MODIFICATIONS AND IMPROVEMENTS OF THE HOUDINI®-II, A REMOTELY OPERATED VEHICLE AT OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

In 1996 the first hydraulically powered, remotely operated, track driven vehicle, commonly know as Houdini®, arrived at the U.S. Department of Energy - Oak Ridge National Laboratory (ORNL). This system supported radioactive waste retrieval for the Gunite Tanks Remediation Project. The Houdini®-I system underwent cold testing at the Robotics and Process Systems Division's Tanks Technology Cold Test Facility at ORNL. The cold tests allowed the full integration of the Houdini®-I system with other remotely operated equipment to complete the Radioactive Tank Cleaning System for the Gunite Tanks Remediation Project.

In July 1997 the Houdini®-I remotely operated vehicle was deployed, and over the next 8 months the Houdini®-I was operated inside two 25-ft diameter tanks in the North Tank Farm at ORNL in a harsh chemical and radiological environment. The system successfully accomplished a variety of tasks that were important for successful waste retrieval, completing the "hot tests" conducted as part of a Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) Treatability Study. During hot tests, many valuable lessons were learned, which were documented, and later communicated back to RedZone Robotics Inc., the manufacturer of the Houdini® I system. A second system, Houdini®-II, was in its design stage during the hot tests. Lessons-learned on the Houdini®-I drove the design and specifications for the second-generation Houdini®-II system. Improvements were targeted at two main areas, reliability and maintenance, in order to meet As Low As Reasonably Achievable (ALARA) exposure principle requirements, and further improve the Houdini® system for use in higher radiation environments. The main redesign focused on improving the ergonomics on the Tether Management And Deployment System and modifying many of the electrical and plumbing features of the vehicle.

The Houdini®-II system arrived at ORNL in September 1998 for cold testing before its deployment in the larger gunite tanks in the ORNL South Tank Farm. In January 1999 the vehicle was deployed into tank W-7 under the Bechtel Jacobs Company LLC contract. The Houdini® -II system successfully completed waste retrieval operations in tanks W-7, W-8, W-9, and W-10. The Houdini®-II system required less maintenance than the original Houdini®-I prototype. It proved reliable during waste retrieval operations, helping to speed up the process, and its versatility proved valuable in completing the Gunite Tanks Remediation Project ahead of schedule.

INTRODUCTION

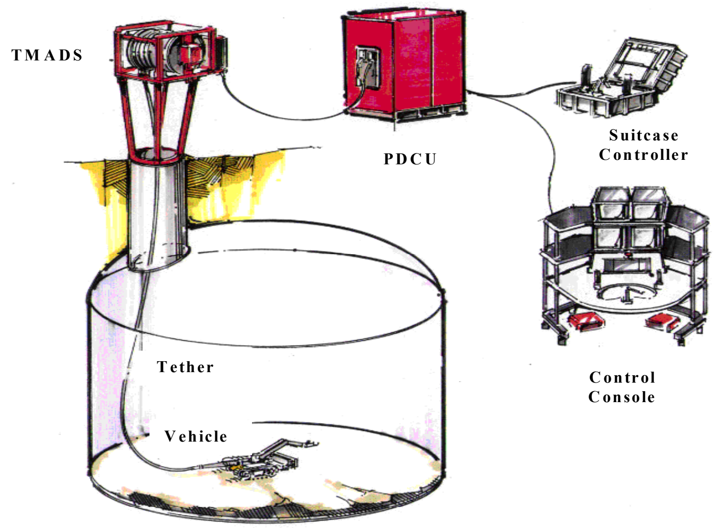
The U.S. Department of Energy (DOE) is cleaning up and closing approximately 300 underground tanks that store radioactive and hazardous waste remaining from Cold War and research and development activities at DOE sites around the country. These tanks contain millions of gallons of low- and high-level radioactive mixed waste and come in many shapes and sizes. Safe and cost effective tank waste retrieval and closure operations are challenging. In order to meet the challenges associated with the tank cleanup activities, more effective technologies are needed. Previous water-sluicing and pumping campaigns have been effective for tank liquid and bulk sludge removal, but are not always effective at meeting the final cleaning requirements necessary to close these large underground waste storage tanks.

The DOE Office of Science and Technology (OST), in cooperation with the DOE Environmental Management (EM) Program, funded the development of a remotely operated vehicle named Houdini® to help meet final tank closure requirements. RedZone Robotics Inc, a small company in Pittsburgh, Pennsylvania, designed the Houdini® System, which was originally developed through the OST Industry Research and Development Program at the National Energy Technology Laboratory (NETL), located in Morgantown, West Virginia. The OST Robotics Crosscutting Program, the Ohio Field Office- Fernald EM Program, and the Oak Ridge Operations EM Program provided technical oversight and end-user feedback. Initially intended for the use in the K-65 Silos at Fernald site in southwestern Ohio, the Houdini® was redirected to Gunite Tanks Remediation Project at Oak Ridge National Laboratory (ORNL), located in Oak Ridge, Tennessee, where it was more urgently needed.

The Houdini®-I system was successfully deployed at ORNL during the Gunite Tanks Remediation Project, from June 1997 through August 1998, in tanks W-3, W-4, and W-6. Lessons-learned from these operations made it apparent that improvements could be made on a second-generation system. This paper summarizes major improvements included on the Houdini®-II system, and describes its performance and maintenance during the final four waste removal campaigns for the ORNL Gunite and Tanks Remediation Project.

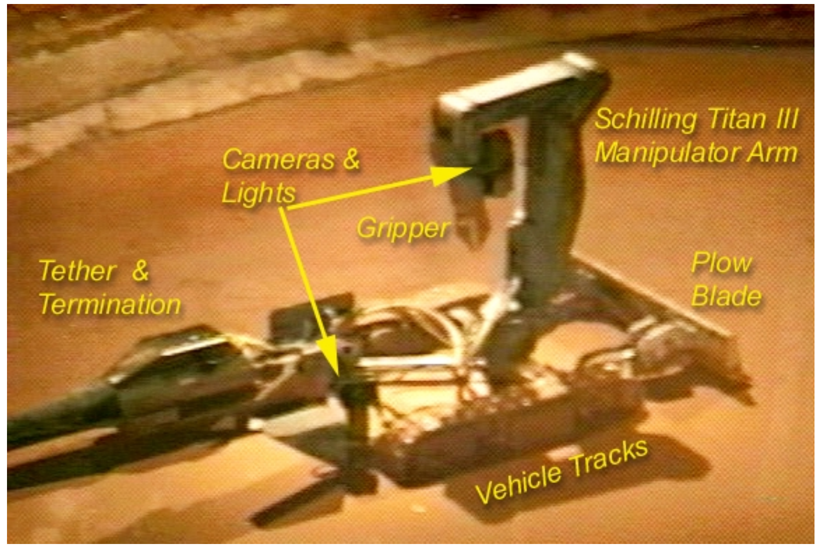
THE HOUDINI®-II REMOTELY OPERATED VEHICLE SYSTEM

The Houdini®-II is a hydraulically powered, remotely operated vehicle that provides important functions for tank waste removal operations. The vehicle's 4-ft by 5-ft parallelogram style frame folds, enabling it to deploy through 24-in tank riser openings. The Houdini®-II is equipped with a front plow blade, a dexterous, high-payload, Shilling Titan III manipulator arm, and a remotely operated, dual camera system. The Operator Control Console can be located a few hundred feet away from the vehicle. The Power Distribution And Control Unit (PDCU) provides pressurized fluids to both the TMADS and to the vehicle (via a tether) to meet the high-power density requirements of the Houdini® system's hydraulic functions. The hydraulic servo valves provide the operator with variable speed control for all vehicle and deployment system operations. The Houdini®-II consists of five main sub-systems (Fig. 1).



(Fig.1) The Houdini® system components include the vehicle, tether, tether management and deployment system (TMADS), the power distribution and control unit (PDCU), the control console, and the optional suitcase controller.

The Houdini® Vehicle



(Fig. 2) The Houdini® is a tracked vehicle equipped with a plow blade, robotic manipulator arm, dual camera system, and lights

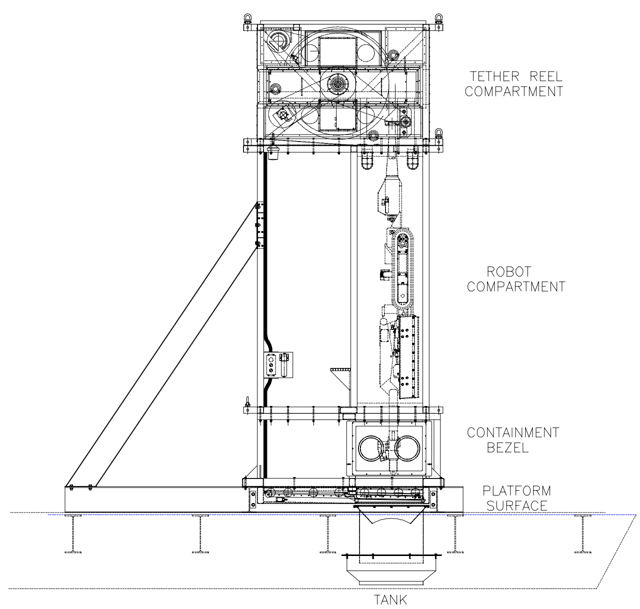
The Houdini® vehicle is a tethered, hydraulically powered, track-driven, remotely operated, "bulldozer type" that is the "work horse" of the system (Fig. 2). The collapsible, parallelogram, stainless-steel frame folds to enable entry into cylindrical tank risers with diameters as small as 24-in. The frame fully expands to a footprint that is about 4-ft wide and 5-ft long that provides a stable platform for a variety of in-tank operations. The stainless steel construction of the Houdini® vehicle makes it well suited for corrosive and high pH environments.

The vehicle is equipped with squeegee-tipped plow blade, and is hydraulically actuated from the Operator Control Console to perform tank waste retrieval operations. The onboard, remote, dual camera system has a variety of functions to fully service the viewing needs of the operator. A 6-degree of freedom, Schilling Titan-III manipulator arm has a payload capacity of 250-lb and a full reach of about 5-ft.

The Tether Management and Deployment System (TMADS)

The TMADS is the mobile enclosure that provides the containment and housing for the Houdini® vehicle before, during, and after deployments into the tank. The enclosure supports tank deployments and maintenance services to the vehicle. The TMADS consists of three main compartments (Fig. 3) that are described below.

The Tether Reel Compartment is the top section of the TMADS assembly. The 4-ft diameter tether reel is hydraulically powered and provides variable speed tether management for tank deployments and operations. It provides up to 3,000-lbs of lifting force for vehicle retrieval. The Tether Reel Compartment also contains the control valves and redundant, fail-safe, braking interlocks to ensure safe operation of the tether reel. The control valves for the tether reel drive are located inside a removable access panel in the front face of the compartment where it can be easily serviced.



(Fig. 3) The TMADS assembly has three main compartments.

The Robot Compartment stores the Houdini® vehicle when not in use. The compartment has 4-ft by 8-ft front and rear panels, fabricated from polycarbonate material to provide a clear view of the vehicle during storage and maintenance activities. Gloveports and a pass-through box installed in the front and rear panels support routine maintenance activities without breaking containment, and a safety chain secures the vehicle to prevent unwanted movement during maintenance activities.

The Containment Bezel is in the lowest compartment of the TMADS structure and attaches directly to the main containment door that isolates and shields the interior of the TMADS from the tank. The containment door opens remotely during deployment and allows the vehicle to enter the tank. The Containment Bezel provides mating flanges for adapting other support systems like a Tether Handling System to support other tooling needs. A 20-in bag-out port was installed in the Containment Bezel, allowing larger items to be inserted or bagged out of the TMADS.

The Tether

The Houdini® vehicle is powered by the tether, which is a multiconductor cable with integrated hydraulic transmission lines. One end of the tether attaches to the vehicle, while the other end is attached to the tether reel inside the TMADS. The tether supplies the vehicle with both hydraulic and electrical power. The tether is approximately 3-in in diameter, with a length of 135-ft. Kevlar material inside the tether provides up to 10,000-lbs of tensile strength for deploying and retracting the vehicle in and out of tanks.

The Power Distribution and Control Unit (PDCU)

The PDCU enclosure consists of an insulated, weather resistant structure that contains the electrical switch gear, hydraulic power supply, and electronic power supply needed to operate the Houdini® system. The interconnecting cables for the PDCU allow the unit to be positioned up to 100-ft from the TMADS. Access doors on each of the unit's four sides provide entry into the PDCU for maintenance and troubling shooting operations. Centrally located on the exterior of the PDCU are the quick connections for the electrical, hydraulic, water, and air supplies.

The Operator Control Console

The Operator Control Console is directly hard wired to the PDCU and provides total control and monitoring for all remote vehicle functions. The console may be located up to 300-ft away from the PDCU. The console contains two joysticks, camera monitors, and a remote control master arm and controller for the vehicle's robotic arm (Fig. 4). The relative position of the joysticks independently controls the speed and direction of each track on the vehicle, simplifying the vehicle's controllability. Warning lights and alarms on the console alert the operator of abnormal conditions, while individual switches control the camera views, tether feed, plow position, and frame folding functions.

(Fig. 4) The Houdini® Operator Control Console provides total control and monitoring for all remote vehicle functions.

SYSTEM COLD TESTING AND REDESIGN MODIFICATIONS

The Houdini®-II system arrived at ORNL in September 1998 with some uncompleted items. Because of schedule and budget overruns, the final integration of the Houdini®-II system and the systems' acceptance testing (originally scheduled at the vendors' facility) were performed at the ORNL Tanks Technology Cold Test Facility. The initial cold test environment was debris free and dry. The primary objective during the initial testing and integration was to operate the system without introducing it into demanding environments. A few potential deficiencies required modification to meet the overall system requirements in the first week of the cold tests.

A major identified problem was the TMADS containment structure's inability to be easily attached to and detached from the tank risers. The process used for the Houdini®-I system required making and breaking the riser extension piece located on the lower side of the Containment Bezel at platform level (Fig. 5 – left side). The TMADS assembly had to be disconnected from the riser extension and sheet metal caps had to be installed to seal the opposing flanges to prevent the spread of contamination. The original TMADS design on the Houdini®-II system had even more of an offset and complicated the disconnection process even more. The TMADS was modified so that it could be separated at the base of the robot compartment (Fig. 5 – right side). Special contamination plates were designed and fabricated to seal off the opposing contaminated openings.

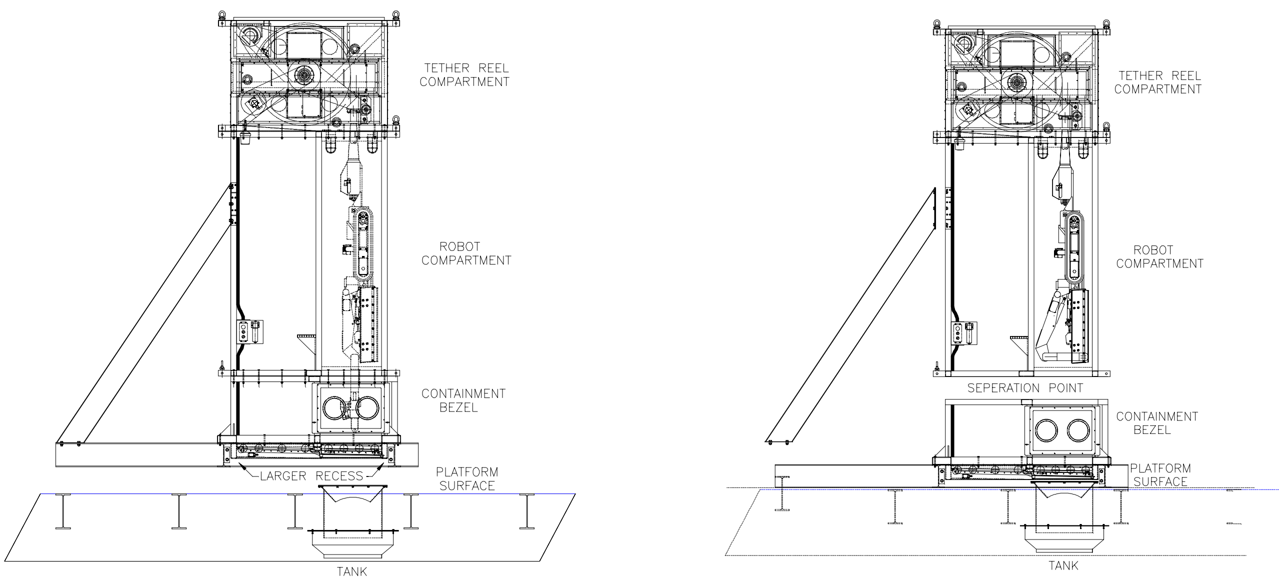


Fig. 5 The Houdini® - II TMADS before (right) and after (left) modification to include a new separation point.

It was also noted that the TMADS would not easily mate with the maintenance tent in the South Tank Farm due to the height of the TMADS Robot Compartment maintenance doors, which were originally designed with a continuously hinged vertical door on each side of compartment. Safety and health physics personnel identified these doors as potential contamination traps that were virtually impossible to thoroughly clean. Modifications were discussed with safety and health personnel to improve contamination control. One door was completely removed and replaced by a one-piece panel with a continuous neoprene gasket that totally seals the area. The other fully hinged vertical door was removed and replaced with a bottom-hinged door that has a dual purpose. First, this door provides containment for the compartment, and second, it functions as a ramp aiding in the removal of the vehicle to the maintenance tent.

TMADS Containment Bezel Modifications

The Containment Bezel is found in the lower section of the TMADS. In the initial TMADS design, access into the Containment Bezel was limited, which made it difficult to perform minor maintenance to the gripper/wrist segment on the vehicle's Schilling am using the vendor supplied glove ports. In addition, these glove ports would not reach and support the added 20-in bag-out port located in the Containment Bezel assembly. Modifications implemented at ORNL to reduce these limitations included the installation of two additional glove ports and viewing windows into the Containment Bezel assembly next to the 20-in bag-out port.

Cold tests were completed on the Houdini®-II system in early December 1998, and the acceptance testing and readiness review were successfully completed by the end of December 1998. The system was ready to provide important waste removal operations in the large, 50-ft diameter, 170,000-gallon gunite tanks located in the South Tank Farm at ORNL.

HOUDINI®-II OPERATIONS IN THE GUNITE TANKS

Tank W-7 Operations

The Houdini®-II system was moved and installed on the tank W-7 equipment platform, and then powered up and checked out on January 26, 1999. The vehicle was deployed and retracted on January 28, 1999 for final procedure and system verification. The Houdini®-II system began full-scale operations the next day and operated for approximately 80 hours over the next 6 weeks. The vehicle speeded up waste removal operations as it plowed sludge toward the Confined Sluicing End-Effector deployed in the tank by the Modified Light Duty Utility Arm. The vehicle's robotic arm was used to pickup debris and move it to a consolidation area for removal out of the tank. The robotic arm also took waste samples and deployed the coring tool, successfully taking 5 core samples from the tank walls.

Minor hardware failures identified during waste removal operations in tank W-7 were successfully repaired while the vehicle was stowed in the TMADS. The tilt-down function of the vehicle's body camera was lost during the first full day of operation; however, the effect of this failure on plowing operations was negligible. Hydraulic leaks were identified on the Shilling arm, the plow cylinder, and on both the left and right track drive motors over the course of the 6 week operations period. The manifold plugs and frame bolts were found to periodically loosen, but were regularly inspected and tightened.

On March 10, 1999 the wrist rotate and gripper open/close functions failed on the Titan III Shilling arm. In addition, the arm developed severe spasms whenever the manipulator hydraulics was powered up. The vehicle continued to be used for plowing operations since waste removal operations were nearly complete in tank W-7, but the arm was positioned out of the plow's way and then "frozen" in place. Plowing operations were completed on March 13, 1999. After the tank W-7 waste removal campaign, several weeks were spent trouble shooting the arm malfunction(s), with some assistance from the Alstom Automation/Schilling Robotics Corporation. The root cause was traced to the tether termination on the vehicle. Water had leaked into the termination canister and caused several wires in the Schilling arm controller cable to short out and burn. Investigation of the tether termination revealed a split in the flexible bend restrictor, which was concluded to be the entry point for the water. Repair of the contaminated tether was impractical, so a new tether was purchased from RedZone Robotics, Inc. The tether was successfully installed on the Houdini®-II system in the maintenance tent at the South Tank Farm in early September. The system underwent a short burn-in period (run time) while awaiting the next scheduled tank deployment.

Tank W-10 Operations

The Houdini®-II system was moved to tank W-10 in October 1999, and then powered up and deployed into the tank on October 14, 1999. During the next week, the system logged over 30 hours of in-tank operations without any major delays. During the 30 hours of operations the vehicle was deployed and retracted 3 times, and was used to deploy the Confined Sluicing End-effector and the coring tool. The vehicle effectively picked up and consolidated debris in the tank, and plowed and moved sludge.

Minor problems encountered during tank W-10 operations. They consisted of a hydraulic leak from a loose plug in the track manifold, which was repaired within 2 hours, and an electrical problem with the manipulator's communication cable that wasn't unmanageable until attempting to take the last core sample in the tank. After completing waste removal operations in tank W-10 in late October, the Houdini®-II system underwent additional trouble shooting for the Schilling arm problems. This time the problem was traced to a cold solder joint that caused inconsistent communications between the arm and its slave controller unit. The Houdini®-II underwent a connector change-out on the Schilling communication cable to fix the problem.

Tank W-8 Operations

The Houdini®-II system was installed on tank W-8 and the vehicle was deployed into the tank on January 11, 2000. Over the next 3 months the Houdini®-II system supported confined sluicing and tank cleaning operations. In addition to it's normal in-tank activities, the vehicle deployed a newly designed wall-washing tool (the Linear Scarifying End-Effector) and eliminated undo strain on the Modified Light Duty Utility Arm, which was suffering from its own tether problems. The Houdini®-II system logged over 75 hours of operations in tank W-8. During these operations, the Houdini®-II system was deployed and retracted 4 times, deployed and made 10 hand-offs of the Confined Sluicing End-Effector, deployed and made 8 hand-offs of the Linear Scarifying End-Effector, deployed and made 12 hand-offs of the coring tool, and also picked up debris in the tanks and plowed sludge.

One minor problem was encountered during operations in tank W-8, identified as another hydraulic leak from a loose plug in the track manifold. This repetitive problem was identified as a design flaw and a permanent fix is on the horizon. Due to schedule and budget pressures the correction will be implemented after completing waste activities in the gunite tanks.

Tank W-9 Operations

The Houdini®-II system was installed on the south riser of tank W-9 in August 2000 and was powered up over the normal 2 to 3 day period. Because tank W-9 was the designated consolidation tank for all sluicing activities for the Gunite Tanks Remediation Project, the sludge levels were higher than normal. The Houdini®-II vehicle successfully performed plowing activities with sludge levels as high as 28-in., leveling and mixing all the sludge piles into the residual tank liquid, making a slurry that was removed by the Confined Sluicing End-Effector. The Houdini® -II system logged over 80 hours of operations in tank W-9, and spent a total of 9 days performing plowing and debris removal activities. In addition, the vehicle was deployed and retracted 6 times, deployed and made 5 handoffs of the Confined Sluicing End-Effector and Linear Scarifying End-Effector, and performed wall washing, wall coring, and sludge sampling operations.

During operations in tank W-9, the Houdini® vehicle suffered another problem with a manifold plug and had to be retracted into the TMADS for repair. During the repair of the right manifold plug, a bungee cord was found wrapped around the track idler sprocket. The vehicle was repaired and deployed in the tank within a few hours.

CONCLUSION

The Houdini® -II system made only one trip to the maintenance tent during scheduled operations in the final four tank cleaning campaigns to replace the catastrophic failure of the tether shortly after it's first deployment in tank W-7. All other repairs were performed in the robot compartment of the TMADS. The vehicle experienced a few hydraulic leaks, with the Schilling arm accounting for most of the leaks during operations in tanks W-7 and W-10, and the track motors and track manifold plug accounting for the leaks during operations in tanks W-8 and W-9. A repair was made to a faulty relief valve in the hydraulic return side of the Schilling arm. This was a challenging repair due to the TMADS limited access when working on certain parts of the vehicle.

Bearings on the drive motor, especially the left rear one under the tether termination, seem prone for frequent failures. Early in the operations in tank W-7, a low hydraulic reservoir alarm warned the operator of a possible hydraulic leak. It was later determined that the shaft seal in the left side hydraulic track drive motor was leaking. After removing and replacing the drive motor, the leaky seal was attributed to a badly worn bearing. Other bearing materials are now being tested, and have out lasted the old bearing material almost three times longer.

The Houdini®-II system successfully performed challenging waste removal operations during the final four waste removal campaigns of the Gunite Tanks Remediation Project. The overall satisfaction with the modified system is high. Both of the Houdini® remotely operated vehicle systems were used as "mini bulldozers" to push sludge toward the confined sluicing intake. The vehicle's robotic arm was extremely valuable for its tool handling and grasping skills, and was successfully used for waste sampling, core sampling, debris consolidation, and waste removal operations. Although both Houdini®-I and Houdini®-II experienced a variety of component failures, the Houdini®-II is clearly an improvement over the Houdini®-I in reliability and accessibility for maintenance and repairs. The maintainability and reliability of the Houdini®-II system has increased considerably over its Houdini®-I counterpart. Most repairs on the Houdini®-II system were directly associated with the harsh environment it was required to operate in. When working in harsh environments, these types of repairs should be expected and factored into regularly scheduled maintenance. Both of the Houdini® remotely operated vehicles were important to successful waste removal operations in 8 large underground waste storage tanks conducted during the Gunite Tanks Remediation Project at ORNL.