as well.

Extended Wear and Reliability Testing

Extended Wear and System Reliability Testing was completed on the Vacuum-mode Mobile Arm Retrieval System (MARS-V) at the Columbia Energy Test Center (CTC) between June 20 and September 9, 2011. The MARS-V was operated for more than 180 hours retrieving a variety of waste simulants to assess the overall impacts due to the retrieval and transfer of heavy and abrasive simulants.

Operationally the Vacuum-mode Mobile Arm Retrieval System performed well. The system adequately retrieved simulants that were mixes of hematite, silica sand, kaolin clay, and chipped marble without demonstrating any reduction in overall system slurry transfer performance over time.

This system is a prototype system and it was expected that a number of needed refinements to the design and equipment would be identified by this testing. This test successfully identified a number of issues, areas of vulnerability, and potential control improvements of the Vacuum-mode Mobile Arm Retrieval System:

- *Pump Speed: It was shown that the wear to system components was substantially reduced when the pump speed was reduced from approximately 2,300 revolutions per minute to between 1,700 and 2,000 revolutions per minute. Further pump operations will be performed in this range.*
- *End Effector Inlet Screen: It was found that performance was substantially enhanced by changing to a 4-inch (10.16-cm) inlet screen that reduced to 2-inch (5.08-cm.) to connect to the inlet. Further evaluation of inlet screen configuration is needed for final deployment.*
- *Internal Flow Management: A number of incidents of eductor plugging demonstrate the need to provide additional control or inhibition of the flow of large particles. Baffles, screening, or other supplemental design tools should be evaluated to protect the eductor system from oversized particles.*
- *Discharge Manifold Configuration: The discharge manifold may require re-design, materials modification, or both, due to*
 - *Excessive wear on the waste return line by the Waste Accumulator Tank eductor*
 - *Excessive entrained air, and*
 - *Material wear as the measurement locations showing the greatest wear from the simulants were part of the Discharge Manifold.*
- *End Effector and Its Connections: Additional design or materials evaluation is needed due to wear exhibited (including exterior abrasion of the hose in the hose cage).*
- *Waste Accumulator Tank Stilling Wells: These were identified as potentially requiring modification in order to reduce solids deposition in the wells which can interfere with the level gauges controlling pump operation.*

- *Slurry Pump Speed Sensors: Erratic behavior, seen previously at elevated hydraulic fluid temperatures, continued to be observed some redesign or modification will be required.*
- *Backflush Nozzles: Testing of the various nozzles found potential plugging of only the backflush nozzles. These nozzles will require minor redesign or operational modification.*

Except for the areas of vulnerability identified, there were no issues related to the reliability of the system's operation. All systems worked individually and systematically, as designed.

With the successful address of the identified issues, the Vacuum-mode Mobile Arm Retrieval Systems tested here when coupled with previously verified above ground support components the of Sluice Mode Mobile Arm Retrieval System should provide the Hanford Site with a robust retrieval tool for deployment to leaking and potentially leaking storage tanks.

As with the MARS-S, the MARS-V will be subjected to Acceptance Testing, later in calendar year 2012, prior to it being readied for turn-over to Operations and Construction for installation in tank C-105.

Lessons Learned:

The effort to provide a new Large Riser in an underground waste storage tank at Hanford, coupled with the development, testing, deployment, and ultimately the operation of the Sluice Mode Mobile Arm Retrieval System (MARS-S) in Tank C-107, has provided the opportunity to identify a number of "Lessons Learned", which, as appropriate, have been/are being incorporated into subsequent versions of the MARS. The only deployments of the MARS in Hanford's C-Farm, are planned for Tank C-107 (MARS-S), and Tank C-105 (MARS-V). The next planned deployment of the MARS after C-107, will be in Hanford's A and AX Tank Farms. Prior to deployment there, some modifications/improvements will be addressed in the MARS. Several of the Lessons Learned from the C-107 MARS-S deployment (both positive and negative) which have been identified includes:

- In the Large Riser installation, as reported earlier, several potential improvements were identified. Two key improvements are moisture control in the compressed air system and hose management of the cutting device.
- During the development of the MARS-S, two separate contractors were utilized for the MARS development, and the field installation design. There were a number of integration challenges encountered. For subsequent deployments either one contractor will be used, or a very good interface control practice will be used.
- A very positive activity will be continued, where the project had very early involvement from the tank farm Operations management and operators in reviewing the design and testing of the equipment. This was possible through the use of a full-scale mockup, and extensive testing and training process.
- The Construction Contractor was also brought into the testing area just prior to commencing field installation activities, and the actual crews were able to practice installation and removal practices, and to become familiar with the equipment. This proved very helpful, especially from efficiency, and an ALARA viewpoint.
- During mock-up testing and operator training, the location of the in-tank cameras was not representative of the locations they are actually in, in the tank. This caused the Operators to have to adjust to the new perspectives provided by these. In the next MARS training/testing evolution, the planned in-tank camera locations will be replicated as close as possible, to make the training/testing perspective match that which will be seen in actual operation.

- The cable on the MARS-S constant tension hoist came off the pulleys during installation, requiring the equipment be removed, and repaired in the field. The design for subsequent versions will address this issue.
- The pump speed sensors have failed on the MARS-S, somewhat limiting the operational process. The MARS-V pump monitoring system will be improved to reduce the chance of a recurrence of this failure.
- The design of the MARS-S had a number of hydraulic fittings in a hydraulic cabinet attached to the Support Platform. It proved very difficult to eliminate leakage from these fittings, causing an operational/maintenance inconvenience. The MARS-V design has utilized more welded fittings, better O-rings, and an enhanced assembly/tightening process to reduce the potential for leakage.

REFERENCES

- [1] "Technology Development Management Plan," TFC-PLN-90, Rev. A-5, Washington River Protection Solutions (2009).
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- [3] "An Evaluation of Single-Shell Tank 241-C-107 for the Addition of a Large Penetration in the Tank Dome," RPP-CALC-43416, Rev. 0, Washington River Protection Solutions (2009).
- [4] "MARS Vacuum Mode Performance Specification," RPP-SPEC-47363, Rev. 0, Washington River Protection Solutions (2010).