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Houdini (TM): Reconfigurable In-Tank Mobile Robot

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Disclaimer

Abstract

This report details the development of a reconfigurable in-tank robotic cleanup system called Houdini™. Driven by the general need to develop equipment for the removal of radioactive waste from hundreds of DOE waste storage tanks and the specific needs of DOE sites such as Oak Ridge National Laboratory and Fernald, Houdini™ represents one of the possible tools that can be used to mobilize and retrieve this waste material for complete remediation.

Houdini™ is a hydraulically powered, track driven, mobile work vehicle with a collapsible frame designed to enter underground or above ground waste tanks through existing 24 inch riser openings. After the vehicle has entered the waste tank, it unfolds and lands on the waste surface or tank floor to become a remotely operated mini-bulldozer. Houdini™ utilizes a vehicle mounted plow blade and 6-DOF manipulator to mobilize waste and carry other tooling such as sluicing pumps, excavation buckets, and hydraulic shears.

The complete Houdini™ system consists of the tracked vehicle and other support equipment (e.g., control console, deployment system, hydraulic power supply, and controller) necessary to deploy and remotely operate this system at any DOE site. Inside the storage tanks, the system is capable of performing heel removal, waste mobilization, waste size reduction, and other tank waste retrieval and decommissioning tasks.

The first Houdini™ system was delivered on September 24, 1996 to Oak Ridge National Laboratory (ORNL). The system acceptance test was successfully performed at a cold test facility at ORNL. After completion of the cold test program and the training of site personnel, ORNL will deploy the system for clean-up and remediation of the Gunite storage tanks.

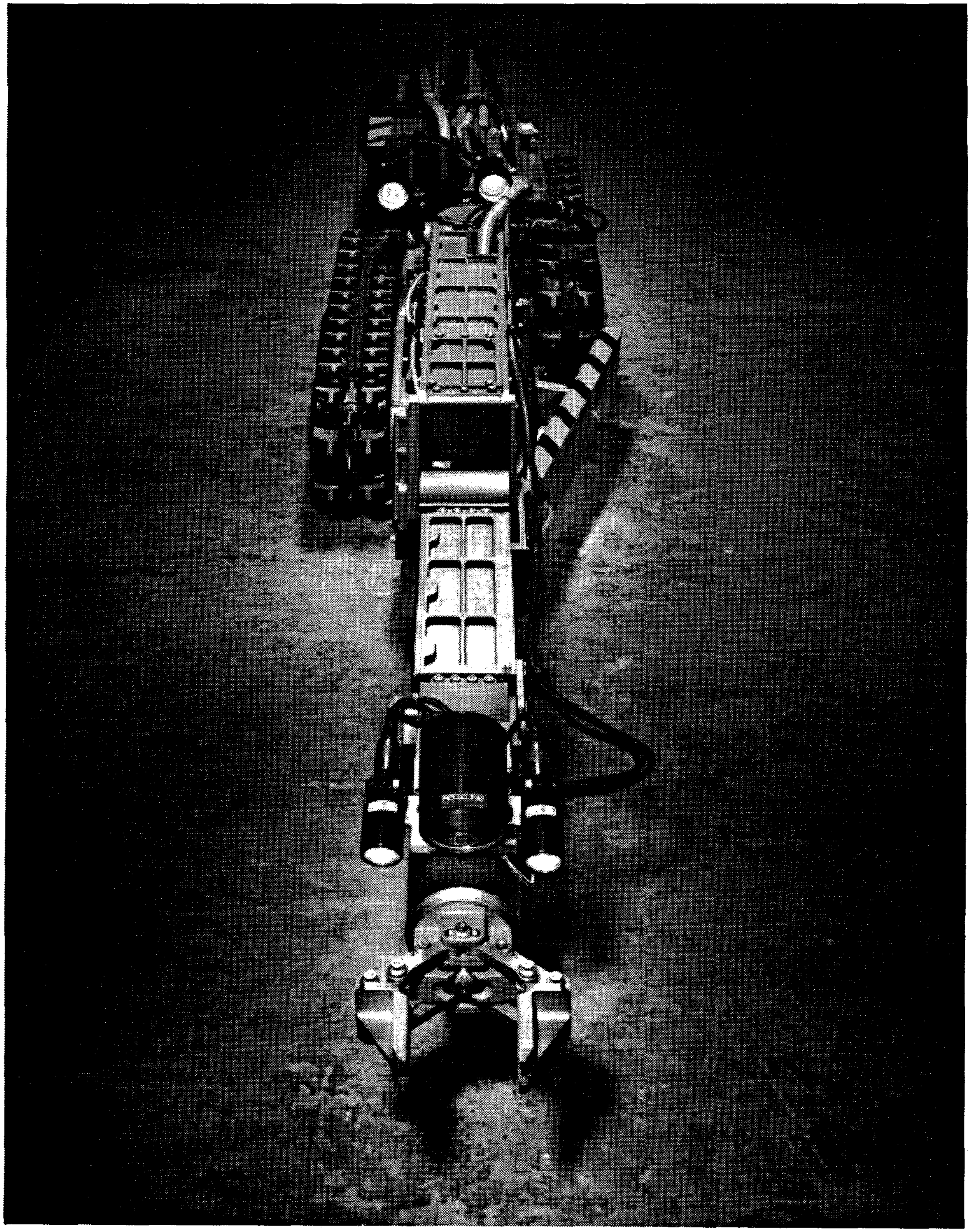

Figure 1 Houdini™ Vehicle

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Chapter 1: Executive Summary

1.1 Program

RedZone Robotics, Inc., in conjunction with Carnegie Mellon University (CMU) has completed the fabrication and testing of an innovative remote mobile vehicle platform to work inside waste storage tanks in support of the Department of Energy's (DOE) Environmental Restoration and Waste Management (EM) Program. The Houdini™ system will perform heel removal, waste retrieval, waste mobilization, waste size reduction, and other tank waste retrieval and decommissioning tasks. The project was funded by the DOE's Environmental Management Office of Technology Development through the Morgantown Energy Technology Center (METC). While originally tailored to the specific needs of the Oak Ridge National Laboratory and Fernald applications, the goal of the Houdini™ project was to develop a technology that would be useful for in-tank operations throughout the DOE's EM program.

1.2 Technology Description

The Houdini™ system consists of five main components and their subsystems; the vehicle, the power distribution and control unit (PDCU), control console, tooling, and the tether management and deployment system (TMADS). See Figure 2. Once deployed, Houdini™ expands to provide a powerful work platform with a substantial footprint (40 inches x 55 inches). Rugged design and sturdy construction make it well-suited for the rigors of waste mobilization and other heavy work tasks. Houdini™ also provides simple, familiar material handling similar to conventional earth-moving equipment such as bulldozers and backhoes. Houdini™ is a reliable, cost effective work platform that achieves performance objectives with minimal risk. For a description of competing technologies, see Appendix 1 pages 18 - 21.

Vehicle

The vehicle is a hydraulically-powered, track-driven, folding frame machine similar to a small bulldozer. The vehicle can fold to fit through a 22.5 inch diameter opening for deployment, and is equipped with a plow blade and a manipulator arm. The plow blade also folds for deployment and can be height-adjusted for plowing materials at various rates. The manipulator is a Schilling Titan class hydraulic dexterous manipulator, which can deploy a variety of tooling to perform work inside a tank. The vehicle tether is attached to the rear of the folding frame assembly. The tether termination will support the full weight of the vehicle and tooling to enable deployment and retrieval. Controlled by an operator who sits at a console outside the work area, Houdini™ provides ample feedback from the work area via multiple cameras, microphones and instrumentation that reports equipment status. Two camera and light assemblies provide visual feedback for remote operation. One camera and light unit is mounted on the forearm of the manipulator and is aimed by orienting the manipulator. The second camera, mounted at the rear corner of the vehicle, includes a pan and tilt unit.

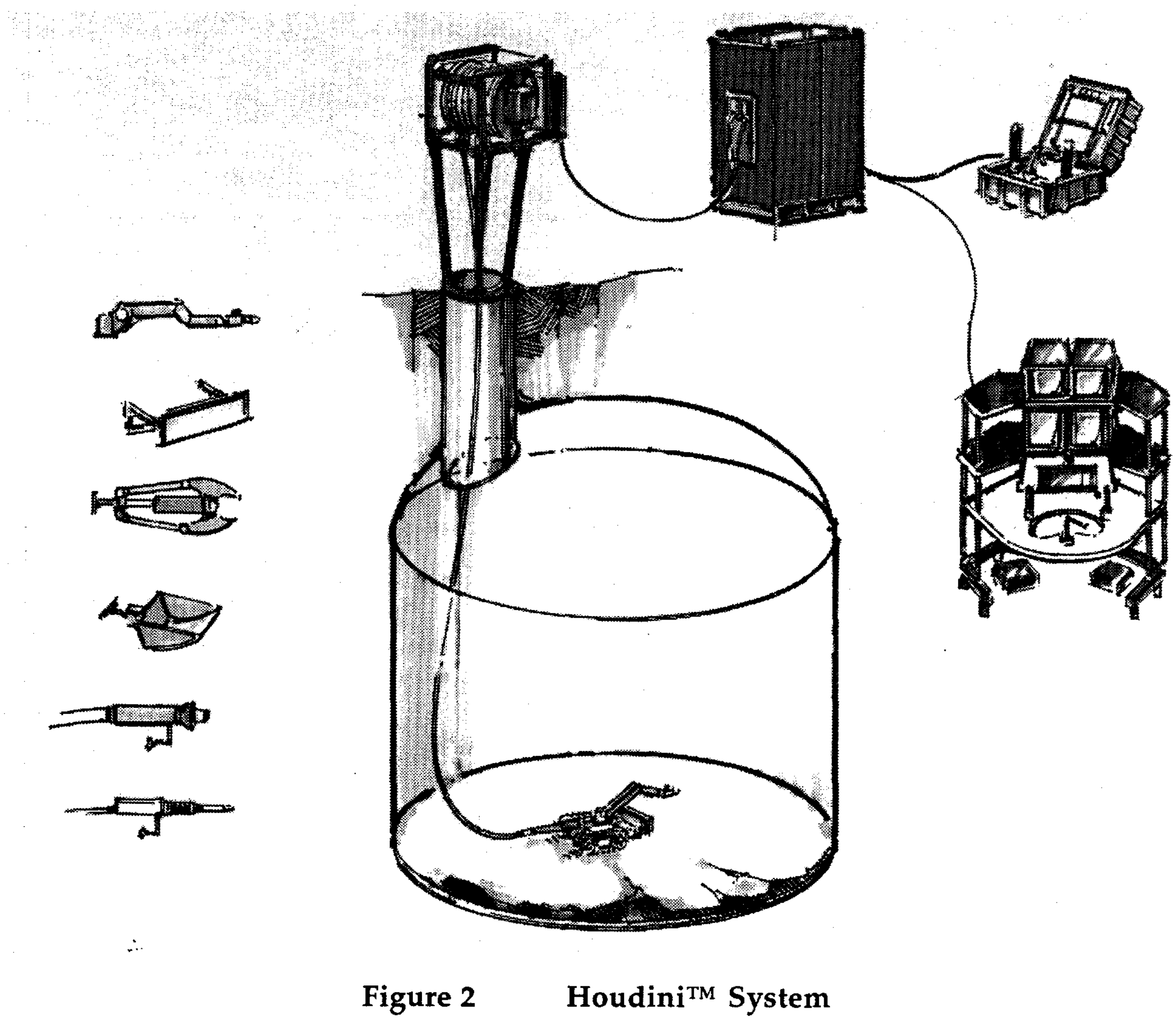

Figure 2 Houdini™ System

Power Distribution and Control Unit (PDCU)

The PDCU houses two pieces of equipment: the electrical enclosure, and the hydraulic power supply (HPS). The PDCU is where all the site interface connections are made, and it serves as the interface between the robot and the operator control console.

Control Console

The control console provides the operator interface to the Houdini™ system. The console includes joysticks, switches, a master manipulator, and video monitors for controlling system functions and monitoring system operation. The control console incorporates ergonomic design considerations for long duration operation. A suitcase controller is available to perform system checkout, local operations, and provide for emergency operations in the case of console/control computer or telemetry failures between the control center and the PDCU. Switches, buttons, and a single remote viewing monitor provides for simple operations from the suitcase controller.

Tether Management and Deployment System (TMADS)

The TMADS provides a convenient way to remotely manage and store the tether, provides the lifting force needed to lower and raise the vehicle to and from a tank, provides a "docking area" for securing the vehicle during storage or transport, and provides a storage area for tools and spare parts. The TMADS system also provides containment when open to the tank atmosphere.

The tether reel is 48 inches in diameter and 30 inches wide. Payout of the tether is controlled by a mechanical level-wind system that precludes tether entanglement during deployment and retrieval operations. The tether reel is driven by a hydraulic motor with a fail-safe brake in case of hydraulic power loss. The hydraulic motor provides a pull force of 3000 lbf, three times the vehicle weight. A payout sensor is used to monitor the length of tether that has been reeled out.

Tooling

Specialized tooling can be deployed from the onboard manipulator or plow blade, depending on application needs. A squeegee located along the bottom of the plow blade provides efficient mobilization of the waste slurry on the floor of the tank. Other tooling, such as shears, scoops or spray wands can be integrated for deployment from the manipulator. For vacuum retrieval operations, Fernald will provide a hose grip that will attach to the Houdini™ manipulator and enable the deployment of a pneumatic vacuum hose. The primary tool for the ORNL retrieval campaign is a waste dislodging and conveyance end effector which will be deployed and moved throughout the waste tank using the Houdini™ platform.

1.3 Results

RedZone has been able to design fabricate, test, and deliver a system ahead of the initial schedule and 20% under budget. The system was delivered to Oak Ridge on September 24, 1996 and has been in operation at their cold test facility for several months in preparation for the hot deployment in the Gunite tanks in early 1997. Results of this activity are being collected by Oak Ridge National Laboratory, Fernald, and RedZone for subsequent use in the redesign activities for the second

Houdini™ system. All indications are that a vehicle based system is a viable approach to waste retrieval.

The development of the Houdini™ system for tank waste retrieval has opened the eyes of many people to the benefits of an in-tank vehicle, and has provided a lower cost alternative to Long Reach Manipulator technology. It has also provided solutions to retrieval problems where LRM's cannot be used. This project has directly resulted in the development of a second system to aid in waste retrieval at another DoE site (Fernald). It has also been of interest to commercial entities for use in non-tank application.

1.4 Future Activities

Immediate plans are underway for the development of a second Houdini™ system to be delivered to Fluor Daniel Fernald in 1997. This second system will be used in the waste retrieval of silos 1,2, and possibly 3 at the Fernald site in Cincinnati, OH. Work surrounding this activity has already begun. The initial task is to evaluate the first Houdini™ system and develop a lessons learned list that will be used to improve the second system. This will be followed by conceptual designs for implementing those lessons learned. Redesign activity is scheduled to begin in or around March of 1997.

1.5 Conclusions and Recommendations

Evaluating the merits of the Houdini™ system for these applications requires comparing it to competing technologies. In comparison to mobile robot systems that are currently available, the folding frame technology on Houdini™ provides a substantially larger work platform which can fit through existing tank openings. As a larger platform, Houdini™ is more powerful, more efficient, and more capable than other, smaller mobile systems.

Several non-robotic retrieval methods are also being planned for use in various DOE tanks. These technologies, such as sluicing, pumping, and pneumatic conveyance, are appropriate or preferred technologies for some of the tanks in the complex. As it will at Fernald and ORNL, Houdini™ can assist in the application of these retrieval and conveyance methods.

Depending on specific work tasks and application sites, Houdini™ can be deployed to either complement or replace a long-reach manipulator (LRM) system. Used in conjunction with LRMs, Houdini™ provides additional or enhanced capabilities inside a tank. In tasks where Houdini™ is preferred instead of LRMs, Houdini™ will be simpler and less expensive to deploy, operate, retrieve, and decontaminate than LRMs.

As a technology for supporting the DOE's EM program, and in comparison or collaboration with other competing technologies, Houdini™ provides many benefits. Because of the similarity to bulldozers and backhoes from the construction industry, Houdini™ provides simple, intuitive, and efficient waste handling techniques. The transportation, installation, deployment, and removal operations are simple due to its compact size. The simplicity and operational capability of Houdini™ lead to cost efficiency with respect to development, operation, and maintenance.

Chapter 2: Introduction

Within the DOE Complex, 332 underground storage tanks have been used to process and store radioactive and chemical mixed waste generated from weapon materials production. Together, these tanks hold more than 100 million gallons of high-level and low-level radioactive waste, very little of which has been treated and disposed of in final form.

The initial objective of the Houdini™ project was to develop the Houdini™ system specifically for deployment at the Fernald site in Cincinnati, OH. During the course of the design process, the design was developed through several design reviews with personnel from Fernald Silos project staff, Fernald Operable Unit 4, and FETC. Just before the fabrication phase of the project, the first Houdini™ system was re-directed to the Oak Ridge site for subsequent deployment into the Gunite tank's north and south tank farms with the understanding that a second Houdini™ system would be built for waste retrieval the Fernald site.

The ultimate goal of the program is to develop and commercialize the Houdini™ system for broad application throughout the DOE Complex. Each system module is available separately and can be customized to meet the requirements of specific tank and non-tank applications at Oak Ridge, Fernald, Hanford, Savannah River, Idaho, West Valley and other sites. Likewise, the Houdini™ system could be applied to commercial applications in the private sector.

2.1 CMU Pre-Prototype

2.1.1 CMU's Effort

Carnegie Mellon University's role in the Houdini™ project, as subcontractor to RedZone, was to develop a pre-prototype system to perform geotechnical testing and gather data relating to overall vehicle performance, vehicle sinkage, traction, drawbar pull, etc. (See Appendix 1 for a full account of CMU's activities.) CMU succeeded in designing a vehicle which ultimately proved the merit of the Houdini™ system for tank waste retrieval. See Figure 3. The pre-prototype was completed and sent to RedZone around October 1995. At that time, RedZone was contacted by Oak Ridge regarding their planned effort to evaluate the use of small remotely operated vehicles for carrying waste retrieval equipment into hazardous waste tanks. RedZone decided to use the CMU developed pre-prototype in this study. RedZone conducted testing of the pre-prototype system in a test pit at RedZone's facility prior to sending it to Oak Ridge for a two week period in December of 1995. In those test, it was discovered that several items had to be addressed before participation in that study. RedZone made design improvements to the controls, control pendant, wiring, track, and tread grousers before sending the system to Oak Ridge. The pre-prototype was extremely useful to RedZone in making key design decision about the final design of the Houdini™ vehicle.

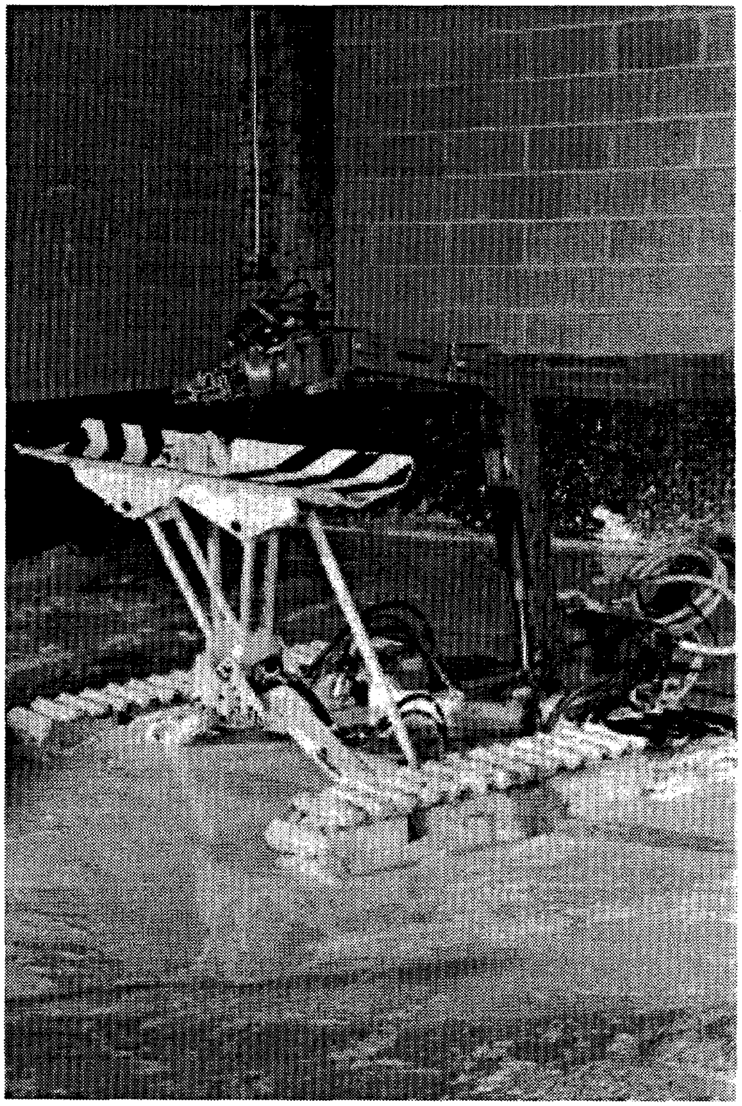

Figure 3 CMU Pre-Prototype in RedZone Tank Mockup

2.1.2 Houdini™ Vehicle Design

The most significant design problem with the pre-prototype was the multiple grouser tread design, which was susceptible to clogging and jamming in the clay-like Gunite tank surrogate waste. This was one of the drivers for RedZone's decision to move to an off the shelf, continuous tread design for the Houdini™ system.

Other realizations early in the project led to the adaptation of a collapsible parallelogram frame design as opposed to the CMU proposed collapsible "diamond" shaped frame design. Notably, there were clear advantages to the parallelogram design because it reduced the number of actuators required to open and close the frame (three rotary actuators vs. one linear). Likewise, the plow blade could be actuated with one linear actuator instead of the two rotary actuators on the CMU machine. It should also be noted that the actuators on the prototype did not generate enough torque to reliably open the frame while in the hanging position or to hold the frame solidly open while turning the vehicle left and right.

Other factors that were considered in changing the frame geometry were based on the overall size of the vehicle and the placement of the Schilling manipulator on the vehicle. It was determined that the pre-prototype's overall size in relation to the manipulator severely limited it's effective workspace, and that maneuvering a large vehicle in tanks as small as 25 feet in diameter could be challenging.

As a result, the smaller, off-the-shelf tread lent itself to the need to build a slightly smaller vehicle, and the parallelogram design allowed the placement of the manipulator to be near the front of the machine, increasing the manipulator's usable workspace.

2.2 ORNL Bake-off

2.2.1 Background

In December of 1995, Oak Ridge National Laboratory conducted an "Evaluation of Remotely Operated Vehicle Systems for Deployment in Inactive Waste Tanks". This effort was known as the "ORNL Bake-off" as it's objective was to test several, currently available vehicle systems for use in the waste retrieval efforts of the Gunite tanks. The vendors in these evaluations were ROV Technologies, RedZone Robotics, and a team comprised of Advanced Sciences Incorporated and Framatome. All vendors were required to supply an existing vehicle, support equipment, and operators to participate in a two week testing period in a mockup of the Gunite tanks and surrogate waste material. Although RedZone had not yet developed the final Houdini™ system, we were able to participate with the CMU developed pre-prototype.

2.2.2 Testing Program

Each vendor performed tests according to a detailed test plan that was intended to simulate situations expected inside waste tanks. Key aspects of the testing program centered on the vehicle ability to drive through the simulated waste without getting stuck, having the ability to carry a 60 pound confined sluicing end effector and attached hoses, and reliability. The simulated waste was a mixture of sand, clay, pebbles, and water which varied in depth from a few inches to twelve inches. Other tests focused on items such as:

- vehicle weight, size, tether
- site requirements
- maneuverability, stability, payload, user interface, sensors
- deployment and retrieval through simulated riser, fail-safe retrieval
- submersibility, decontamination
- remote operation, cameras
- end effector grasping and positioning
- waste mobilization

2.2.3 Results and Conclusions

As a result of testing conducted over a two week period, it was determined that the Houdini™ prototype proved to be an adequate machine, and a good candidate for waste tank remediation. The prototype machine developed by CMU performed sufficiently to prove the merit of the Houdini™ system that was currently being designed. It was this vehicle testing program that began the required contract modification to send the first Houdini™ system to Oak Ridge, instead of Fernald. This was achievable due to the expected near term need at Oak Ridge and the schedule flexibility that could be afforded at the Fernald site.

2.3 ORNL Design Modification

When the decision was made to redirect the first Houdini™ system (in the assembly and integration phase) to Oak Ridge in support of North and South tank farm waste retrieval, RedZone had to address the major difference is in the existing infrastructure (bridge platform) over the tanks and the plans for deployment, decontamination, and maintenance. The only part of the system that was affected was the Tether Management and Deployment System (TMADS). Originally designed to be installed at the Fernald site in Ohio, the TMADS was to hang from the roof of an equipment room that would be constructed over the tanks. At Oak Ridge, the TMADS was to rest on the bridge platform that had been constructed over the North and South tank farms as well as the Cold Test Facility. To accomplish this, RedZone had to provide two pieces of equipment and perform several modifications to the TMADS. The two pieces of equipment were the TMADS stand and the containment bezel. See Figures 4 and 5. The purpose of the TMADS stand is to support the TMADS over the tank riser. The containment bezel connects the TMADS to the wash down spray ring and tank riser and is located between the bottom of the TMADS and the spray ring provided by ORNL. It provides containment while the riser is open and will be used to introduce tools into the tank and for removal of tank non-pumpables. Other modifications that were made include:

- addition of glove ports and viewing windows to the TMADS
- addition of a spray wand inside the TMADS to aid in decontamination
- addition of a barrier to block between the tether reel and the storage compartment contamination from hitting the tether reel during decontamination with the spray wand.
- addition of an access port to introduce a camera inside of TMADS
- addition of a safety chain to secure the vehicle during maintenance

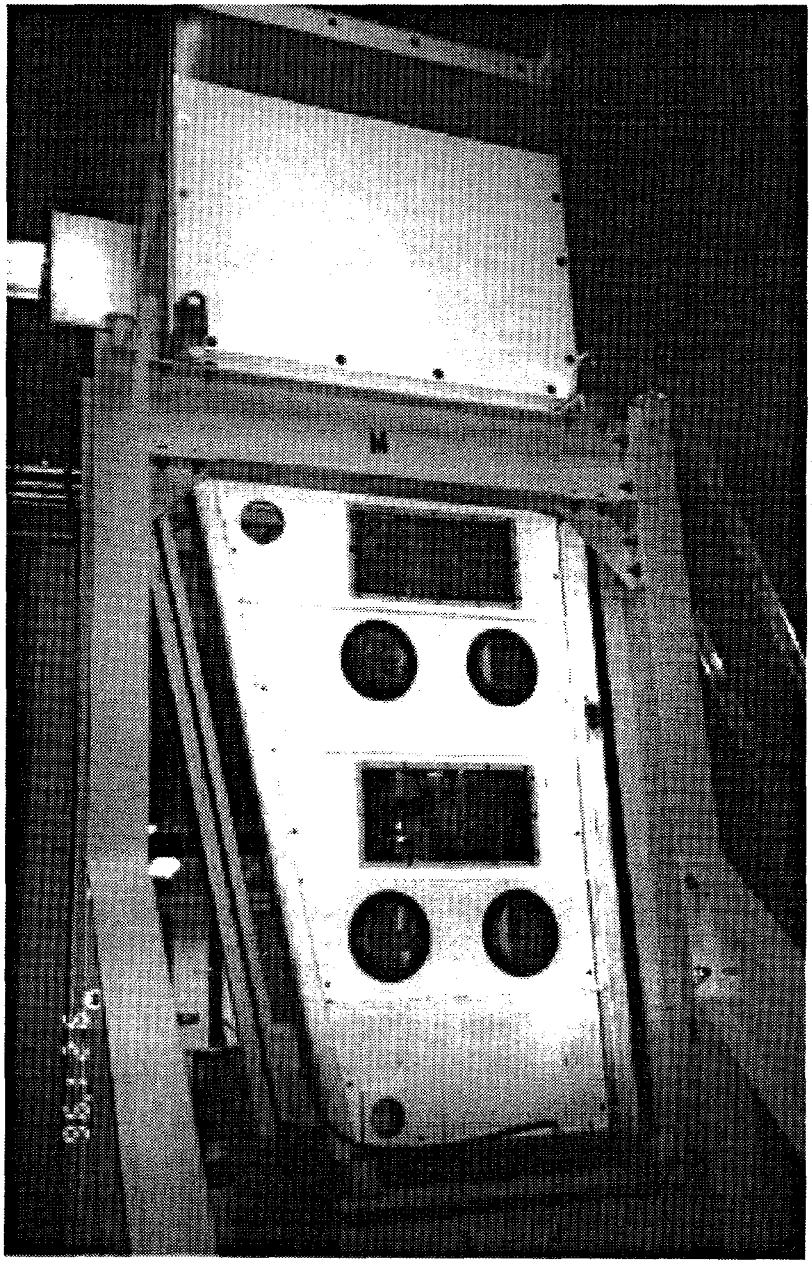

Figure 4 TMADS on ORNL Stand

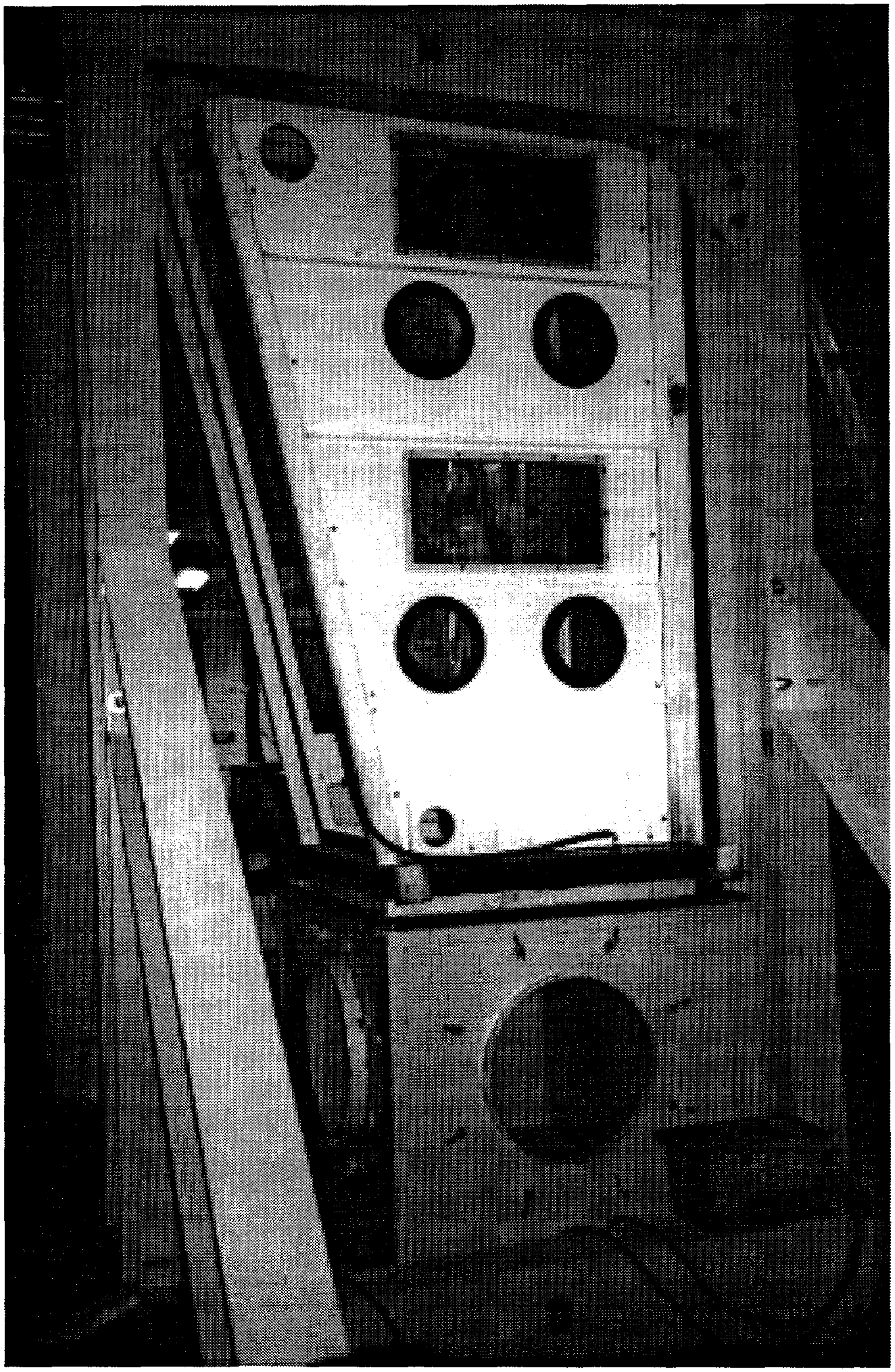

Figure 5 **TMADS on Stand with Containment Bezel**

Chapter 3: System Description

3.1 Vehicle

The centerpiece of the Houdini™ system is the vehicle. See Figure 6. It is a tethered, hydraulically-powered, track driven, tele-operated, work machine with a folding frame chassis that allows it to fit through a 24 inch nominal diameter opening. When fully deployed, the vehicle has a footprint that is 44 inches wide and 48 inches in length. Its overall size and weight gives the vehicle excellent turning characteristics and maneuverability and plenty of plowing force. The vehicle is capable of locomotion over and through a variety of waste forms. It can operate fully submerged as long as sufficient support and traction is available (such as on the floor of the storage tank). The ability of the vehicle to be used on top of the waste surface depends largely on the mechanical characteristics of the waste material, the amount of water that is added to the waste, and the effect of the water on that waste.

The operator directly controls the vehicle's motions from the control console. The vehicle has four functions:

- left track drive (forward/reverse)
- right track drive (forward/reverse)
- plow blade (raise/lower)
- vehicle frame (open/close).

All four functions are hydraulically actuated. One hydraulic cylinder is used to open and close the frame of the vehicle, and one smaller cylinder is used to raise and lower the plow. The plow blade is used for breaking up heel at the bottom of waste tanks and mobilizing (pushing) this material to a waste conveyance system (pump) for removal. It is also used as a stiff arm to support larger payloads for the manipulator. Two rotary actuators provide the drive force for each track. The vehicle can be driven forward, reverse, or along any path by varying the relative speeds of the two tracks. The vehicle can also be turned about its own axis by driving the tracks in opposite directions.

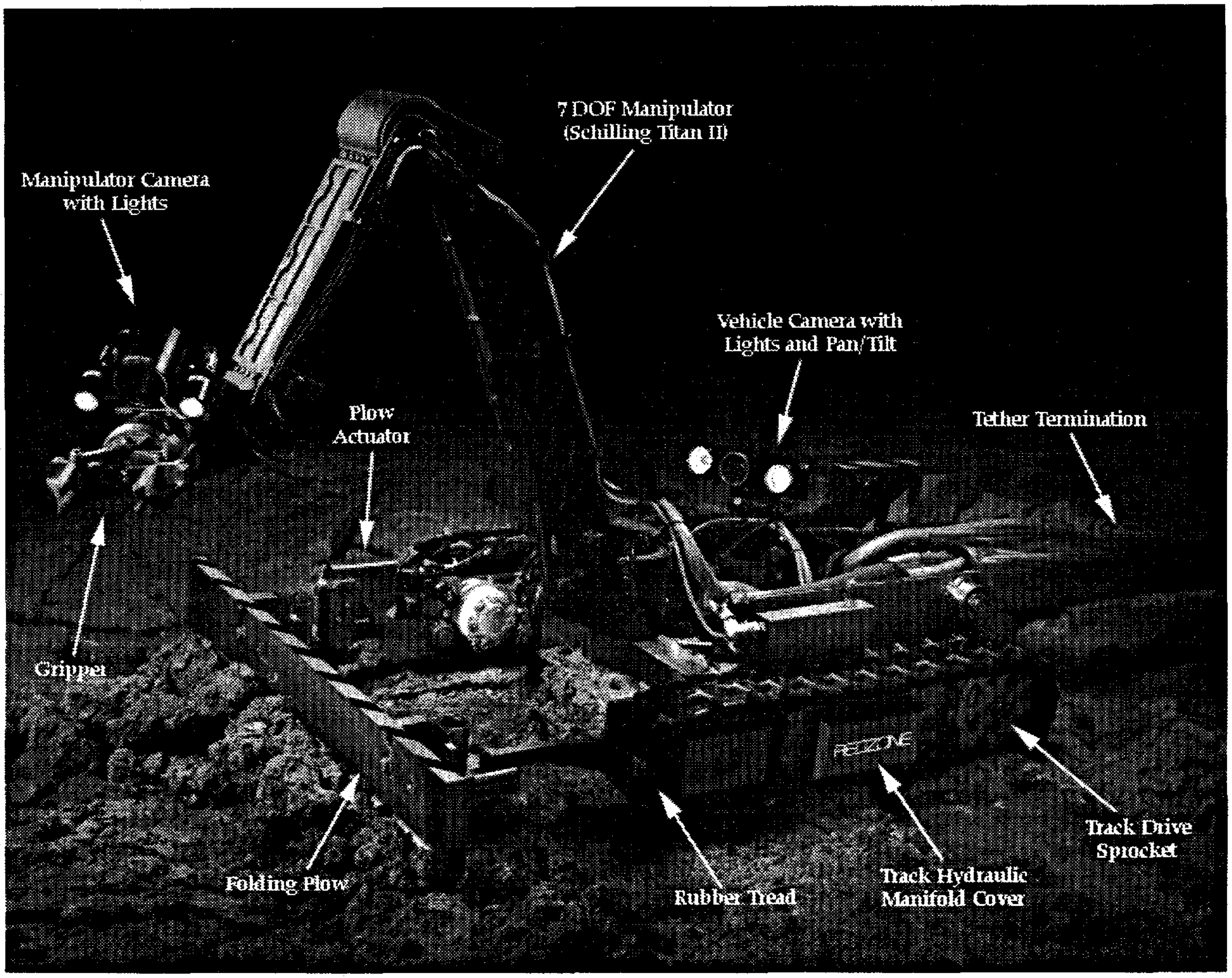

Figure 6 Houdini™ Vehicle

Manipulator

A Schilling Titan II (6-DOF) manipulator is mounted to the frame and is used for object retrieval (unpumpables) and operation of specialized tooling such as the Confined Sluicing End Effector (CSEE). Tooling must be equipped with a T-handle interface to the standard Schilling gripper. The manipulator is made of corrosion resistant Titanium and can also operate fully submerged. The interface to the manipulator is through the slave controller (mounted on vehicle) and a master consolette that is integrated into the RedZone control console. The Schilling arm provided with this vehicle has been upgraded to allow joint angle positions to be read through the RS-232 port at the rear of the control rack. Refer to the Schilling Technical Manual (System Serial Number 10891) for specific information.

Cameras and Lights

Two color CCD cameras are mounted on the vehicle. The vehicle camera is mounted to the rear of the right track, several inches above track height. It has two 75 watt wet/dry lights for illumination and is mounted to a pan and tilt unit. The lights do not have intensity control. The camera has an automatic iris that adjusts for changing light conditions. It also has a 12:1 zoom function, and can be either manually or automatically focused. It is used for driving the vehicle, monitoring the tether, and gross positioning of the Schilling arm when attempting to grasp an object.

The manipulator camera is fixed to the Schilling arm, near the gripper. There are two 75 Watt wet/dry lights mounted adjacent to the camera to illuminate the area directly in front of the grippers. The lights do not have intensity control. The camera has an automatic iris that adjusts for changing light conditions. This fixed focal length camera, fitted with a wide angle lens, provides two functions. First, it provides a useful view for performing dexterous tasks such as picking up a glove or wrench and grasping tooling. Second, the Schilling arm can be positioned such that the camera is useful for driving. The manipulator arm serves as a fast pan/tilt unit for looking around the vehicle.

Tether Termination

The tether is terminated at the rear left track of the vehicle. The termination is a trunnion style pivot that allows approximately 30 degrees of rotation to successfully deploy and retrieve the vehicle. It is mechanically connected to the left track manifold so that the vehicle is free to collapse under gravity upon emergency retrieval.

3.2 Tether Management and Deployment System (TMADS)

TMADS Stand

The purpose of the TMADS stand is to suspend TMADS over the tank riser. Internal cross bracing has been minimized to allow unobstructed access to all four sides of the storage compartment of TMADS for decontamination and routine maintenance. The TMADS stand is a structural piece of equipment that is bolted to the TMADS. It has no moving parts and the operator does not directly interact with the stand.

TMADS

The TMADS consists of two compartments, the Reel Compartment and the Storage Compartment. See Figure 7. The Reel Compartment is the upper portion of TMADS. It houses the tether reel and the reel drive components. The operator controls the function of the tether reel by deploying or retrieving tether as relevant to vehicle operation. The operator monitors the amount of tether that has been let out by watching the tether payout indicator on the console.

The Storage Compartment is the lower portion of TMADS where the vehicle is stored when it is not deployed in the tank. The operator controls the operation of the storage compartment door. This door must be fully opened before and during deploying and must be fully closed after retrieval. The tether reel will not function unless the door is fully opened, and the door will not be able to close unless the vehicle is completely retrieved.

Five pairs of glove ports and two viewing windows are available on the east and west sides of the storage compartment. The ports and windows are used for routine maintenance and manual decontamination of the vehicle. During manual wash down or maintenance, where personnel are in close proximity to the vehicle, a safety chain may be manually attached to the vehicle as a safety precaution. A hose reel and spray wand are provided inside the storage compartment to facilitate manual wash down of the vehicle. The hose reel is manually operated via a hand crank. A synthetic rubber barrier is located between the Reel Compartment frame and the Storage Compartment frame. This barrier confines the spray caused by manual wash down to the Storage Compartment, decreasing the possibility of adding contamination to the reel compartment.

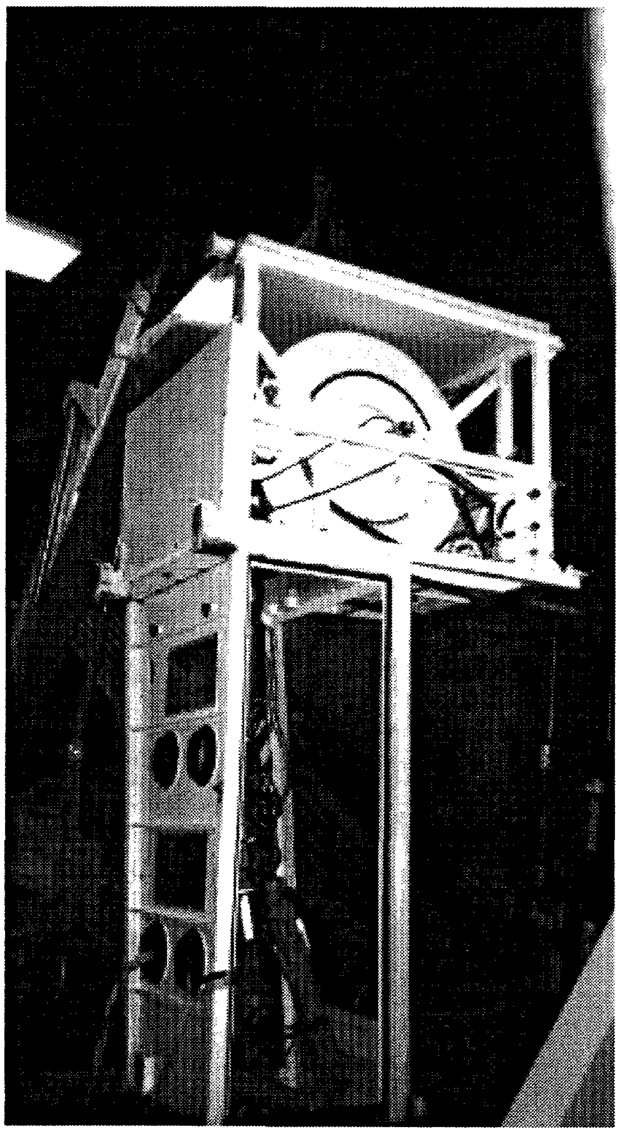

Figure 7 TMADS

Containment Bezel

The containment bezel (CB) is located between the bottom of TMADS and the riser extension. The operator does not control any functions on the containment bezel. The bezel provides containment while the riser is open and will be used to introduce tools into the tank and for removal of tank unpumpables. There are two sealed access doors for loading and unloading discrete tooling.

3.3 Power Distribution and Control Unit (PDCU)

The PDCU is an enclosure that can be positioned up to 75 feet from the deployment riser. It's function is both the "brains" and the "muscle" of the Houdini™ system. It is comprised of two subsystems. The electrical enclosure is the "brains" of the system and the hydraulic power supply (HPS) is the "muscle" of the system. See Figure 8.

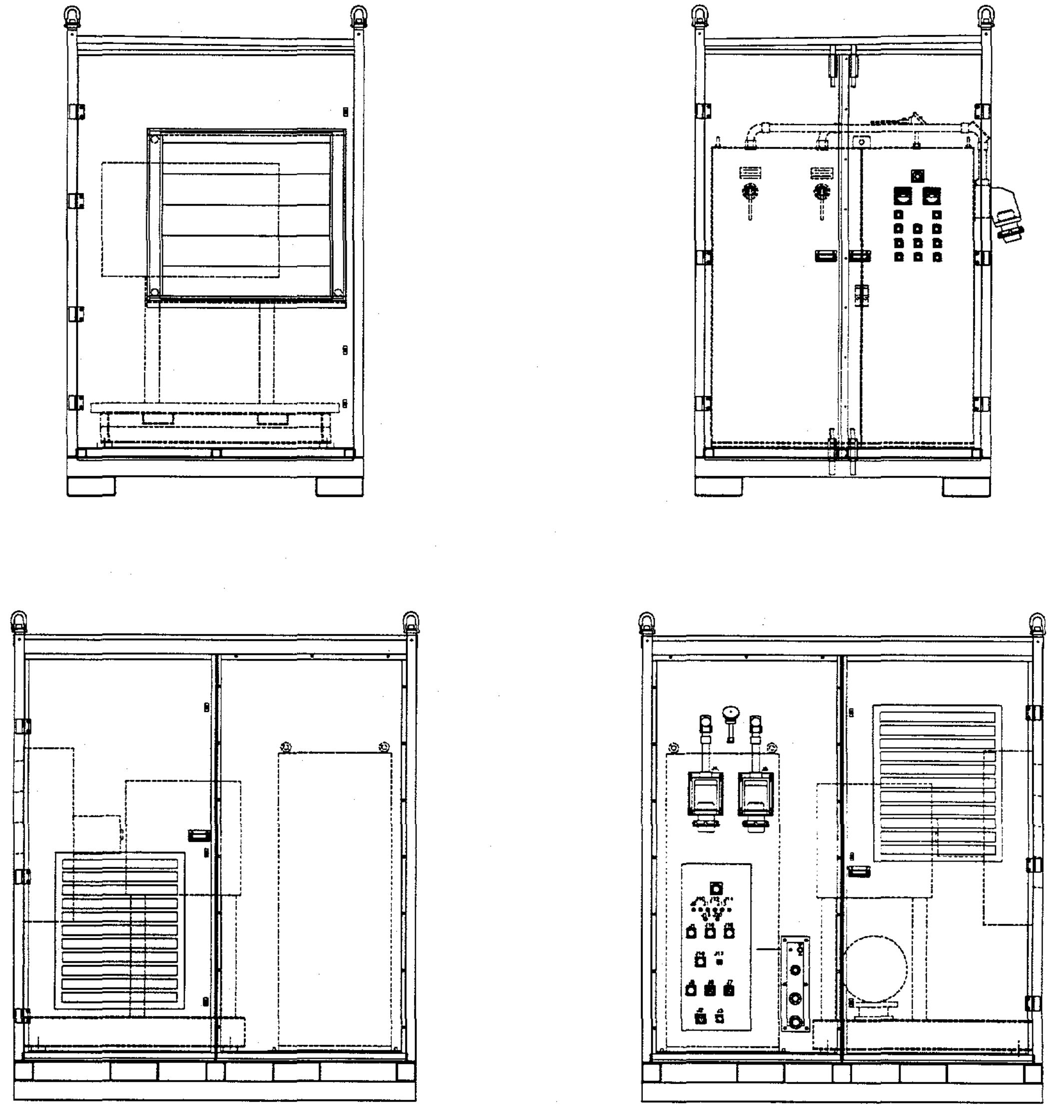

Figure 8 PDCU

The PDCU structure is fabricated from welded steel tubing. Lifting rings are provided in each of the four upper corners of the structure to allow for positioning via an overhead crane. Fork lift points are provided from each direction to facilitate transportation while at ground level.

The sides, and roof of the PDCU are fabricated from fiberglass reinforced plywood panels and function as insulation, protecting the PDCU at the lower range of operating temperature. The exterior of the FRP panels are glossy white and reflect the sunlight, minimizing heat build-up within the PDCU during the summer months.

The electrical enclosure side of the PDCU has a set of overlapping doors, hinged to provide access to the electrical enclosure. The HPS side of the PDCU has a removable panel to provide access to the HPS for maintenance.

A cutout in the FRP panel provides access to the bulkhead mounted connectors on the electrical enclosure. Another cutout in the FRP Panel provides access to the hydraulic quick disconnect connectors mounted on the HPS, and to the connection point for the heat tracing cable. A ventilation panel near the electrical enclosure provides the air inlet for the electrical enclosure heat exchanger. A louver assembly near the HPS provides an air supply for the HPS heat exchanger.

3.3.1 Electrical Enclosure

The electrical enclosure meets NEMA 4 standards for sealing, and is manufactured by Rittal. Site power enters the enclosure through two box mounted weatherproof flanged inlets. Site power requirements are 480 VAC, 3Ø, 90 Amps, and 120 VAC, 1Ø, 50A. See Figure 9.

Two circuit breaker operating mechanisms are mounted on the left door of the enclosure. The leftmost is for the 120 VAC 1Ø, and the rightmost is for the 480 VAC 3Ø power. The operating mechanisms are lockable in the OFF position to prevent unauthorized energizing of the equipment. The operating mechanisms also secure the electrical enclosure doors in the ON position to prevent access to the hazardous voltages that exist inside the enclosure during operation.

The right door of the electrical enclosure is the message area of the system. It contains an elapsed time meter for the HPS pump and the kidney pump, and indicators which provide a visual status of the 3Ø Monitor, the 1Ø Monitor, the HPS main pump, the kidney loop pump, the heat exchanger fan, the pressure line filter, the kidney loop filter, the TMADS filters, the reservoir temperature, the reservoir level, and the system pressure.

The right side of the electrical enclosure contains bulkhead mount electrical connectors to allow for rapid deployment and movement of the PDCU between tank locations. Additionally, it contains an Emergency Stop push-button which disables the hydraulic system when pressed.

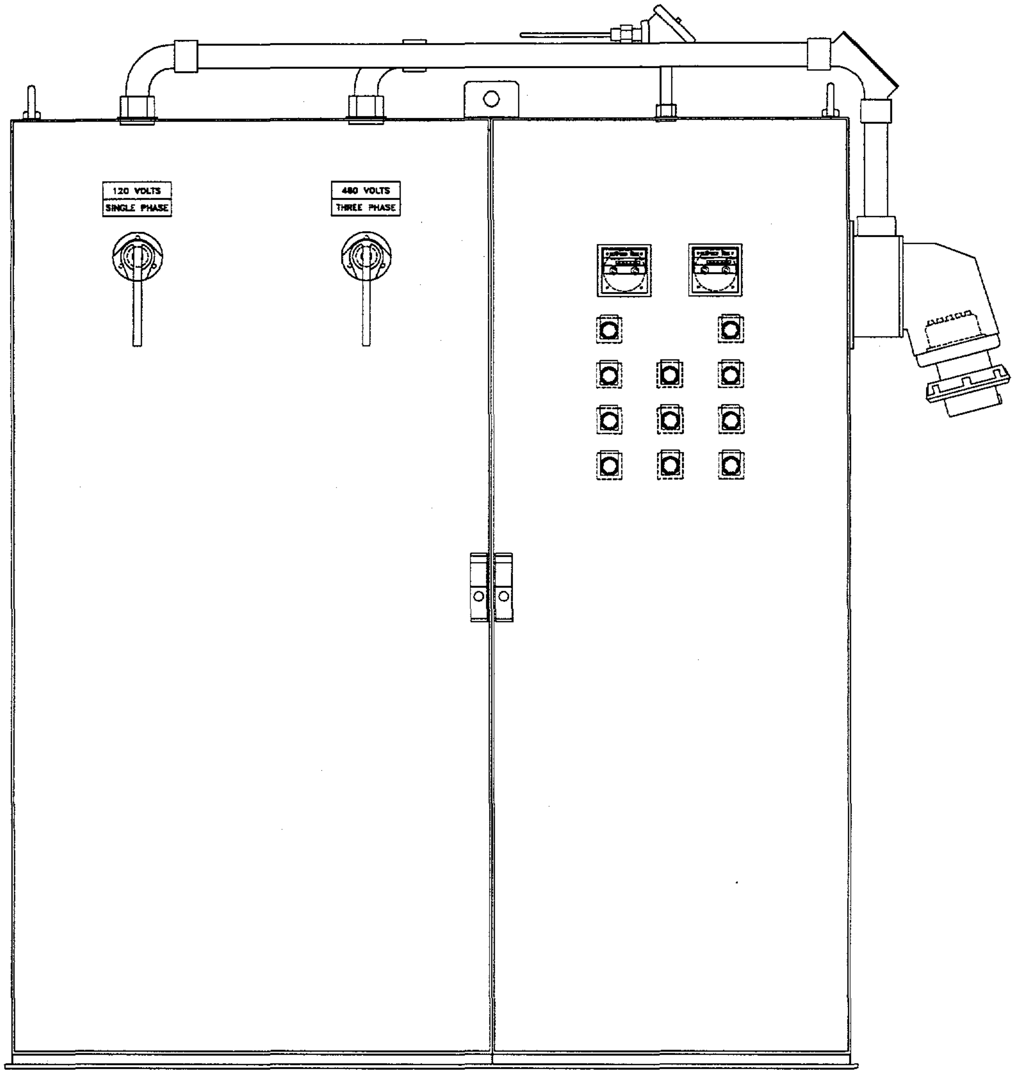

Figure 9 PDCU Electrical Enclosure

Behind the left door is the switch gear used for control of the HPS and the robot. The panel mounted circuit breakers mate with the handles on the door and function as the main power disconnect switches for the PDCU. The circuit breakers are 3 pole breakers and will open should a short circuit occur in either the electrical enclosure, the hydraulic power supply, the tether, or the robot. They include a ground fault sensor to provide an extra measure of safety for equipment protection. Fusing is installed to provide a second degree of protection should circuit overloads occur. Overload relays are provided to protect the motors on the HPS. A three phase monitor watches the incoming 480 VAC power and detects a phase loss, a phase reversal, a phase unbalance and an under voltage condition. A single phase monitor watches the incoming 120 VAC and detects under voltage conditions. The main power contactor inside of the PDCU is controlled remotely from the control console (or suitcase controller). No power can be applied to the Houdini™ robot or its hydraulic system until this contactor is engaged.

Behind the right door is the industrial controller and I/O modules used to control the HPS, the robot, and the control console. The industrial controller is programmed in Cyrano 200, a multitasking language developed for industrial control.

The local and remote I/O modules of the controller are in themselves intelligent controllers, providing distributed control of the system. Each I/O module has separately programmable addresses, watchdog timers, interrupts, and event/reactions. The digital I/O modules can implement input latching, edge detection, square wave outputs, pulse outputs, frequency inputs, and pulse period detection. The analog modules can implement filtering, slew rate limiting, level detection, automatic scaling, and unit conversion. They can interface to virtually any analog sensor, voltage or current. Additionally, the analog modules can implement PID control loops local to the modules. Each I/O point is optically isolated from the sensor and the other channels to 4000 VAC. All digital output points contain fusing to prevent damage to the I/O unit should a short circuit occur.

On the right side of the enclosure are the driver boards for the servo valves that convert the voltage signals from the industrial controller I/O modules to the current levels required by the servo valve.

3.3.2 Hydraulic Power Supply

The HPS consists of a skid mounted motor, pump, 50 gallon reservoir, and control enclosure. Together, they supply 10 gpm to power both the Houdini™ vehicle and the hydraulically driven tether reel. All moving components of the motor and pump are covered to prevent accidental injury in accordance with OSHA standards. A bell housing covers the pump/motor coupling and a guard covers the motor fan.

The HPS contains a separate cooling and filtration "kidney" loop which provides filtration to ISO 12/9 (less than 17 particles per ml larger than 5μ, and less than 2 particles per ml larger than 15μ). Again, all moving components of the motor and pump are covered to prevent accidental injury.

A heat exchanger (Thermal Transfer AO-40) is included in the kidney loop to provide cooling for 100% of system capacity up to 100 °F ambient air temperature. A resistive heating element is installed in the reservoir to maintain hydraulic fluid temperature at 40 °F minimum which will allow system startup in temperatures as low as -0 °F.

Two pressure switches are mounted on the HPS to provide system pressure feedback. A level sensor and a temperature transmitter are installed in the reservoir to provide status of the hydraulic fluid. These sensors are monitored by the industrial computer in the electrical enclosure and reported to the operator on the control console. Additionally, these signals are monitored by the interlock circuitry and can disable the HPS should a fault occur.

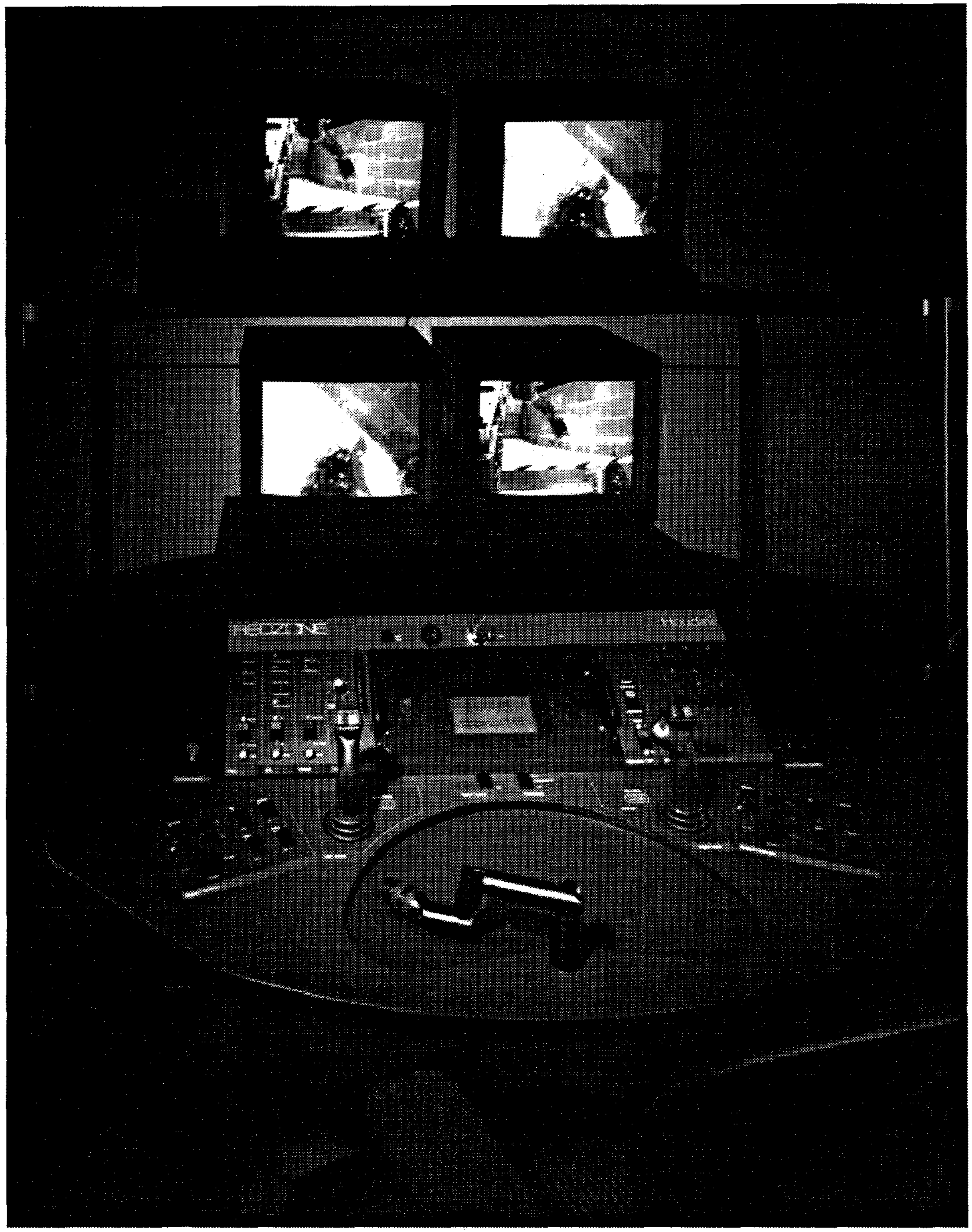

Figure 10 Operator Control Console

3.4 Control Console

The control console provides control and monitoring of the Houdini™ system from a remote location up to 300 ft from the PDCU. See Figure 10. The control console contains two joysticks, two dual foot pedals, a 6-DOF master consolette, various switches and indicators, and four remote-viewing monitors. The operator can control the vehicle with standard joystick inputs or choose "hands free" operation utilizing the foot pedals. A slanted status panel and audible alarm keeps the operator aware of any system malfunctions, while views from the two vehicle cameras and two overview cameras (customer supplied) are displayed on the monitors. To control the Schilling arm, the standard Schilling consolette has been incorporated into the status panel, and the master arm has been relocated to the front edge of the console control panel. A kidney shaped insert in the control panel can be removed to allow the operator to dip the master arm below panel level. The Schilling consolette and master arm are easily removable for transfer to the suitcase console when required.

The operator panel assembly replaces the desktop supplied with the Anthros furniture. It contains all the controls and feedback necessary for operation of the Houdini™ system. As seen in Figure 11, the operator panel consists of two separate surfaces, the Control Panel, and the Status Panel. The Status Panel consists of two elements: controls which are infrequently used, or status indicators which provide the operator with feedback on system performance. The Control Panel contains the controls which are frequently used during operation of the machine. Both panels are described in detail in the following sections.

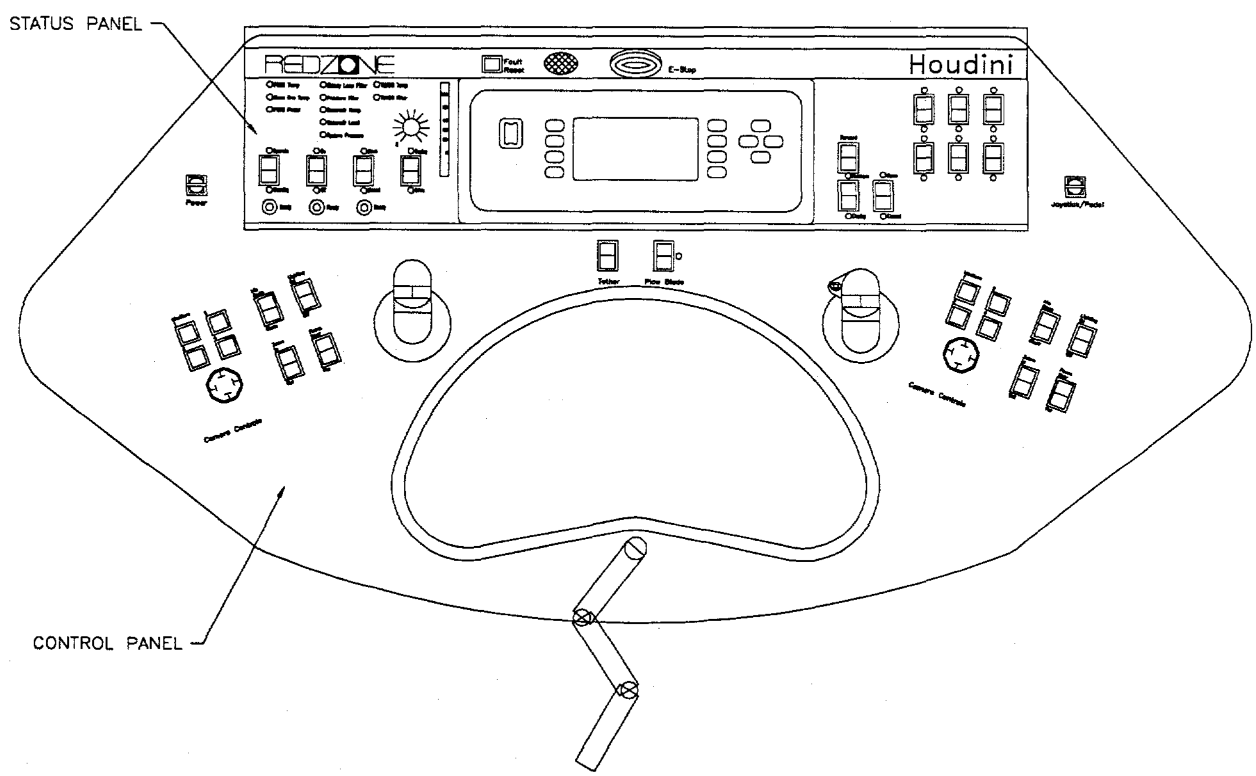

Figure 11 Houdini™ Operator Panel Assembly

3.4.1 Status Panel

The status panels for the Houdini™ system are shown in Figures 12 and 13 The left status panel contains the controls and feedback for the PDCU, the HPS, the TMADS, and the Tether. The right side contains the controls and feedback for the Hydraulic Tool, the Vehicle Frame, and the Auxiliary Functions. The controls are grouped logically according to functions, and the functions are arranged in the typical sequence required for system operation. A description of each function block follows.

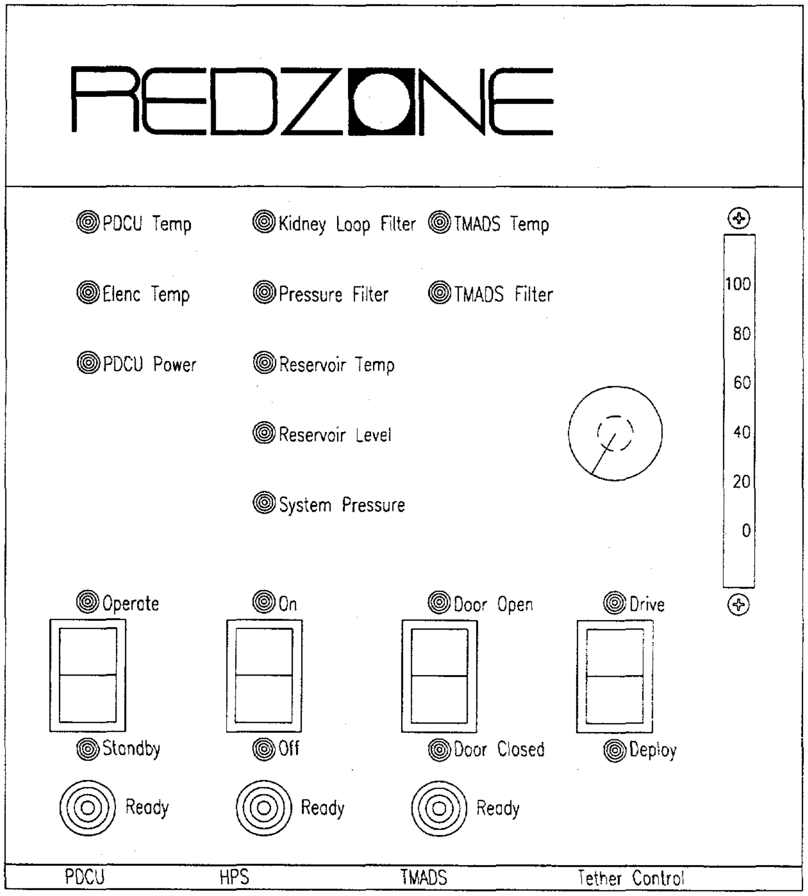

Figure 12 Houdini™ Status Panel (Left Side)

- **HPS On/Off** - This switch turns on the main hydraulic power supply for the system. It is linked with the emergency stop and system interlocks to automatically turn the HPS off should an emergency situation occur. Two indicators are used to show the status of the HPS (ON or OFF).
- **PDCU Standby/Operate Switch** - This enables the PDCU and allows control of the vehicle. Two indicators are used to show the status of the PDCU (Standby or Operate).

- **TMADS Door Open/Close Switch** - This switch controls a solenoid valve which opens or closes the door of the TMADS. Two indicators are used to show the fully open or fully closed conditions.

- **Tether Deploy/Drive Mode Switch** - This switch controls a solenoid valve which switches the speed range on the tether drum. The Deploy position is used when either entering or exiting a tank and is a low speed, high torque range. The maximum speed in deploy mode is six inches per second. The drive mode is used for operations other than deploying or retrieving, and is a high speed, low torque range. The maximum speed in drive mode is 24 inches per second. Two indicators are used to show the current mode (Deploy or Drive). The default is Deploy Mode.

- **Tether Speed Control** - This is a rotary control that sets the desired tether speed from 0 to 100% of maximum velocity. This allows the operator to control tether speed during deployment and driving.

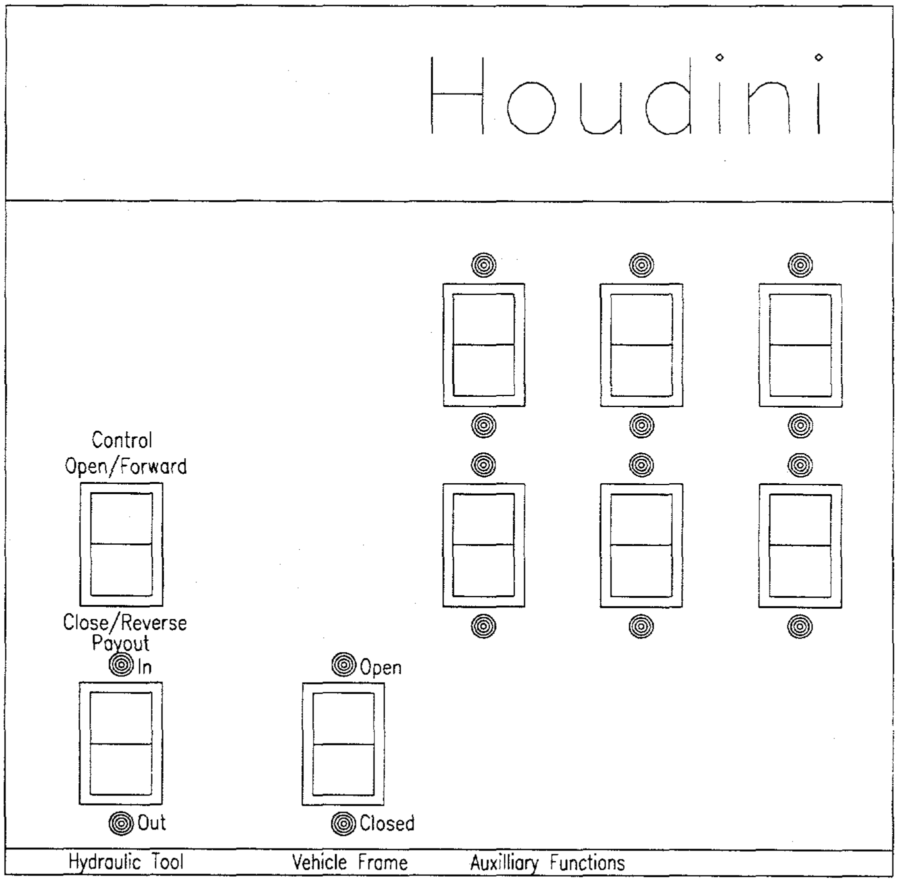

Figure 13 Houdini™ Status Panel (Right Side)

- **Frame Open/Close Switch** - This switch controls valves on the vehicle which opens the frame on deployment and closes the frame on retrieval. Two indicator lights are provided to show the fully open or fully closed positions.

- **Hydraulic Tool For/Rev** - This switch controls a solenoid valve on the TMADS unit which is used to control a hydraulic tool being used by the vehicle.

- **Hydraulic Tool Deploy/Retrieve** - This switch controls an electric motor on the TMADS unit which is used to drive the drum holding the hose for the hydraulic tool. Two indicators are used to show the fully deployed and fully retrieved conditions.

- **Emergency Stop Switch** - This illuminated red push-button is located in the center of the console above the Schilling Controller. Its function is to immediately disable the hydraulic system on the PDCU in the event of an emergency. Also, the frame and plow are placed in the fail-safe condition (gravity collapse) when the emergency stop switch is pressed.

- **Fault Reset Switch** - This momentary push-button switch is used to silence the audible alarm when a fault has occurred in the system and is located above of the Schilling Consolette. The fault reset switch will not extinguish an LED that has illuminated due to a fault condition.

- **Schilling Consolette** - The Schilling Consolette is used to control the Titan II robotic arm attached to the vehicle. Please consult the Schilling Operational Manual for instructions on use.

- **Auxiliary Functions** - The Auxiliary Functions block is comprised of six switches and twelve status indicators, two for each switch. These switches control outputs on the PDCU, and can be interfaced to control site equipment. The outputs are 120 VAC, with a maximum rating of 3 amps each. The indicators are not connected and are provided for future expansion.

In addition to the switches, indicators are provided on the status panel for the following items:

- HPS Kidney Loop Filter Status
- HPS Pressure Filter Status
- HPS Reservoir Temperature Status
- HPS Reservoir Level Status
- HPS Pressure Status
- HPS READY
- PDCU Temperature Status
- Electrical Enclosure Temperature Status
- PDCU Power Status

- PDCU READY
- TMADS Temperature Status
- TMADS Filter Status
- TMADS READY
- Tether Payout Sensor (Analog display showing feet of tether let out)
- Plow Blade Status (Home Position)

3.4.2 Control Panel

The Control Panel contains the controls that are most commonly used during vehicle operation. These can be subdivided into three groups: Track Controls, Camera Controls, and Schilling Control. Each Group is described below.

- **Track Control Key switch-** This key switch determines the control mode for the tracks on the vehicle. The center position is the Joystick Mode, and is the only position where the key is removable. In this mode the tracks respond only to joystick commands. The left position is the Joystick/Foot pedal Mode. In this mode the tracks respond to both joystick and foot switch commands. The right position is the Foot switch Mode. In this position the tracks will only respond to foot switch commands.

- **Left and Right Track Joysticks** - These joysticks control servo valves on the robot for driving and steering. The joysticks are single axis type with a thumb switch function and a trigger actuated deadman switch. The left joystick thumb switch controls the tether feed direction and the right joystick thumb switch controls the plow height. Additionally, a push button on the right joystick controls the water jet used for camera cleaning. There is no coordinated motion between the left and right tracks.

- **Left and Right Dual Foot Pedals** - The foot pedals can be used as an alternative to the joysticks for controlling the tracks. The Left Dual Foot pedal controls the left track, and the Right Dual Foot pedal controls the right track. The foot pedals are arranged to drive the tracks as shown in Table 1.

As with the joysticks, the foot pedal commands are processed through a nonlinear function to give high sensitivity during low speed operation where maneuverability is most important. Unlike the joysticks, the foot pedals do not have a deadman switch, so care must be exercised during use. The greatest asset of the foot pedal controls is that the operator can be driving the vehicle and operating the Schilling arm or camera controls simultaneously.

	Left Dual Foot pedal		Right Dual Foot pedal	
	Left	Right	Left	Right
FORWARD		X	X	
REVERSE	X			X
TURN LEFT	X		X	
TURN RIGHT		X		X

Table 1 Foot pedal Operation

Camera Controls

There are two color cameras mounted on the Houdini™ vehicle. One camera is a fixed unit with lights mounted on the forearm of the manipulator arm. The second unit is a pan and tilt camera with lights, mounted at the rear of the vehicle. Additionally, there are connectors on the PDCU for two auxiliary cameras which can be controlled through the console. Figure 14 shows the layout of the camera controls. Each function is described below.

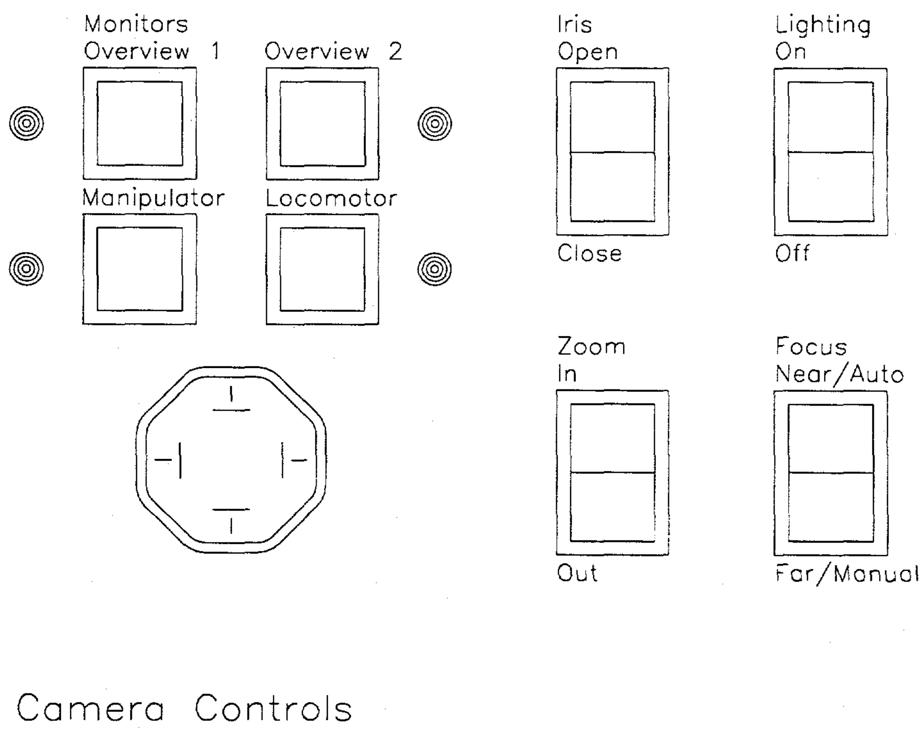

Figure 14 Camera Control Switches

- **Camera Selector Switches/Indicators** - These four momentary switches allow the operator to select which camera you wish to control (one of the four vehicle and overview cameras). Four indicators are used to show which camera is currently selected. The vehicle camera button has a dual purpose. When pressed in conjunction with the Focus Near rocker switch, the vehicle camera is switched to Auto Focus Mode. When pressed in conjunction with the Focus Far rocker switch, the vehicle camera is placed in Manual Focus mode.
- **Iris Open/Close Switch** - This rocker switch will either open or close the iris of the selected camera. Neither the vehicle camera nor the manipulator camera have adjustable irises. This switch is for control of the irises on the Overview (auxiliary) cameras that the user can interface to the system.
- **Lighting On/Off Switch** - This rocker switch will either illuminate or extinguish the lights of the selected camera. Both the vehicle and the manipulator camera have local lighting. Note that this is not an intensity control.
- **Focus Near/Far Switch** - This rocker switch is used to control the manual focus adjustment on the selected camera. The manipulator camera has a fixed focal distance and will not respond to this switch. The vehicle camera, when placed in Manual Focus Mode (see above) will respond to this switch when selected. This control is also used to adjust the focus of the Overview (auxiliary) cameras if installed.
- **Zoom In/Out Switch** - This rocker switch is used to control the manual zoom adjustment on the selected camera. The manipulator camera does not have a zoom adjustment. The vehicle camera will respond to this switch when selected. This control is also used to adjust the zoom of the Overview (auxiliary) cameras if installed.
- **Pan and Tilt Switch** - This four quadrant rocker switch is used to control the pan and tilt angles of the selected camera. The manipulator camera is fixed and will not respond this command. The vehicle camera will respond to this switch when selected. This control is also used to adjust the pan and tilt angles of the Overview (auxiliary) cameras if installed.
- **Schilling Master** - This is a 6-DOF control that is used to operate the Schilling arm. The Schilling Master Arm has been relocated to the front of the control panel for ease of use. The kidney shaped cutout (as seen in Figure 3-6) can be removed, and allows operation of the master arm below the surface of the control panel.

3.4.3 Operator Chair

The Aeron chair designed by Herman Miller was chosen for operator comfort and adjustability. The chair's highly permeable Pellicle material allows air, body heat, and water vapor to pass through the seat and backrest to help maintain even and comfortable skin temperatures and prevent moisture buildup on the skin's surface.

The chair offers the following features:

- Seat height adjusts from 14.4 in to 20.9 in
- Lumbar height/lumbar depth pad adjusts vertically 4.5 in/forward 3.25 in, back 1.25 in
- Arm rest angle pivots independently 17.5° inward to 15° outward
- Arm rest height adjusts independently within a 4 in range
- Forward tilt adjusts the seat angle 5° forward.

3.4.4 Suitcase Console

A portable suitcase control console, as shown in Figure 15, provides an alternative means of controlling the Houdini™ robot, by-passing the operator console. The suitcase controller includes a single color LCD video monitor for camera feedback and a 4:1 audio/video switcher to select the desired camera view. The control panel consists of switches, buttons, and joysticks providing a subset of the controls available on the main console. The suitcase provides for on-site debugging, local operations, system checkout, and emergency recovery.

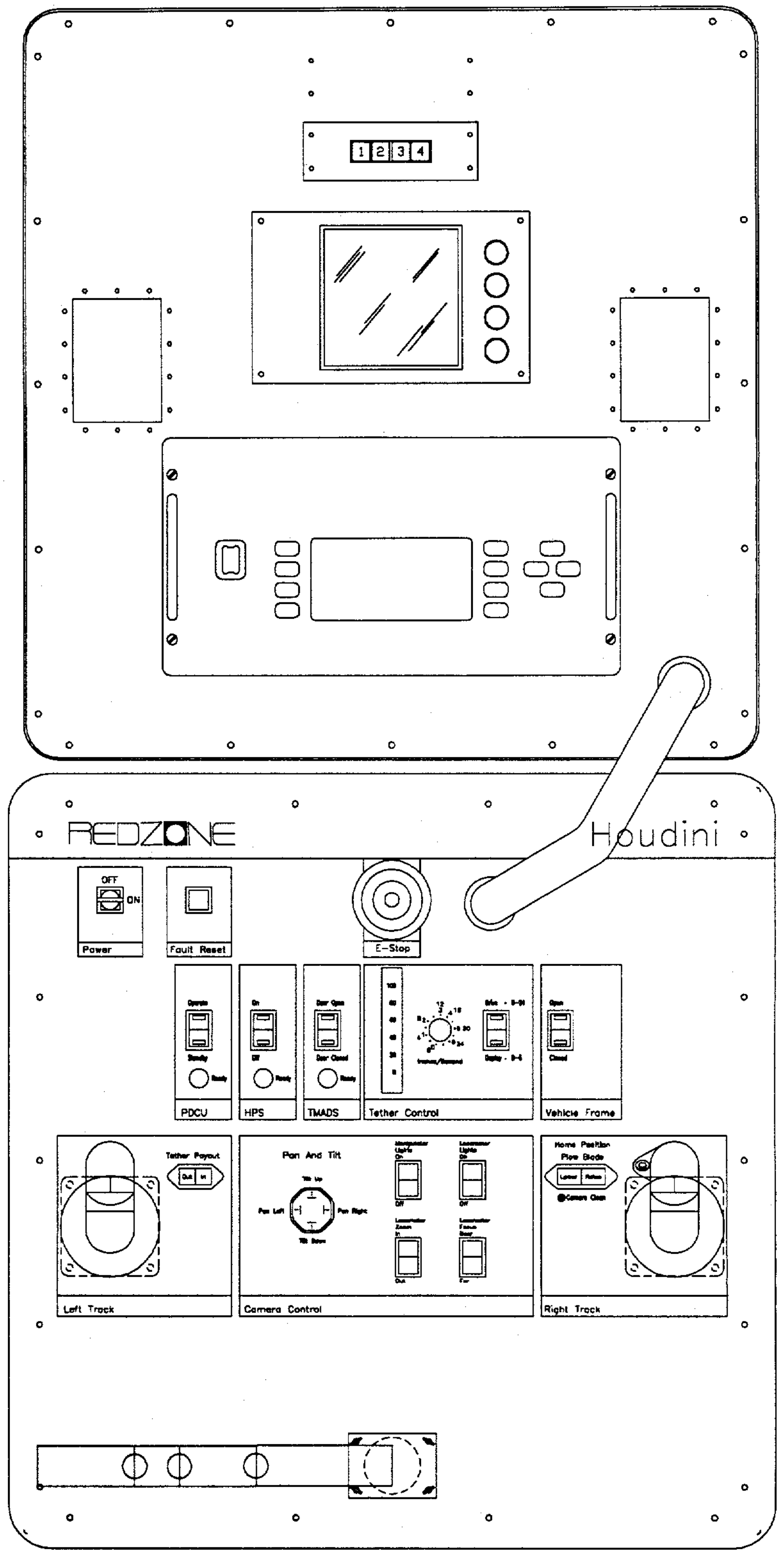

Figure 15 Suitcase Controller

3.6 System Specifications

The following is a summary of the system specifications.

System Requirements	
Operating Temperature	0 °F to 100 °F
Storage Temperature (powered)	0 °F to 100 °F
Storage Temp. (unpowered)	40 °F to 120 °F
Vehicle	
Weight	925 lbm (with manipulator)
Dimensions	
Frame Open	(44 x 48 x 15 in) (L x W x H)
Frame Close	
Drawbar Pull	(82 x 21 x 15 in) (L x W x H)
Speed	400 lbf (on dry concrete)
	12 in/sec max.
TMADS	
Weight	8400 lbm
Dimensions	(13 x 5 x 6.5 ft) (L x W x H)
Tether Payout Length	100 ft)
Reel Pulling Force	3000 lbf
PDCU	
Weight	25000 lbm)
Dimensions	(97.5 x 63 x 85 in) (L x W x H)
Hydraulic Power Supply	
Motor Size	14.9 kW (20 HP)
Maximum Pressure	3000 psi
Maximum Flow	10 gpm
Fluid	Houghto-Safe 620 (water glycol)
Video Feedback	
Vehicle Camera	Underwater, color CCD camera
	12:1 Zoom lens
	(2) 75 Watt wet/dry lights
	Underwater pan/tilt
Arm Camera	Underwater, color CCD camera
	Fixed focal length
	(2) 75 Watt wet/dry lights
	Wide angle lens
	Built in microphone
Manipulator	
Reach	76 in from base of arm
Payload	200 lbf max.
Control Console	
Rack Mount Unit	(22 x 026 in)
Control Station	(72 x 51 in)
POTS Station	(28 x 44 in)
Suitcase Controller	
Weight	50 lbm
Dimensions	(30 x 30 x 16 in) (L x W x H)

Table 2 System Specifications

Chapter 4 Results and Discussion

Most of the items discussed below have been observations made after shipment of the Houdini™ system to Oak Ridge. Oak Ridge has been conducting tests of the Houdini™ system, MLDUA, and the Confined Sluicing End Effector at their Cold Test Facility in preparation for an internal readiness review prior to going hot with these systems. All of these issues are currently being addressed for the second Houdini™ system that is being developed for Fernald.

4.1 Houdini™ Vehicle

4.1.1 Deployment Issues

A critical and absolutely essential requirement of the Houdini™ system is that it be capable of deploying and retrieving through the 24 inch riser in a reliable manner. This is in part driven by the desire to reduce radiation exposure to the vehicle by storing the vehicle in TMADS when not performing waste retrieval activities, but even more so by the need to decontaminate the vehicle after a typical work shift to prevent the hardening and build-up of waste on the vehicle.

Although the vehicle has been designed to fit through a 22.5 inch opening, the operational challenge is to get the vehicle started into the riser opening when it is not centered over/under the riser. For deployment, this is a matter of using the manipulator to guide the vehicle into the riser, then taking advantage of the funnel style lead-in provided by ORNL's riser sleeve to guide the body of the vehicle into the riser. Landing on the tank floor has proven to be simple and reliable. This is accomplished by using the manipulator and plow blade for initial touch-down and as pivot points. As the vehicle is lowered, it pivots down into a horizontal orientation and lands on the bottom of its tracks. For retrieval, guides at the back, top, and underside of the vehicle serve as bumpers to guide the vehicle safely into the riser opening. However, because the vehicle does not hang perfectly straight, some operator skill is needed to retrieve the vehicle without risk to damaging hoses and cables. This amounts to the operator adjusting the position of the manipulator to change the vehicle's center of gravity at the point where the manipulator begins to enter the riser. The operator must then simultaneously lower the manipulator for retrieval while retracting the vehicle into the riser. Deployment and retrieval was demonstrated successfully at RedZone and at ORNL.

4.1.2 Mobility Issues

An early vehicle design consideration was the effect of tether size on the traction and mobility of the vehicle. The tether is 2.7 inches in diameter with a 24 inch bend radius and weighs 2.4 lbm/ft and imparts large side loads on the vehicle which are unnoticeable by the operator and cause no trouble when trying to drive the vehicle. At times the tether has been pushed into the tank walls unknowingly by operators because of slow or poorly positioned overview cameras. The vehicle has more than enough traction and push/pull/turn force so that the effects of a tethered vehicle go unnoticed. In fact, the stiffness of the tether has aided in operations to the extent that the operator does not have to worry about running over the vehicle's tether during turns and reversing scenarios because the tether is forced out of the way due to its own stiffness. In short, there are no mobility limitations caused by the tether.

Other aspects of mobility such as speed control, traction, turning ability, slope climbing, and tip over have been tested. Houdini™ has proven to be highly controllable via dual joystick, infinitely variable speed control from 0 ft/sec to a maximum speed currently set at approximately 1.2 ft/sec. Houdini™ is capable of driving in the folded configuration. In a deployed/open configuration, Houdini™ can turn within its own length and can plow with up to 650 lbf on clean dry concrete. Depending on manipulator and payload position, Houdini™ can climb up a 35° ramp and will remain stable even on a 45° slope. Houdini™ has proven to be the stable work platform that it was intended to be.

4.1.3 Vehicle Performance Issues

Vehicle performance inside the tank environment is largely a function of the waste material, its water content, and the resulting vehicle mobility on this waste. After system testing at RedZone in surrogate waste that is representative of waste found in the Gunite tanks at ORNL, we can make some qualitative statements concerning vehicle performance. The surrogate was a mixture of kaolin clay, sand, and water mixed roughly to the consistency of wet cement and varied from 8 to 16 inches deep. Operating in this environment, the vehicle was able to mobilize waste effectively. Using the front mounted plow, we could easily push the surrogate to a centralized pumping area. The plow is equipped with a squeegee on the bottom edge of the plow which left the tank floor virtually clean and dry. The plow performed equally well in reverse where it was used to pull waste away from the edge of the tank wall.

Although the vehicle was able to mobilize waste effectively, it was possible to place the vehicle in a position where it would become stuck in the surrogate material. If the surrogate was able to apply sufficient pressure to the frame members of the vehicle, the ground pressure under the treads would be lowered to the point where sufficient force was not developed by the tracks to move the vehicle. More often, the surrogate was not able to support the weight of the vehicle, and the vehicle would sink to the level of the tank floor, and still develop sufficient force to plow material while submerged in the surrogate.

In addition to plowing successfully, the vehicle's manipulator was used to acquire and deploy a hydraulic shear that was lowered into the tank separately. Using the manipulator, the jaws of the shear were remotely positioned around a piece of 1/2 inch conduit and size reduced the piece into roughly 12 inch long sections. The manipulator also was effective in locating, retrieving, and placing unpumpables, ranging form heavy cinder blocks to light plastic bags, into a barrel for subsequent retrieval.

The vehicle has also been used to retrieve and carry Oak Ridge's Confined Sluicing End Effector around the tank while pumping waste. The vehicle is capable of stabily controlling this 60 lbm end effector and associated large hoses without trouble. It can also position the end effector vertically, up to four feet high, against the tank wall simulating scabbling scenarios. Controlling standoff distance from the wall is difficult because it is a teleoperated system. This is a task which is better suited for the MLDUA.

4.1.4 Decontamination Issues

Vehicle decontamination at RedZone could only be demonstrated manually through the use of a regular garden hose. While decontamination of a vehicle based system is expected to be difficult, some encouraging results were achieved. Through manual wash down we were able to remove approximately 95% of surrogate material that was stuck to the vehicle. Several approaches can be taken towards decontamination. The first approach is the use of a high pressure spray ring. If areas of the vehicle are not effectively cleaned by this means, then a spray wand mounted inside of TMADS can be used to manually reach the difficult areas. As an alternative to manual wash down, a technique of vehicle self wash down using the vehicle's manipulator was tried with some success. In this scenario, a spray hose is lowered to the vehicle while in the hanging and open position. The manipulator then grasps the spray nozzle and performs a self wash down by pointing the nozzle at the difficult to reach areas. Robot kinematics, however, limit the reach of the manipulator and increase the complexity of this operation.

4.2 TMADS

4.2.1 Deployment/Retrieval Issues

Spray Ring

During testing at Oak Ridge, several instances occurred where the Houdini™ vehicle would become caught by leading edges between the spray ring and containment bezel. In one instance, they managed to tear off the manipulator camera and protective covers. This was remedied by adding a funnel shaped transition between the two pieces and has eliminated the problem.

Overall Length

Retrieving and storing the vehicle inside of the TMADS has proven to be a difficult task. This is because the overall length of the TMADS is too short to contain vehicle without having to fold the manipulator before closing the TMADS door. This was caused by a design constraint that was present at Fernald, but was not an issue at Oak

Ridge. It is further complicated by unpredictable orientation of the vehicle when it is retrieved, requiring that the manipulator be folded differently for each retrieval. This task requires direct observation by personnel at the TMADS in radio communication to the operator to effect a complete retrieval.

Payout Sensor

When retrieving the vehicle into the TMADS, set points in the software control when the vehicle has been fully retracted. At times the sensor (potentiometer) stopped the vehicle retrieval a few inches too soon, and the TMADS door could not be closed. This was complicated by the already tight fit of the Houdini™ vehicle inside the TMADS. To fix this, RedZone has installed a mechanical limit switch inside the TMADS which now stops the vehicle repeatedly and reliably.

Camera

To aid in the retrieval of the vehicle, it was determined that is was extremely useful to have a camera mounted inside of the TMADS for a view of the vehicle coming through the riser and also to aid the operator when folding the manipulator for storage.

Door Seal

The door seal on the TMADS was found to be ineffective at containing the direct water spray of the spray wand inside of the TMADS. The original seal was replaced with an inflatable seal which greatly improved the situation. Small leaks are still being detected at two corners of the seal. Efforts to resolve this issue are ongoing.

4.2.2 Maintenance

Routine vehicle maintenance can be performed inside TMADS. This would include the change-out of the vehicle mounted cameras and lights, tread replacement, and onboard hydraulic valve replacement. Other maintenance activities will require the vehicle to be removed from TMADS and the vehicle frame opened. More detail on the maintenance requirements will be learned and demonstrated during cold testing at ORNL.

4.3 Operator Efficiency/Effectiveness Issues

Controls

During testing, several ORNL operators visited RedZone to become familiar with the system and to log operating time at the console. Operators reported that the system was easy to learn and adjust to. The dual joystick control (one for each track) was very intuitive as were the easily accessible joystick mounted controls for the plow blade, tether control, and camera cleaning system. The operators were driving the vehicle effectively in less than and hour. Most training time was spent mastering the control of the vehicle mounted manipulator. The system is enhanced through the addition of foot pedal controls as an alternative to the joysticks. The operator can keep his hands free to operate the manipulator and cameras while using his feet to make adjustments to the vehicle position. Foot pedal control has been described as too mentally taxing to use effectively. The foot pedals were chosen because the pedal setup would be less physically demanding. Alternative pedal controls will be explored.

Cameras

Houdini™ is equipped with two onboard cameras. One is hard mounted at the manipulator gripper and the other is mounted to a pan/tilt unit at the rear of the vehicle. At the test facility at RedZone, one fixed overview camera was available to aid in remote operations. Using the onboard cameras and the limited overview camera we were able to perform all testing and operation of the vehicle remotely. In a true tank deployment, one would expect several overview cameras with pan/tilt/zoom control which will only simplify remote operation. During operation inside the tank it is expected that cameras will become obscured by waste that may get splashed onto the camera lenses. Houdini™ has a camera lens cleaning system that sprays the camera housing lens with water followed by air for drying. This method of cleaning is initiated by the press of a button at the control console and was demonstrated successfully. Oak Ridge operators have underlined the importance of the camera cleaning mechanism as the cameras are often splashed with surrogate waste.

Chapter 5: Conclusion and Recommendations

RedZone has delivered the first Houdini™ system to Oak Ridge National Laboratory. The system has been in operation at their cold test facility for several months in preparation for the hot deployment in the Gunite tanks. Several areas of improvement in the Houdini™ design have been identified as a result of this activity. These items are summarized below.

5.1 Houdini™ Vehicle

Deployment Issues

Deployment and retrieval was demonstrated successfully at RedZone and at ORNL. However, while we believe that the guides implemented at the rear of the vehicle do a sufficient job at centering the vehicle into the riser, they need to be better integrated into the main structure of the vehicle. We also believe that to simplify deployment and retrieval, the vehicle should hang straight. Currently, the operator has to go through too many operations to complete a retrieval into the riser, increasing the risk to damaging the vehicle. With respect to deployment of the vehicle, we make the following recommendations:

- Redesign the vehicle riser retrieval guides to be an integral part of the vehicle. They may be best positioned on the tether termination as that is the first part of the vehicle to enter the riser.
- Investigate how far the tether termination point would have to be lowered in order to get the vehicle to hang straight. The trade off is with keeping the tether high enough so that it is does not become an anchor in the waste.
- Reposition the tether termination so that in an end view, the tether is in the geometric center of the vehicle. This would simplify the retrieval guide design and make retrieval less sensitive to vehicle orientation.

Mobility Issues

Houdini™ has proven to be the stable work platform that it was intended to be. Its overall size, while much smaller than the CMU pre-prototype, is still very stable and can handle the full payload of the manipulator. It should operate comfortably in the 25 foot diameter tanks at Oak Ridge. The tether has not restricted mobility and does not get in the way during operations. The "off the shelf" tread selection has shown good wear characteristics, sufficient traction, and the vehicle has never thrown a tread or been jammed by rocks during testing. We do, however, want to look at ways to reduce the track ground pressure for applications where the vehicle will have to operate on top of a waste surface as opposed to the hard floor of the waste tank. With respect to mobility of the vehicle, we make the following recommendation:

- Investigate ways to lower the track ground pressure. This could be a combination of lowering the vehicle weight and or increasing the width of the currently used tread.

Vehicle Performance Issues

With respect to waste mobilization, the vehicle has performed well. The vehicle has supplied sufficient plowing force to move a significant amount of waste. The plow and squeegee concept have worked fairly well, although the plow blade has been occasionally bent during deployment and retrieval.

The manipulator has been effective in retrieving unpumpable objects and grasping tooling and end effectors such as a hydraulic shear and the confined sluicing end effector. However, in operations at Oak Ridge, the manipulator has become a maintenance and reliability issue with the system. With respect to performance of the vehicle, we make the following recommendations:

- Redesign the plow blade to be more robust and make squeegee replacement easier.

- Consider alternative manipulators.

Decon Issues

Decontamination of the vehicle is an important aspect, especially when considering the need to do maintenance on the vehicle. Data is being gathered at Oak Ridge concerning decon of the vehicle and more will be known in the near future. As always, we feel the need to improve on issues regarding decontamination. With respect to decontamination of the vehicle, we make the following recommendations:

- Reduce and/or eliminate crud trap points.

5.2 TMADS

Deployment/Retrieval Issues

Retrieving and storing the vehicle inside of TMADS has proven to be a difficult task. It is personnel intensive and takes longer to accomplish than it should. Due to the number of chains which drive the payout sensor, it is not accurate enough to stop the vehicle at the appropriate height within the TMADS, and without the aid of a camera, the operator has no idea of what is happening. Also, attention to the door seal is required in order to contain the waste water from the manual spray wand inside of the TMADS. With respect to the TMADS, we make the following recommendation:

- Increase the length of the TMADS so that the vehicle can be retrieved and stored without folding the manipulator.
- Implement a mechanical limit switch to positive control the height of the vehicle inside the TMADS.
- Implement a camera inside the TMADS to give the operator a view of the retrieval process.
- Design a new door seal that will positively hold back the force of water caused by the spray wand inside the TMADS.

5.3 Operator Efficiency/Effectiveness Issues

Controls

Operator feedback has shown that the foot pedal controls supplied with Houdini™ are too difficult to use and operate the vehicle effectively. The foot pedals are a pair (left and right track) of dual pedal controls that require the operator to push down with the foot to move the respective track forward or reverse, for a total of four pedals. With respect to controls, we make the following recommendation:

- Investigate the use of two bi-directional foot pedals so that the operator can maintain each foot on one pedal only.

Cameras

Several issues around the vehicle cameras have been noted during operations at Oak Ridge. First, the manipulator camera is too big, making it easier to damage when grasping and operating end effectors. Second, the pan and tilt unit on the vehicle camera is too slow and is sensitive to damage when folding the vehicle for retrieval. Third, the vehicle camera should be slightly higher to give a better view around the vehicle. With respect to cameras, we recommend the following:

- Source a new camera vendor with a smaller integrated camera and light package. Also, maybe integrate the camera into the manipulator as is done on some of the Schilling Titan III manipulators.
- Source a new pan and tilt unit with integral cabling, a more robust base, and faster pan and tilt motions.
- Design into the vehicle a mechanism for raising the height of the body camera.

Overall, we believe that the Houdini™ system as delivered to ORNL will be a capable and reliable system for the Gunite tank waste retrieval efforts. Through the design, fabrication, and testing of this first unit, and through additional testing at

ORNL and subsequent hot deployment in 1997, we expect to deliver a more robust and capable system to Fernald in 1997.

Chapter 6: Future Activities

6.1 DoE Tank Applications

The Houdini™ system is useful in a variety of other DOE tank waste retrieval operations. Houdini™ can be deployed in a tank prior to the major removal action to collect additional information about the waste content and tank interior.

In support of other in-tank work systems, such as long reach manipulators, Houdini™ can be used to deploy cameras, lights, and sensor systems. The mobile deployment of such monitoring equipment will provide viewing and data gathering flexibility that cannot be achieved by mounting such equipment on fixed masts or on a long reach manipulator.

The long reach manipulator (LRM) systems that are being considered for tank waste retrieval will require a variety of tools to accomplish their tasks. The Houdini™ crawler can serve as a mobile tool carrier for a LRM, carrying several tools and making them available at the most appropriate location inside the tank.

In support of final tank decontamination and decommissioning, Houdini™ can deploy tools to scarify internal tank surfaces.

6.2 Oak Ridge North and South Tank Farms

The first application of the Houdini™ system is to support the waste retrieval action planned for the final remediation of the Oak Ridge National Laboratory (ORNL) Gunite storage tanks.

The north and south tank farms at Oak Ridge National Laboratory have a total of 16 domed, cylindrical, single-shelled, underground storage tanks known as the Gunite and Associated Tanks (GAAT), ranging in diameter from 20 to 50 feet and equipped with 24 inch diameter accessways. These tanks were used to store laboratory waste and are expected to contain a wide variety of materials, with estimated radiation levels of 1 to 100 R/hr. During 1983-1984 the tanks were emptied through a sluicing method, leaving a heel of soft sludge generally 6 to 8 in deep The heel waste must be removed to prevent the migration of waste material out of the tanks.

A treatability study has been undertaken at ORNL to evaluate waste removal and treatment technologies prior to final remediation activity. Houdini™ and other remote equipment will be used during this study to retrieve heel material from tanks in the North tank farm.

In March of 1997, through commitment from the Environmental Management Office of Technology Development, the integration skills of Oak Ridge National Laboratory and the execution of RedZone Robotics, Inc., the Houdini™ reconfigurable vehicle will become the first robotic system to be deployed in a hot underground storage tank within the DOE Complex. This unprecedented trailblazing deployment will not only validate the feasibility of vehicle based in-tank waste retrieval, but more importantly establishes a significant benchmark for the robotics community in the high level waste tank clean-up application.

6.3 Fluor Daniel Fernald

The second application of the Houdini™ system is to support the final remediation of Silos 1, 2, and 3 at the Fernald Site. The Houdini™ system will be used for heel and debris removal from the silos, during and after the bulk material removal. The retrieved waste will be stabilized through encapsulation or vitrification and then shipped to its final location for long term storage. Other applications including Bentonite cap skimming, remote inspection, and pump maintenance are under consideration.

The Operable Unit 4 at the Fernald site, managed by the Silos Project Staff, contains 4 above-ground, concrete waste silos. All four domed waste silos are 80 feet in diameter, 36 feet high at the center of the dome, with 27 foot high vertical walls. Four 20 inch diameter accessways are evenly distributed around each tank dome at 15 feet from the side walls, at a slant of 17 degrees from horizontal. A fifth 20 inch accessway near the center of the dome will be eliminated when a seven foot opening is created to support the remediation activity. Fernald is planning on deploying Houdini™ from enclosed equipment rooms supported by superstructures that span the silo dome and adjacent berm.

Waste material in Silos 1 and 2 has the consistency of toothpaste. The waste is covered with a 12 inch thick layer of Bentonite clay to reduce radon emissions from the waste. Material in Silo 3 is a light, dry metal oxide powder similar in consistency to talcum powder. The Silo 3 waste may be compacted near the bottom of the silo. In addition, each silo contains pipes, wrenches, sample bottles, gloves, and other debris that has been deposited into the tanks over the years. The fourth silo is identical to the other three, but was never used for waste storage. It will be used as an uncontaminated mock-up facility to fully test all procedures prior to remediation of other silos. Silo 4 may be partially filled with a surrogate waste material to support these tests.

The primary retrieval method for Silo 1 and 2 waste will most likely be hydraulic removal though other alternatives are still being considered. Under this scenario, a sluicing pump will be lowered into the tank from the equipment room. Water will be added to the waste material and the liquefied waste will be pumped out of the tank. In Silo 3, pneumatic conveyance will be used to retrieve the waste material.

The methods will remove the bulk of the waste materials from the tanks, leaving only debris and a waste heel to be removed by other means.

RedZone is currently under contract with Fernald to look at lessons learned from the first system and to do conceptual redesign for the second Houdini™ system.

6.4 Other Potential Houdini™ Activities

In addition to the planned activities at ORNL and Fernald, other applications for Houdini™ have been identified in support of tank waste retrieval operations in the DOE (Savannah River and Hanford have expressed interest) and private sector. Also, several tasks outside of tanks have been identified for which Houdini™ would be useful.

Commercial Tank Applications

Periodic cleaning and inspection of storage tanks in petro-chemical industries are becoming common maintenance procedures. It is likely that these procedures will be required by law in the US in the next few years. The cleaning tasks for these tanks involves the removal of thick sludge material from the tank floor. Houdini™ and other DOE-developed technologies are applicable to these commercial tank cleaning opportunities.

Non Tank Applications

Alternate uses currently envisioned for this system include indoor as well as outdoor tasks. In support of buried-waste excavation programs, Houdini™ could perform fine excavation and monitoring to assist a larger remote excavator, perform fine excavation to isolate and extract specific objects, and assist removing a drum in one piece. In support of decontamination and dismantling programs, Houdini™ could be used as a small platform to gain access through tight areas for selective equipment removal and could lend assistance to larger work systems as a tool-carrier platform, size-reduction system, or waste packaging system. In support of surveillance and monitoring operations, it could perform such functions as monitoring drum storage areas and decommissioned processing areas requiring access to tight corridors. Removal of the tether is possible through the use of and IC-engine or batteries and the interface of a radio telemetry system. These application are being pursued by RedZone with private industry, divisions of the armed forces, and the Federal Bureau of Investigation.

Appendix 1: CMU Final Report

HOUDINI: Reconfigurable In-Tank Robot

Topical Report

for the period:

01/06/95 – 03/31/96

Work performed under Contract: DE-AR21-95MC32092 SUBCONTRACTOR

CMU - Subcontractor to RedZone Robotics, Inc.

Prepared for:

U.S. Department of Energy
Morgantown Energy Technology Center
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March 31, 1996

Abstract

The project described in this report details the development of a reconfigurable in-tank robotic cleanup system. Based on several key design criteria and site visits to Fernald's K-65 silos, a proof-of-concept prototype robot system, dubbed *Houdini*, was designed and built, which was shown to be able to collapse to fit through a 24" diameter manway opening, while carrying a manipulator and a plow with it into the tank to perform waste dislodging and transfer tasks. *Houdini* was delivered to RedZone Robotics, Inc., the prime in this contract, for their use in a trial-run at the Oak Ridge gunnite-tank test facility. The robot was tested and declared a viable candidate for in-tank cleanup, prompting Oak Ridge to order an additional system for cleanup of their gunnite tank farm in late 1996. A complete paper[1] describing the prototype design was submitted to the American Nuclear Society Annual Winter Conference, held in early November in San Francisco, CA - a copy of the paper is included in the appendix.

The effort CMU engaged in was in the role of a subcontractor to RedZone Robotics, Inc. CMU's role consisted of developing a pre-prototype system to perform all forms of geotechnical testing related to robot sinkage, traction, tooling, etc. Due to the nature of the development though, RedZone decided to use a commercial dozer and grouser system and retrofit it to allow it to pass through small openings. Based on this effort, CMU developed only the pre-prototype and jointly with RedZone, deployed it at Oak Ridge successfully. Additional grouser experiments were carried out on the commercial tread, and it was determined that the deployment scenario of the system at Fernald would have to be tailored to insure the maximum utility of the robot without sinkage.

CMU's PI decided to terminate the subcontract, with RedZone taking the project the rest of the way to developing prototypes for Fernald and Oak Ridge during calendar year 1996.

1. "*Houdini: Site and Locomotion analysis-driven design of an in-tank mobile cleanup robot*", by H. Schempf, American Nuclear Society Winter Meeting, Oct. 29 - Nov. 2, 1995, San Francisco, CA

Acknowledgments

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Dr. Barry Burks

- **RedZone Robotics, Inc.**

Mr. Adam Slifko

Troy - Technician

- **Carnegie Mellon University**

Eric Rollins

Jef Franks

Todd Camill

1.0 Executive Summary

1.1 Background

Many DoE processing facilities across the country are slated for decontamination and dismantling activities over the next few decades. Most of these facilities harbor large number of above- and underground hazardous waste storage tanks, which many times contain unknown chemical mixtures of radioactive waste.Since many of these tanks are confirmed or potential leakers, remediation of the waste material becomes necessary. The proper method to extract and then process the waste material has been an ongoing argument for many years. CMU teamed with RedZone Robotics to develop a remote, reconfigurable workmachine that could enter tanks through existing openings, while bringing with it substantial tooling to assist in the waste removal and tank cleanup and decommissioning. The Department of Energy funded the proposed project via the Morgantown Energy Technology Center. CMU has decided to discontinue its subcontract to RedZone, leaving RedZone to complete the project and prototype development for two DoE sites, namely Fernald and Oak Ridge.

1.2 Programmatic

The *Houdini* project at CMU was intended to explore the issues relating to overall design, tread optimization, geotechnical studies and tooling and overall performance optimization. CMU developed a fully operational pre-prototype for testing purposes, which RedZone took and used for a proof-of-concept demonstration at Oak Ridge's gunnite test-tank facility. Since RedZone decided to go with a modified OEM bulldozer system (KOBELCO), the full set of experiments for grouser design and optimization were no longer necessary and were thence replaced with tests to determine the performance of the KOBELCO-tread.

1.3 DoE Site Visits

The CMU development team visited Fernald's silos, and developed a better idea of the site and operational requirements. It was decided that Fernald would supply a form of surrogate waste material to CMU for their testing program. FERMCO appointed a POC to interface with RedZone on all the other issues of the deployment and system operation.

1.4 Robot System

The proof-of-concept robot crawler system was designed to be a hydraulically powered and remotely controlled self-locomoting mechanical bulldozer system suited for access into tanks through 24-inch diameter openings. The system consists of two side-by-side track locomotors, connected through a reconfigurable frame, whereto is a attached a plow and a master/slave telemanipulator. A picture of the prototype built at CMU is shown in Figure 1-1 on page 5. It was determined that the overall design worked very well, and that all the safety features did indeed work as anticipated (gravity collapse). The tread system required some modification, but should future custom treads be required, we would know how to design them. The internal hydraulic valving systems should be built into a manifold, to avoid leaking fittings and conserve space. The tread support on the bottom of the crawler should be kept to rolling support, rather than sliding support as it is currently implemented - another potential future improvement. The rotating plow turned out to be extremely useful and necessary to ease transitions from the hanging to the horizontal position.

All of these realizations gathered from the prototype, were all summarized and continually passed on to RedZone for consideration in their system design.

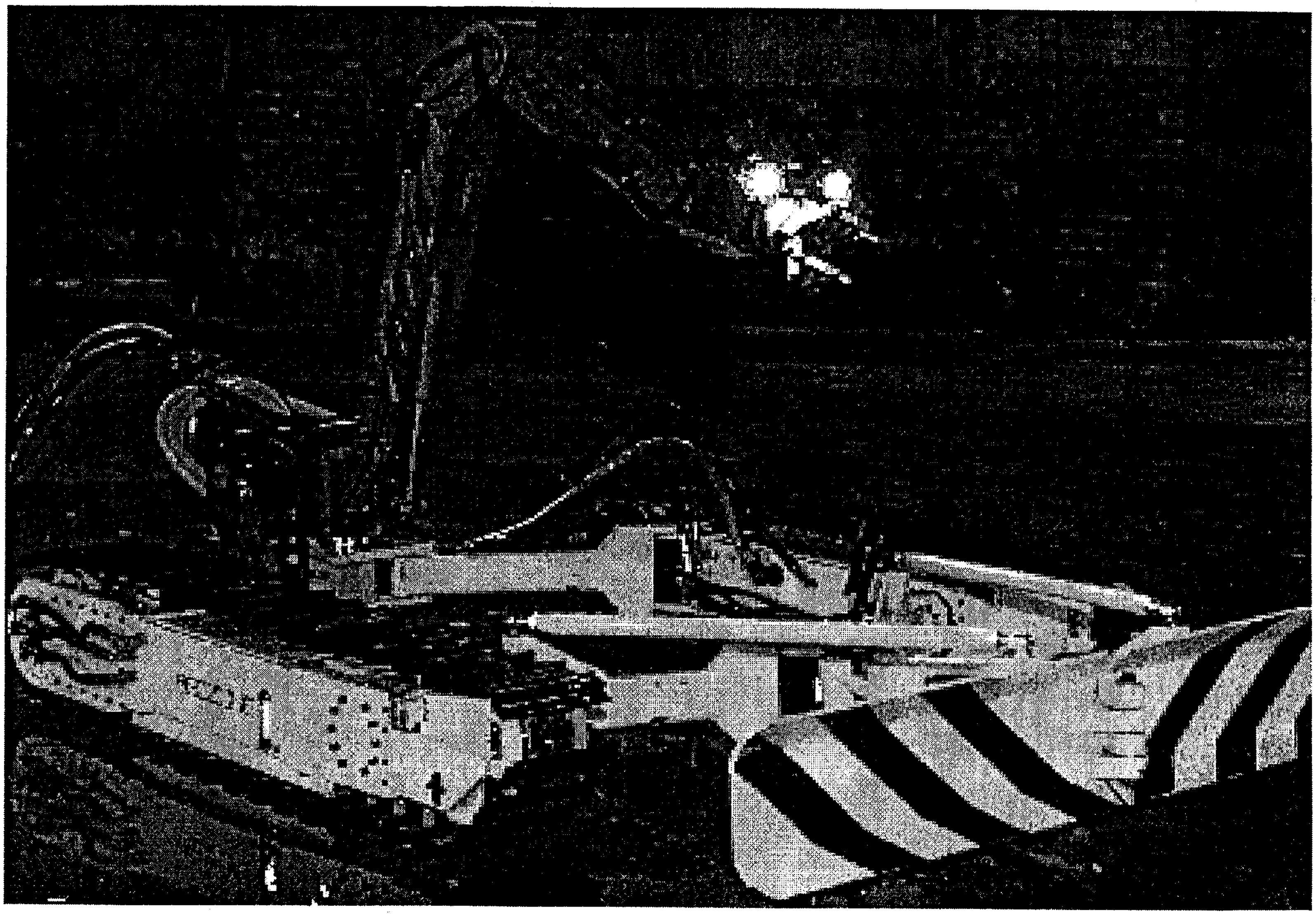


Figure 1-1 : The *Houdini* pre-prototype robot system built by CMU

1.5 Experimental Program

A full set of experiments was carried out with the CMU prototype in the RedZone test-tank, prior to its shipment to Oak Ridge for another battery of tests in their gunnite tank test facility. A whole week of experiments resulted in the approval of a *Houdini*-like system for use in the gunnite tank remediation project. *Houdini* performed very well in the waste tests and was able to carry out all sorts of waste and tool-handling tasks as prescribed by the Oak Ridge test-plan. Other than a few exceptions, the system performed admirably well and led RedZone to receive a formal request for another Houdini-like system for Oak Ridge's use.

A CMU-resident experimental program was developed for the testing of the Fernald surrogate material, as well as the OEM-tread. The testing was looking at the solid/plastic/liquid behavior of the surrogate waste material in order to determine the ability of the vehicle to sit atop the waste and locomote through the material without sinkage and while being able to apply substantial forces to carry out waste-moving operations. It was determined that the surrogate waste has a small solid region (0 to 30% water content), an even smaller plastic region (30 to 45%) and a very large liquid region (> 50%). The implications are that the RedZone crawler will have a tough time sitting on the Fernald tank-waste during all phases of the removal. Chances are that it will sink as the level of waste sinks, and thence would have to work from the central floor-location outwards, and without the continual use of the pump, potentially limiting the throughput of waste to the pilot vitrification plant. FERMCO is currently developing a plan on how to best make use of the robot during the phases where its guaranteed to be able to sit in the tank and/or atop the waste.

The experimental results collected during this extensive experimental program were invaluable for drafting a list of technical conclusions and recommendations for future design modifications. In summary, the robot was able to move around in surrogate waste and move material and tools as required. The surrogate waste form was found to be only marginally stable in that it is able to support the RedZone crawler only over a small range of water content in the tank, ranging between 30% to 45% water content.

1.6 Conclusions and Recommendations

The prototype testing period proved most of the successfully implemented designs, while highlighting those subsystems that could use further improvement or re-design. In addition more general knowledge about the overall surrogate waste material and the potential performance of the RedZone crawler were gleaned from terramechanical tests. The conclusions drawn from the results of our experimental testing and the proposed recommendations for each of these areas are detailed below:

***Houdini* Prototype** - We would recommend to improve the grouser design to allow for more clearance for extrusion of soils. Adding roller-contacts for underbelly rolling contact of the grouser chain is also advisable. If not possible a slightly vertically displaced rolling contact in the center of the locomotor would work very well. Any design option that retains all of the current capability but uses less actuators would be a plus. Changing the valve-design to a manifold design to reduce fittings and thus leakage should be strived for. A rooster-tail configuration for the tether-exit is recommended to ease turning of the robot.

Grouser Prototype - The KOBELCO grouser performed rather well in the test-pit at RedZone. However, it will not be the optimal solution for the Fernald tank. Hence the operational scenario needs to be tailored to make as wide a use of the robot while sitting atop the waste is feasible, and then transition it onto the tank floor for undercut-mining clearing of the waste material. The surrogate waste material was very sensitive to water content and hence its accuracy and relevance to the actual waste material are critical. This question is unlikely to be resolved until the robot is actually deployed, and all we can do is to try to anticipate as much as possible and have several backup plans.

2.0 Introduction

This report is intended to provide a summary of the CMU subcontract activities for the development of ***Houdini***: Mobile in-tank waste cleanup robot, funded under contract # DE-AR21-95MC32092. Towards that purpose, we provide the necessary background in this section to understand the focus and results of the effort.

2.1 Background

The environmental restoration and waste management problem addressed in this project focuses on the cleanup of hazardous waste storage tanks inside Department of Energy (DoE) facilities across their entire complex of processing plants. The storage tank problem is particularly vexing, as many tanks are known to leak, and such leaks cause substantial public concern and potential issues with environmental pollution and safety. The DOE's waste storage tanks contain hazardous, mixed, and nuclear waste products, precluding human entry for cleanup operations. The use of remote equipment had been identified as the necessary mode of tank waste removal[1]. Mobile worksystems, such as CMU's *Houdini* system[2], can access tanks through existing ports and deploy a variety of tools for in-tank operations. Such systems represent a feasible stand-alone and/or complementary solution to the scenarios of sluicing, and heavy-duty long-reach manipulation. Two major sites were identified as first-term users: Fernald's K-65 silos and Oak Ridge's gunnite tanks.

• Fernald's K-65 silos

Silos 1 and 2 in CERCLA/RCRA Unit 4 (CRU4) are two 80-foot diameter and 28-foot deep concrete-walled storage tanks partially filled with 95% damp radium residue[3]. Their remediation requires the removal of roughly 4,000m^3 of material[4]. Current plans are to sluice the bulk of the material out of the tanks and to perform heel removal with a mobile robot system. Silo 3 contains a talcum-like oxide powder which will also need to be removed through vacuum pumping and other mechanical means. Silo 4 is currently empty and will be used to perform cold-tests of the pumping and sluicing system to remove the bulk of the material in all other silos.

The *Houdini* system would be an appropriate and useful heel removal tool in the Fernald silos. *Houdini* could be deployed through one of the existing tank risers being made for the sluicing pump, with the deployment system housed within the currently planned sealed equipment room. Depending on the consistency of the heel material, *Houdini* could dig, plow, rubbelize and otherwise break up and move the material to a central conveyance system (such as the mixing pump that will be used for the sluicing action). During the heel removal action, the crawler would be fully supported by the tank floor, eliminating any concerns about traction or sinkage. The edges of plow blade could be specially shaped so that the system could scrape the corners of the tank clean. Other needed cleanup actions *Houdini* could engage in were detailed earlier, and could be applied in these tanks.

We currently plan to use *Houdini* in a cold tank test in silo 4 to demonstrate its capabilities and operational use, before it is re-deployed into the contaminated waste tanks 1, 2 and 3 for real cleanup operations.

• Oak Ridge's Gunnite Tank Farm

The north and south tank farms at Oak Ridge have a total of 16 domed, cylindrical, single-shelled, underground storage tanks made of gunnite (similar to concrete), ranging in diameter from 20 to 50 feet and equipped with 25 inch diameter manway penetrations[5]. These tanks were used to store laboratory waste and are expected to contain a wide variety of materials, with estimated radiation

1. U.S. Department of Energy - Environmental Restoration and Waste Management Five Year Plan, FY 94 - 98, Volume II
2. U.S. Patent # 5,451,135, September 19, 1995
3. WEMCO RFP No. GM 2-2985: Remote Mechanical Waste Retrieval System (WRS) for Fernald Environmental Management Project (FEMP)
4. WEMCO:ER(AR):92-041: Remedial Investigation Report for Operable Unit 4 - Task 6 Report, Oct. 1990

levels of 1 to 100 R. During 1983-1984 the tanks were emptied through a sluicing method, leaving about a 2 foot heel at the bottom. Since the liquid was drained from the tanks, the heel has solidified, similar to the salt-cake at Hanford. The heel waste must be removed to prevent the migration of waste material out of the tanks. The *Houdini* system will be deployed in these tanks - equipped with a rubbelizing tool, such as an air jet or vibratory chisel, *Houdini* will break up the heel material and feed it into a mechanical, pneumatic, or hydraulic conveyance system.

2.2 Robot Concept

The proposed robot system consists of an in-tank mobile crawler, an on-tank deployment system, and an off-site control trailer, all shown in Figure 2-1 on page 9. The crawler is a hydraulically-powered, track-driven, folding frame work machine similar to a small bulldozer. The crawler can fold to fit through a 24-inch diameter opening for deployment. The crawler is equipped with a plow blade and a manipulator arm. The plow blade also folds for deployment and can be height-adjusted for plowing various materials at various rates. The manipulator is a Schilling Titan 2 hydraulic dexterous manipulator, which can deploy a variety of tooling for performing work inside a tank.

The *Houdini* deployment system consists of a tether winch and management system, a hydraulic power supply, a control/power distribution box and a shipping container (not shown). The deployment system is optimized for the proposed deployment scenario at Fernald, where a steel truss supports a sealed deployment room over the opening to the tank.

The control center consists of a trailer that houses the operator control consoles. A hard-wired suitcase controller (console housed in a portable enclosure/suitcase) will also be available to perform system checkout, local operations and provide for emergency operations in the case of console/control computer or telemetry failures between the control center and the deployment system.

The *Houdini* system is inherently reliable due to a low number of moving parts, which are made up of simple OEM components. Track drives are well studied and the system will take advantage of off-the-shelf technologies as much as possible. All components will be sealed against spray and rated for full immersion, while surfaces will be kept smooth and entrapment corners will be avoided as best possible to simplify decontamination. The inherent low speeds (3 m.p.h. MAX) and low forces generated by the system represent an inherent safety margin with respect to potentially damaging the tank during all operations of plowing, digging, etc.

Maintenance is simple, due to the modularity of the system. The plow and manipulator system are bolt-ons, and should the drive mechanism need replacement, a few bolts and two hydraulic lines are all that need to be removed. All major components are standard and off-the shelf, and shall be packaged and encased for easy decontamination

The fail-safe features of the system are such that blow-by valves and gravity loads assure that the robot frame will always collapse under gravity even in the event of a power or actuator failure. The suitcase controller will provide hard-wire controls for the system at the deployment system, insuring that in the case of any computer or telemetry failure, the system can still be operated and safely removed from the tank. The winch system is designed for manual operation via hand-crank to allow complete removal of the vehicle in the case of complete site-power or hydraulic supply failure.

2.3 Prototyping and Experimentation Program

Our principal objective for this subcontract was to pre-prototype as many of the critical systems as possible and test them. As part of that effort, we designed and built a prototype crawler system, which was subsequently used to demonstrate in-tank vehicle viability at Oak Ridge. Since the prime decided to go with an OEM tread and grouser bulldozer system, the experimental portion of the program did no longer focus on the optimization of grouser and tooling systems, but rather the performance

5. X-10 Site Visits and Discussions with Robotics and Process Systems Division-Telerobotic Systems Section Personnel, Oak Ridge National Laboratory, Oak Ridge, TN

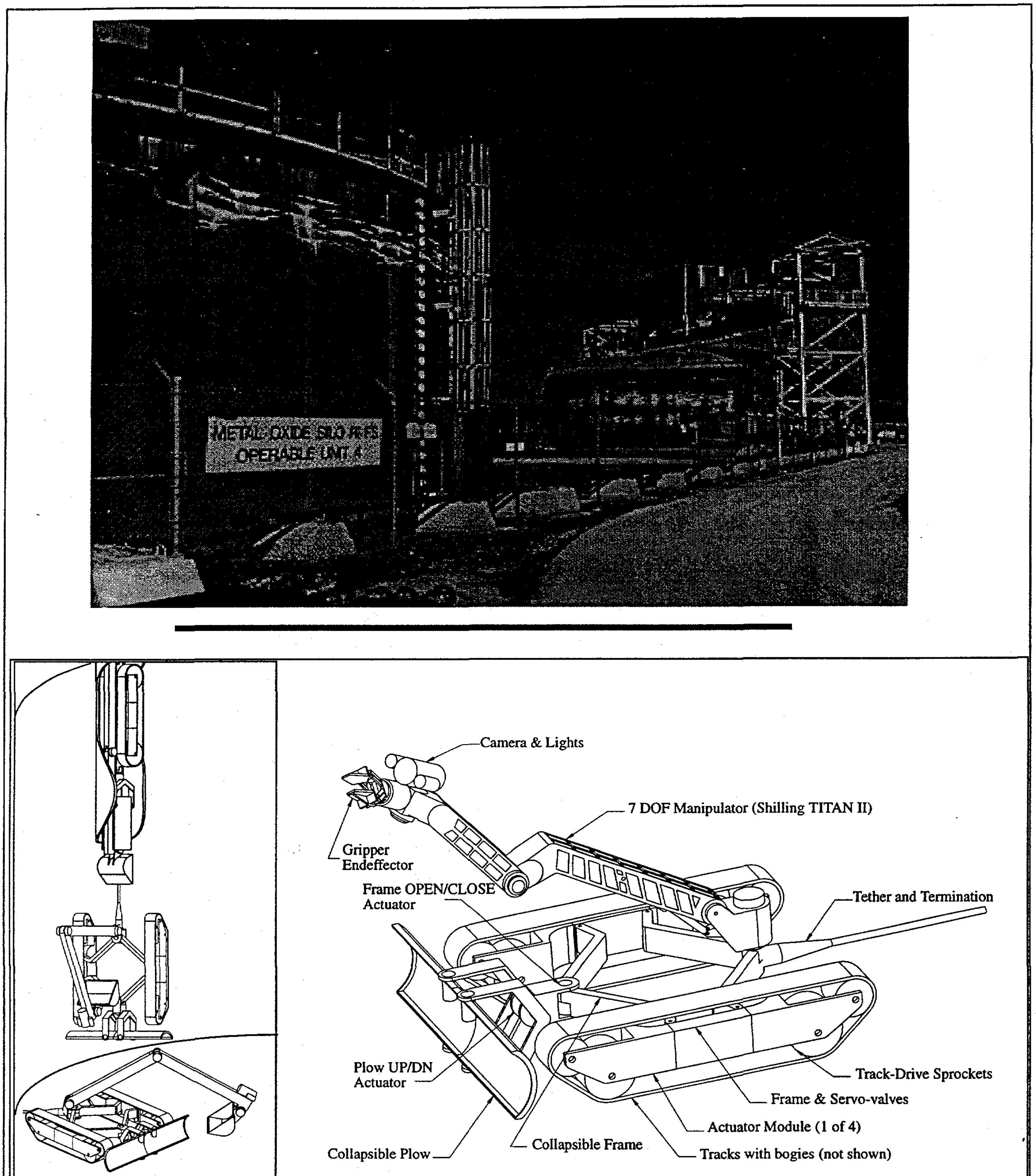


Figure 2-1 : Operational scenario for the deployment of *Houdini* in the Fernald K-65 silo, the K-65 silos at Fernald, as well as a the concept design of CMU's pre-prototype *Houdini* system.

classification of the OEM-tread performance in Fernald's surrogate waste material. The details of the individual task activities and the results and recommendations from this first phase are further detailed in the sections to follow.

The remainder of the topical report is organized as follows:

Chapter 3: Project Overview details the activities during the program effort as described by the task list in the METC contract.

Chapter 4: Robot Design gives additional detail on the key portions of the overall system design.

Chapter 5: Experimentation describes the tests we performed with the pre-prototype system in the laboratory and at Oak Ridge, as well as the grouser testing results.

Chapter 6: Conclusions describes the conclusions drawn from the experimental testing performed during the program. These conclusions are all mainly targeted to benefit the continued work by RedZone Robotics.

Chapter 7: Recommendations provides a more detailed summary and description of the proposed improvements based on the experimental results.

Chapter 8: Appendices collects all reference material, in this case a copy of the published *Houdini* paper, and a copy of the grouser testing laboratory report.

3.0 Project Overview

• Objective

The objective of the proposed work is to develop a waste retrieval system capable of remote operation inside storage tanks. As part of that objective, we identified a variety of experimental, design, procurement, fabrication, and demonstration tasks to provide guidelines for the development of a more complete robot system by RedZone Robotics, the prime in this contract. CMU's role was limited to the development of pre-prototype system(s) to study geometry, locomotion and terramechanic issues. The goal of this program was to provide for a comprehensive experimentally based knowledge base for the development of a commercial prototype by the industrial prime over an 18-month period.

• Success Criteria

The prototype would be considered a success, if at the conclusion of the proposed subcontract effort, we could demonstrate, that the crawler is indeed able to deploy, transition onto the floor and locomote through and over a variety of waste forms, and be removed in case of complete failure - all through a 24-inch diameter pipe riser. The success was to be measured by how effectively the overall design would work and how reliable and rugged it could be. A measurement of the crawler's ability to locomote atop and through waste forms was to be made based on surrogate waste materials and various tread and grouser configurations.

• Scope of work

During CMU's subcontract effort, applied engineering design and experimentation efforts were focussed on the overall crawler configuration, optimal frame geometry and location of drive/tooling modules, locomotor actuator and actuated frame geometry, optimized and reconfigurable grouser system designs and miniaturized hydraulic component packaging. A prototype crawler, dubbed *Houdini*, was to be built and used as a generic testbed. Grouser designs were to be tested and implemented on the full-scale prototype. The scope was slightly modified in that the prototype was used by RedZone to carry off an in-tank feasibility test and demo for Oak Ridge's gunnite-tank cleanup project, and the custom-grouser notion was overridden by RedZone's decision to use an OEM-tread made by KOBELCO (fixed design with no option to optimize). CMU was able to dynamically fit into the altering SOW, and was able to generate substantial results in a very short timeframe to aid the exposure of the project within the DoE, and to prove once and for all that mobile worksystems have a role in the waste-tank cleanup agenda across the DoE complex. We expect RedZone will use our experience and put it to good use in their own prototype crawler design (as of yet unnamed).

4.0 Robot Design

The robot design activity can best be described by providing a summary of the prototype design activities CMU engaged in over the duration of the program. The most appropriate way to describe the flow of the design process and justify the design selections would be to cover the main two topics, namely:

- **Problem Description**
- **System Overview**

Each of these topics is covered in detail in the following sections.

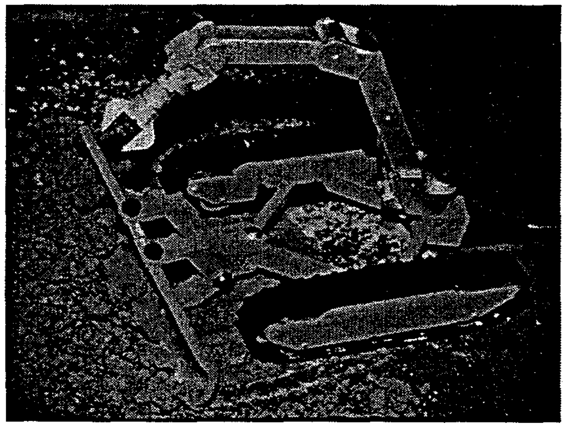
4.1 Problem Description

Environmental restoration of several sites in the DoE's Nuclear Weapons Complex requires remediation of numerous waste storage tanks, such as those at Hanford, Washington, Oak Ridge, Tennessee, and Fernald, Ohio. Due to the hazardous nature of the wastes contained within these tanks, human entry is precluded and the use of remote equipment has been identified as a suitable alternative. Mobile worksystems that would access the tank through existing ports and deploy a variety of tools are viable candidates for in-tank operations, and represent a feasible stand-alone and/or complementary solution alongside the already proposed scenarios of sluicing, and long-reach manipulation.

4.2 System Overview

4.2.1 System Configuration

The cleanup of hazardous waste in storage tanks requires the access of robotic equipment through 0.3m (12"), 0.4m (16"), 0.51m (20") or even 1m (42") diameter pipe-risers. The proposed robotic equipment envisioned for this task, shown in Figure 4-2, is a mobile robot outfitted with the proper sampling and tooling devices (a folding plow and a dexterous manipulator), to access the tanks through the different pipe-risers, and once in the tank, fold out and achieve proper working dimensions and configuration. Currently considered tooling encompasses a manipulator/backhoe and a plow. Other solutions would allow for the use of a manipulator with quick-change tooling adaptors to add different tooling to the endeffector, such as a pry-bar, shovel, etc.



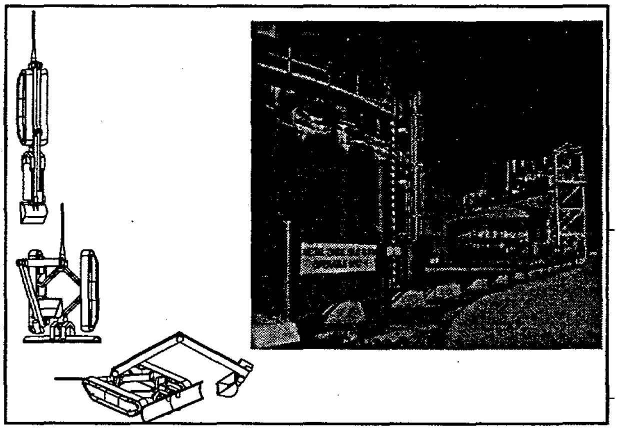


Figure 4-1: *Houdini* Concept Model and In-Tank Deployment Sequence for Fernald OU4 silos 1& 2 (silos 3 & 4 shown)

The robot is to be tethered and teleoperated using cameras on-board the robot and bird's eye views of the entire tank area using one or several cameras deployed through one or several other smaller access pipes [Armstrong et al, 1995]. Such a robot system would eventually operate with a large degree of autonomy, aided by the proper arrangement of sensors, actuation and computational smarts. The robot is lowered into the tank from the deployment pod in its collapsed position via the electro-hydraulic tether, and once in proximity to the ground the frame is actuated to unfold, and the tooling is deployed (backhoe & plow), so that the system can be set onto the ground and begin operations.

The system (shown in Figure 4-2 with partial treads & without plow-blade/manipulator for clarity) is based on the conceptual design in Figure 4-1 and has been built and has undergone testing at the Field Robotics Center (FRC) at CMU. We designed the system to be able to test different exchangeable tread/grouser systems using a conveyor-chain drive, as well as different plow-designs to optimize system performance in different surrogate waste materials.

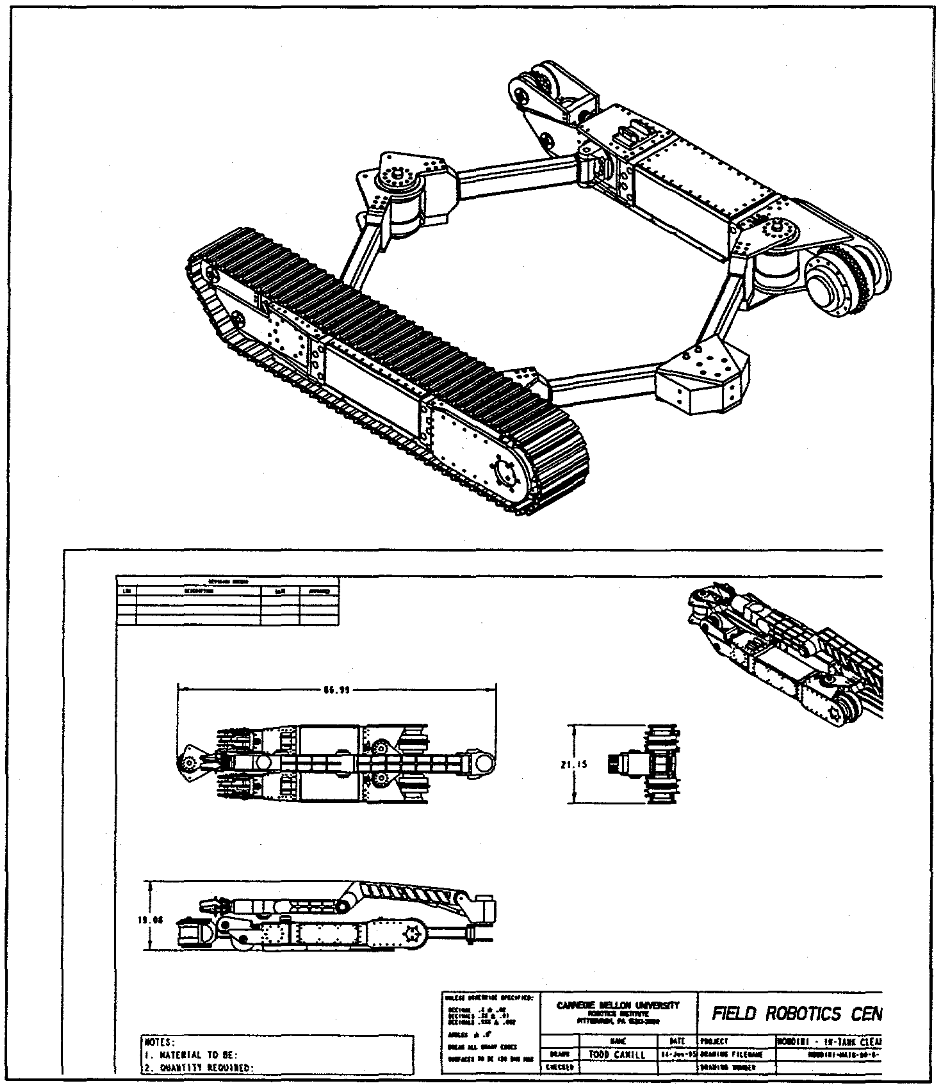


Figure 4-2 : Prototype *Houdini* crawler robot

The systems as shown was implemented, and initial testing excluded the top-mounted manipulator. The overall functionality of the tread-drive and the collapsible frame-geometry were tested in the vertical and horizontal position. A test was conducted to verify that the system would indeed fit through a 24-inch diameter pipe. Pictures showing the individual configurations and tests are shown in Figure 4-3 on page 14.

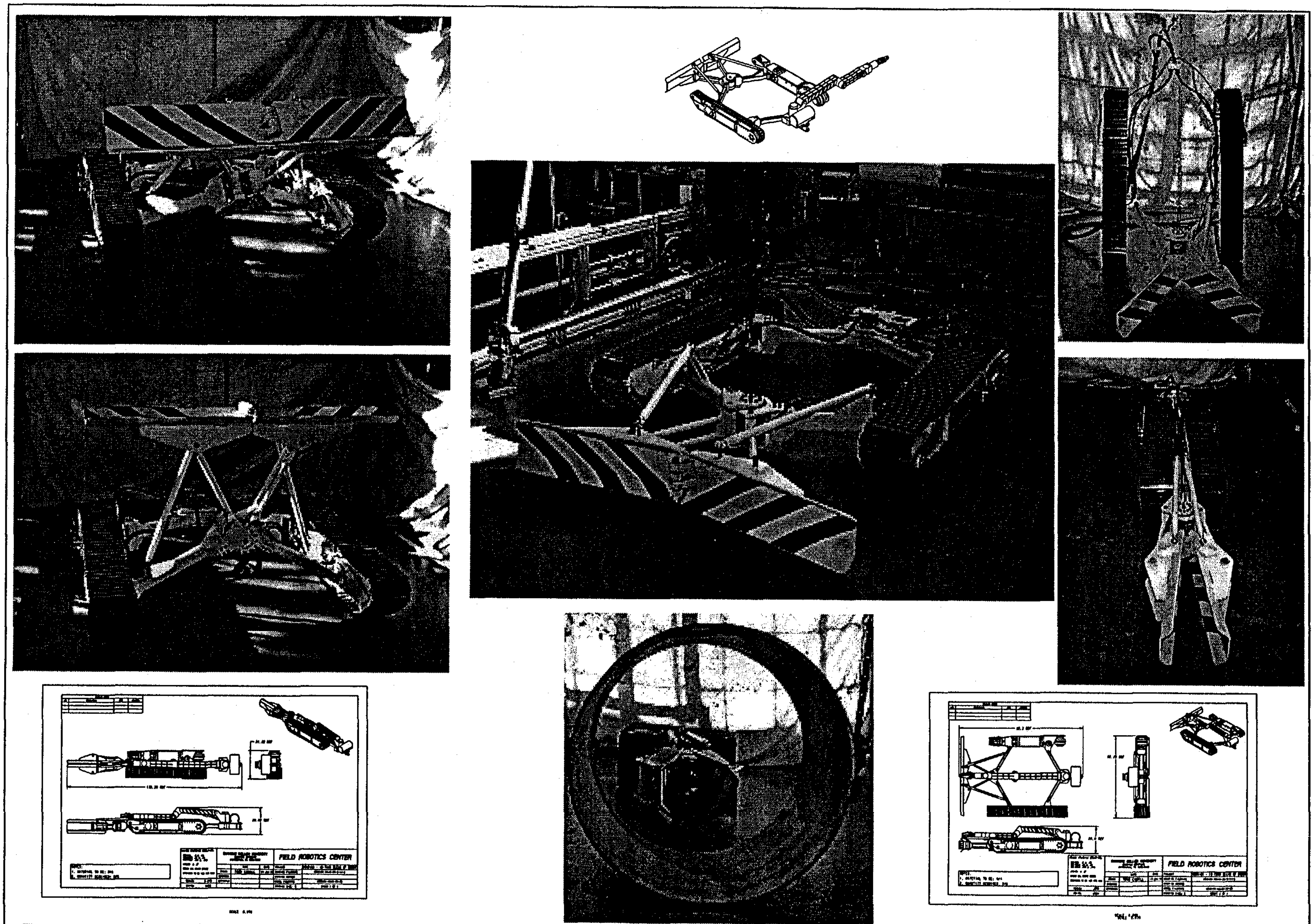


Figure 4-3 : Overview of *Houdini* prototype robot system in various configurations

The overall system configuration was built and assembled at FRC in the late summer of 1995. We began learning from the start that the use of multiple banks of hydraulic valves interlinked by a set of fittinged hose assemblies left a lot of design freedom, but also brought with it some nagging problems. Due to the tightness of the fit of all valves into the side-beams of the robot, there was little room to tighten fittings properly and no way to festoon the cables to avoid them loosening up under vibration.

The fully assembled unit was delivered to RedZone for mounting of the manipulator and further testing. The final system configuration of the *Houdini* robot system is shown in Figure 4-4.

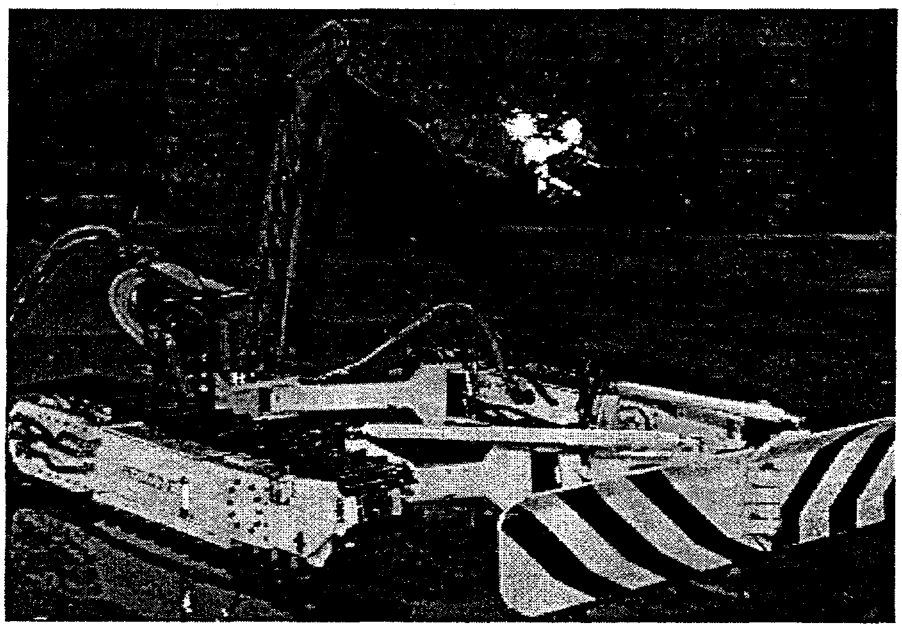


Figure 4-4 : Final *Houdini* prototype

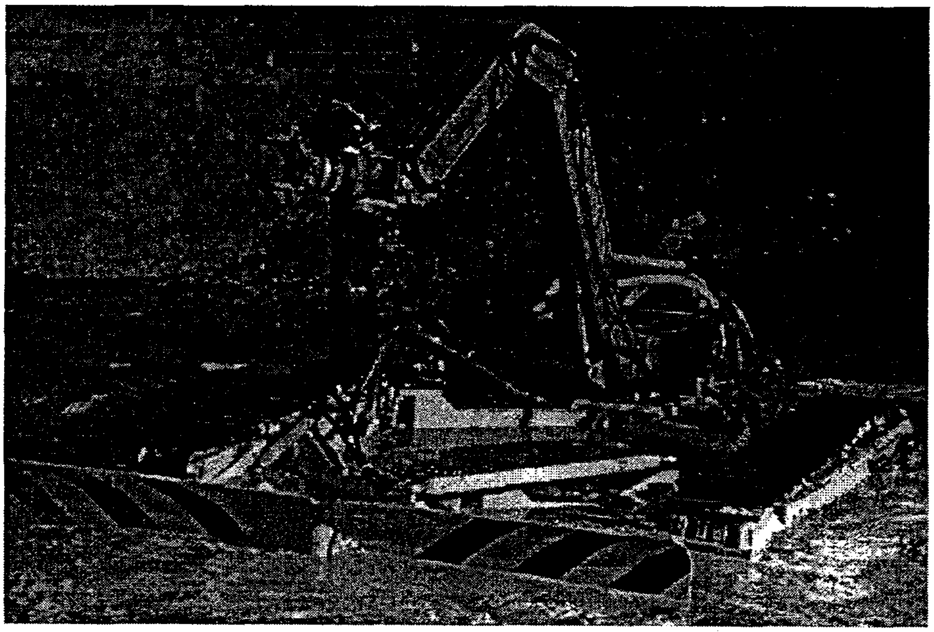


Figure 4-5 : *Houdini* in operation in the simulated waste-pit

We performed additional tests in their simulated waste-pit (see Figure 4-5 on page 15) and realized that we had to modify the tread system to work in fine silty soils, since the treads would jam up due to clogged treads since they were toleranced too tightly. The sliding-friction tread support on the underside proved to be too inefficient for soil-work, and hence had to be modified by covering them with low-friction material.

Upon conclusion of the testing at RedZone, *Houdini* was shipped to Oak Ridge for gunnite test-tank evaluations. Based on the communications RedZone and Oak Ridge have had, the testing went very well, and *Houdini* proved itself as a viable in-tank cleanup system. Oak Ridge has gone ahead and placed an order with RedZone for delivery of a commercial *Houdini* system for their upcoming gunnite tank-remediation project.

4.2.2 Design Considerations

• Component Layout

Achieving access through the small circular man-ways required the design of a novel active frame-structure to carry locomotors and tooling through the man-way and into the tank. This was achieved through a diamond- or benzene-ring shaped structure with triple rotary hydraulic actuation to open and collapse the frame via remote control (a single rotary actuator/hardstop solution is also possible). Identification of suitable OEM components for the track-locomotor and layout of a collapsible plow (or back-fill blade), as well as packaging of a commercially available hydraulic manipulator system rounded out the preliminary system configuration and design phase. Safety concerns were addressed by providing reliable and redundant actuation systems, low-voltage and explosion-proof servo-valving, inherent spark-proof operation of hydraulics, self-collapse under gravity during extrication, and the use of the tether as an emergency retrieval umbilical.

• Terramechanic Optimization

Mobility on, over, and through the existing tank contents can be insured through proper design of vehicle weight and dimensions, and the development of custom locomotor devices. In order to properly size the track-system, theories and data developed by [Bekker, 1958, 1960, 1969] and experimental data gathered by [Everett et al, 1995] and [Schempf et al., 1995], were used to justify and specify the proper arrangement of locomotor design parameters. A test-pit was designed and built, as shown in Figure 4-6, which allowed us to use different materials in tanks to test a full or partial tread section using strain-gauges and LVDTs to measure applied loads and displacements to determine sinkage and contact pressure, as well as soil-failure and thus maximum drawbar-pull.

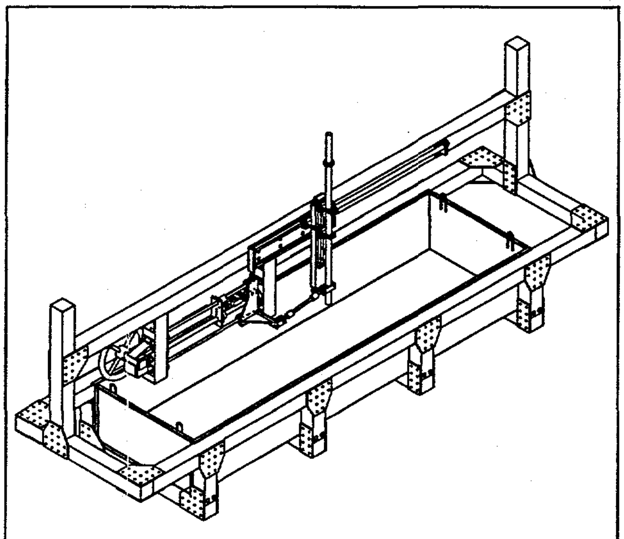


Figure 4-6 Tread Prototype Test-Stand (Frame, Tank, Instr.)

The theoretical comparison and experimental analysis was limited to those soils that most closely resemble those materials bound to be in silos 1 and 2 of The Feed Materials Production Center's OU4 in Fernald, Ohio (FEMCO) [WEMCO RFP, 1991, 1992]. In order to define such parameters as the track-width **b**, the track-height **D**, track-length **l**, grouser depth **h** and the robot weight **W**, use was made of the well-known Bekker-parameters (internal friction angle ϕ, cohesion coefficient **c**, density ρ, deformation moduli $\mathbf{k_c}$ and $\mathbf{k_\phi}$, power ratio **n**, and derived parameters $\mathbf{N_c}$, $\mathbf{N_q}$ and $N\gamma$) and their use in several key equations derived by Bekker and listed below.

- **Contact Pressure 'P' vs. Sinkage-Depth 'z':(1)**

$$P = \left(cN_c + \rho z N_q + \frac{1}{2}\rho b N_\gamma \right)$$

- **Sinkage-Depth 'z' vs. vehicle weight and soil parameters:(2)**

$$z = \left[\frac{\frac{W}{A}}{\frac{k_c}{b} + k_\phi} \right]^{\frac{1}{n}}$$

- **Traction vs.soil shear (A_c), coulomb friction (Wtanϕ) and grouser (H')(3)**

$$H = Ac + H' + W\tan\phi$$

- **Motion Resistance: R (R_c=compaction > R_b=bulldozing > R_e=entrainment)(4)**

$$R_c = 2\left[(n+1)\ (k_c + bk_\phi)^{\frac{1}{n}} \right]^{-1} \left[\frac{W}{l}\right]^{\frac{n+1}{n}}$$

- **Drawbar-Pull - DP=H-R_c (compaction resistance only)(5)**

$$DP = H - R_c$$

One of the important rules-of-thumb was to consider that the track-sinkage should be less than 40% of the track-height, or the tracks would not be able to move through the medium, requiring as large a contact area as possible. Track-width also had to be maximized to reduce sinkage in cohesive materials (loam and clay). In order to increase traction while reducing compaction and bulldozing resistance, the track-length had to be optimized to allow for good traction (in addition to sizing and shaping the grousers) and reduced sinkage, without affecting the turning ability of the robot (expressed as the aspect-ratio of overall length to width, which should remain between 1.0 and 1.8).

In order to make reliable design decisions, geotechnical soils data had to be used, which most closely represents the expected materials to be encountered inside the tanks. Since very little if no data (of the kind we were interested in) was available from inside the tanks, published [Bekker, 1960; Wong, 1989] and experimental data [Schempf, 1991][Everett, 1995] was used to at least bracket the expected system performance of the robot. After several experimental and numerical iterations, the *Houdini* system was laid out with the design parameters and the predicted physical performance characteristics shown in Table 1.

Vehicle Weight	454 kg (1,000 lb)	20.7kPa (3 psi)	Contact Pressure
Track Width	0.20m (8")	1.1	Aspect Ratio
Track Length	1.22m (48")	5cm (2")	Sinkage Depth
Track Area	$0.49m^2$ ($768in^2$)	2,050N (670 lbs.)	Drawbar-Pull
Track Height	0.30m (12")	0.013m (0.5")	Grouser Height
Vehicle Width	1.47m (58in)		

Table 1:*HOUDINI* Design and Performance Parameters

Based on these specifications a proposed grouser design, shown in Figure 4-7 has been implemented and is currently mounted as part of the tread system. Note that we have designed an extruded aluminum backbone around which 60-durometer poly-urea is poured to achieve a self-sealing grouser shape with a 0.5" grouser height attached to a conveyor-chain-link.

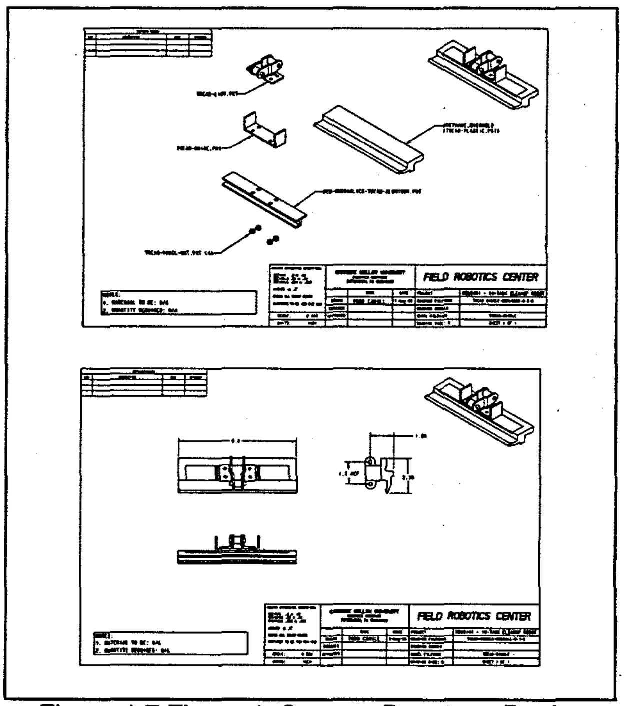


Figure 4-7 Figure 4: Grouser Prototype Design

4.3 Competing Technologies

There are of course several other commercially available systems which are used to perform in-tank operations. The different approaches known to the author are listed here for completeness sake and as a qualitative illustration of alternative systems and their specialized application niches.

4.3.1 Mobile tank-internal spray-gun(s)

The most simple robotic or remote tank-cleanup system consists of a manually emplaced or hydraulically driven folding-frame base spray-gun that is used to spray the insides of the tank with a solvent to make the contents pumpeable - the pump is typically a separate unit situated somewhere off along the inside edge of the tank near a manhole.

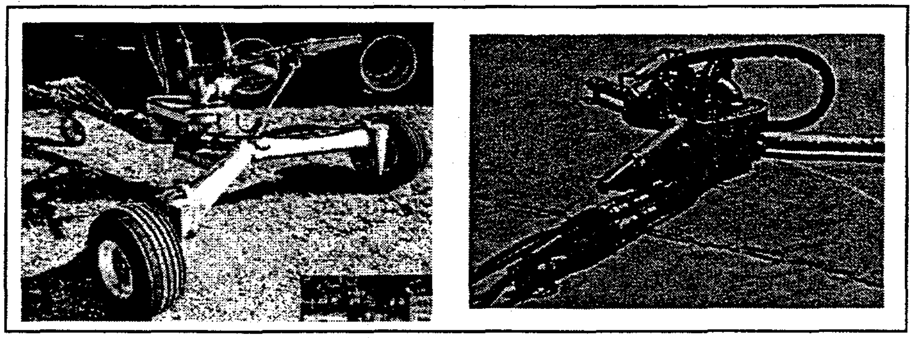


Figure 4-8 Sludge cannon system from *HBM* and *3I*

The systems shown in Figure 4-8 on page 19 clearly show similarities between deployment (foldable frame size for up to 18 inch diameter manway access) and mobility capability (driven wheels vs. fixed supports). These devices, albeit very simple and rugged, require manual assistance to enter/exit and be emplaced, and will only work well with materials that do not need to mixed vigorously (such as by the driving action of treads or augering devices), hence limiting their applicability to certain types of tank contents.

4.3.2 Tracked/Wheeled Self-Mobile Auger/Pump/Skim

There are a few companies that make and lease/service devices for use in all kinds of above-ground storage tanks. Most of the time the task at hand requires the sluicing for/and removal of the tank contents with one and the same vehicle. Depending on the fluid type, people have used systems that are comprised of snap-together components (tracks, body, gun, hose, etc.) which have to be taken apart, manually reached through the manhole and re-assembled inside the tank before they can be used. Such a system is currently in wide use by LANSCO, Inc. (no picture available). Said device simply uses a set of tracks to move a spray-gun delivering heated diesel fuel to spray down heavy-crude tank residues and then plow them to a point along the periphery of the tank where a pump removes the contents for treatment. Additionally, there is a tank-inspection/cleanup system, based on the Scavenger-robot built by *ARD*, in operation (no picture available).

Another device, originally built by 3I and modified by OCEANEERING, Inc., uses a simple backhoe-skimmer/auger system to collect in-tank sludges and pump them outside the tank for reclaiming and disposal (see Figure 4-9). The system uses a set of enclosures and explosion-proof lights and cameras to provide a remote operator with a view to allow for completely entryless operation. This device on the other hand needs a much larger manway than other comparable units (for fully assembled access), even if it is broken down into subpieces which have to be manually re-assembled inside the tank.

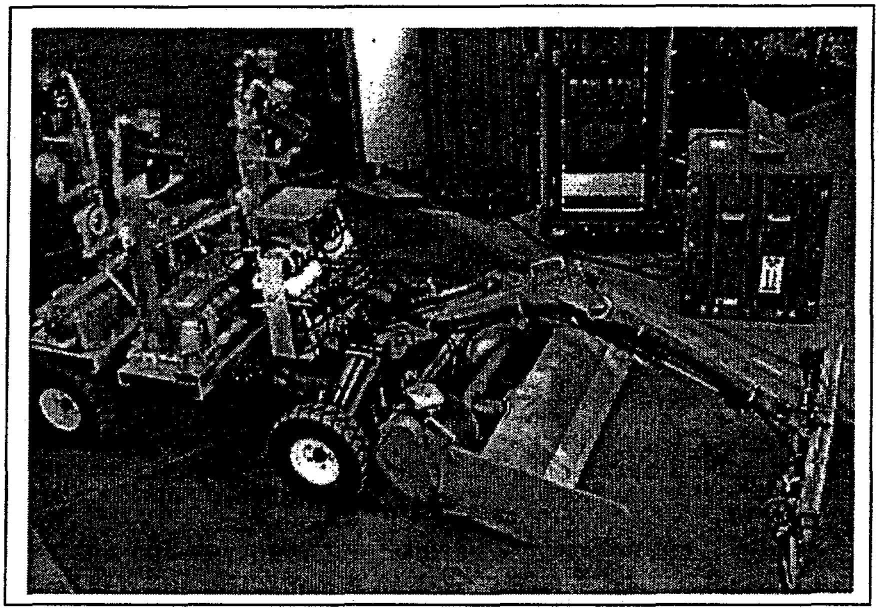


Figure 4-9 : Explosion-proof Sludge-Bug Robot from *Oceaneering, Inc.* with skimmer-backhoe and auger.

A more simpler set of systems, dubbed tracked pumps, simply use a set of dedicated tracks (rubber on steel chain or tread on wheels) with a centrally mounted pump unit to extricate the tank contents (see Figure 4-10 and Figure 4-11 on page 21).

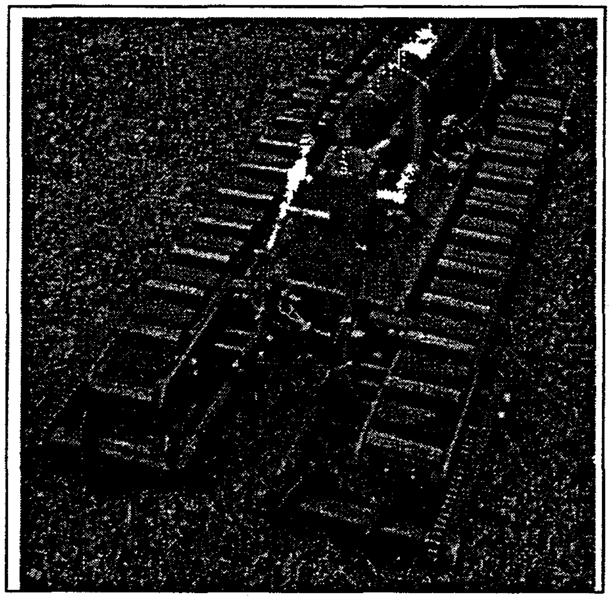


Figure 4-10 : *H&H Pump and Dredge Co.*'s tracked pump

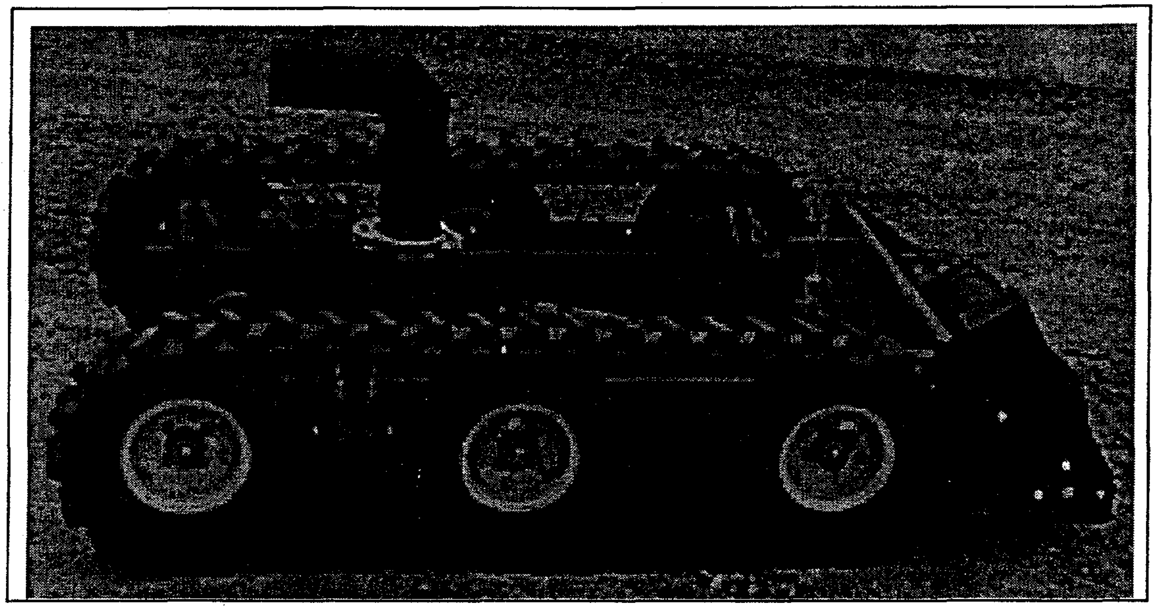


Figure 4-11 : *Liquid Waste Technology*'s system

In either case a frontal (full or partial) auger is used to convey the contents to the pump aided by driving motions. Both systems use either a downward-folding track frame (H&H) or an assembleable/actuated in-line hinged frame design (LWT) to allow the system to enter a tank through a 0.61m (24in.) diameter manway.

Of course there are a variety of currently existing methods to expand and contract frames to which track mechanisms can be attached. Such devices can range from directly perpendicular linear extension mechanisms (US Pat.#3,712,398 & 3,820,616), to collapsible parallelogram configurations (US Pat.#3,700,115), to even dual triangular frame members (USSR Pat.#K9875A/50*SU-591-349).

5.0 Grouser Testing

We used a sample of the KOBELCO-tread that was going to be part of RedZone's crawler system, and tested it with the surrogate waste supplied by FERMCO to see what flotation properties the soil would have under the loading conditions at Fernald. The goal was to determine over what ranges of moisture content of the tank-contents the robot would be able to sit atop the waste and perform useful operations. Since FERMCO is using sluicing as the method to convey the material out of the tank, it becomes important to clarify the role of the crawler in terms of a contents mobilization and pump-assistance device. All results should also be qualified by the fact that the surrogate waste probably does not represent the actual waste in terms of its mechanical properties throughout the tank. In the end it will be a highly test-and-try approach which FERMCO will have to use to see if the crawler can be used to their advantage.

Two types of experiments were carried out, namely the soil analysis and the sinkage tests. The details on the latter test are appended in the appendix in the form of a laboratory report.

5.1 Surrogate Waste Testing

The results we collected were interesting in that they showed the surrogate material to have a somewhat typical solids region for clays, namely 0 to 30% water content (by weight). A surprise was that the plastic region of the material was relatively small, in that it lay between 30 and 45% water content. Any higher moisture content was classified as rendering the material into a liquid.

The important conclusion to be drawn from this result, is that the Fernald tanks are already at their upper solids-limit in terms of water content (30%), and hence any addition (without removal) of water will render the material plastic and very easily liquid if water is left standing in a certain area. This finding was essential, as it will need to be used to optimize the deployment scenario of pump and crawler in order to maximize the use of the crawler during all parts of the deployment.

5.2 Sinkage Testing

A short piece of grouser was used in a soil bin and loaded up with weights to simulate the 3 psig (50 pound load) ground pressure that RedZone's crawler is expected to generate. It was determined very quickly that water contents up to 45% would certainly support the crawler with sinkages only as low as 0.25 inches. Any more water would cause the crawler to sink unstoppably. Charts supporting this fact are shown in Figure 5-1.

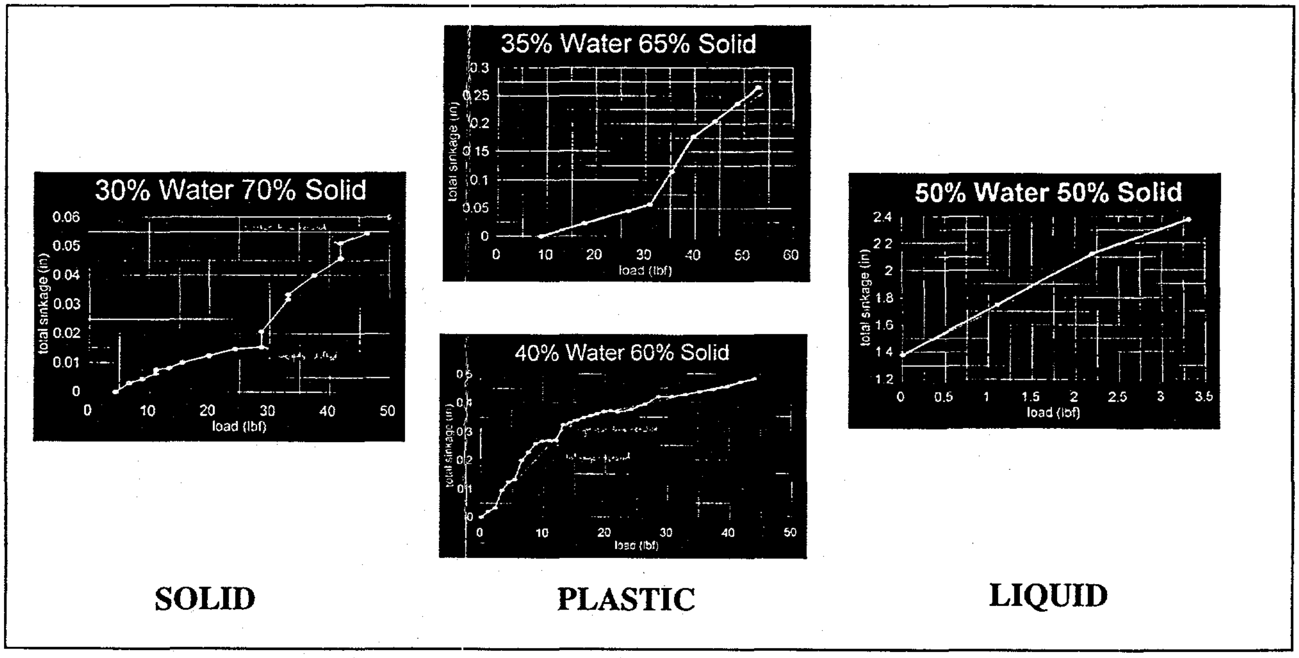


Figure 5-1: Grouser Sinkage charts

6.0 Conclusions

This section details overall conclusions drawn from the executed program.

6.1 *Houdini* Prototype Performance

The CMU-designed-and-built *Houdini* prototype performed admirably well and very closely to the design specification. Some minor flaws were brought out in the design, which have been passe on to RedZone for their crawler design. The use of a reconfigurable worksystem for use in waste-tanks has been validated on the technical capability front as well as the operational utility front. A full set of system performance tests attest to the fact that the system can indeed collapse, drive and carry tooling and be fully collapsible in an emergency retrieval. Its use as a telerobotically controllable waste mobilization system was validated through the in-depth DoE testing performed at Oak Ridge.

6.2 Grouser Performance & Design

The custom-designed grouser system worked well as a basis off the conveyor chain. If a future version is to ever be built, a design with more clearance between adjacent links would work very well even in fine and silty environments.

The OEM-tread from KOBELCO, being as it is a molded product, is satisfactory for use in the material in Fernald's and Oak Ridge's tanks. It is not as wide nor as long as CMU's custom-designed *Houdini* tread, but RedZone has made the decision to use it in its modified crawler. Its performance is expected to be adequate for the envisioned deployments in DoE tank-farms.

7.0 Recommendations

Recommendations that CMU would like to make are based on the experimental and design experience gained from going through the *Houdini* prototyping process. A structured list summarizing these recommendations is given below:

- **Crawler Modifications**

  Based on CMU's *Houdini* prototype experiences, we recommend the following improvements for said machine, or the inclusion of the following into the prototype crawler design from RedZone:

  - *Use or make a molded tread in order to reduce costs and simplify the mechanism.*
  - *Develop a hydraulic manifold as part of the frame system to reduce number of fittings and overall leakage potential.*
  - *Reduce the number of actuators as much as possible (such as 1 to lift/lower the plow, rather than the current 2).*
  - *Provide for guides on the bottom of the tread, and a single off-center-mounted guide-wheel to reduce tread-to-body friction on the body underside.*
  - *Hard-tube run all external hydraulics as much as possible.*
  - *Run the tether termination out of the robot in a 45 degree rooster-tail to ease turning and reduce dragging of the tether on the floor and through the waste.*
  - *Slower speed frame open-close and plow raise/lower motions should be implemented by the use of a needle-valve flow-restrictor on those axes.*

- **Deployment**

  Based on the grouser and surrogate waste material experiments we recommend the following:

  - *Use the crawler sitting atop the waste material as much as possible to plow waste into the center of the tank and to the sluicing pump. Use the pump as much as possible to drain off any excess water.Once the crawler can no longer sit atop or locomote through the waste, remove it from the tank and let the pump bury a hole through the waste down to the tank-floor. Once there, the crawler should be set on the floor and be used to under-dig the waste surfaces and let the pump convey the material out.*
  - *Try to keep the overall tank water content below 45% by weight.*

Overall we believe that since the OEM-tread system has been favored by RedZone, the utility of the CMU *Houdini* prototype has been minimized, since it was meant to be a test-platform for various tread and grouser designs. Furthermore, since RedZone decided to go with a different frame design, it is unclear how much of CMU's design and operational experience will have been captured by the RedZone crawler design. The latter point will be resolved once they have their prototype built and tested later in the summer of 1996.

8.0 Appendix

This section contains all the attachments to the topical report.

8.1 *Houdini* ANS Paper

conf
paper
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separately.

8.2 KOBELCO Grouser Testing Report

Houdini Soil Test Results

Todd Camill

Field Robotics Center

February 12, 1996

Summary:

A series of four tests were performed using a sample of tread from the Houdini mobile robotic system and a sample of soil prepared with a known water content. The sinkage of the tread was measured as vertical load was applied to the tread. The test was repeated for levels of water ranging from 30% water to 70% water based on total sample weight. The soil properties were very time dependent as the added water settled into the soil. The liquid limit -- the maximum percentage of water that the soil can incorporate homogeneously -- was surpassed between the 40% and 50% water tests, setting the upper bound of usefulness of the soil. The tread did not begin to sink significantly until the 40% level, and even then it still maintained an approximate equivalent weight of 1320 lb for the whole robot. The small volume of the soil sample caused the heaving of the tread to reach the sides of the testing box. This problem could cause the measured load carrying capacity of the tread to be slightly higher than reality.

Abstract:

The Houdini project developed at the Field Robotics Center at Carnegie Mellon is a mobile robotic system which utilizes tank-style treads for locomotion. A variety of experimental tests must be conducted in order to insure that the tread operates satisfactorily within a typical range of soil conditions. The experiments described below test the soil's ability to support a static load for varying soil moisture levels.

Test Setup:

The soil tests were conducted in a watertight wooden box that was previously constructed for other tread soil tests. The box was subdivided by another piece of wood, since the soil sample was not large enough to fill the entire box. The divider was supported by scraps of wood, and sealed along its edges and surface using duct tape.

Once a particular water percentage was mixed into the sample, the soil was placed into the box, and allowed to set up for at least 12 hours so that the water content was evenly distributed throughout the soil. The surface of the sample was covered with plastic wrap to prevent moisture loss by evaporation, while the sample rested.

Before the test was run, a small sample of the soil was removed from the box, weighed, and placed into an oven set to 110 degrees Fahrenheit. After at least twelve hours, the heated sample was weighed again, and the water content of the sample was calculated. When the actual test was to be performed, the tread sample was placed in the center of the soil sample, and wood scraps were used to create a level surface above the tread. A dial displacement gauge was setup referencing the wood surface. Flat weights were piled onto the surface in regular increments, until the stack of weights became unstable, or the tread sunk to an unacceptable level. For each increment of weight, the total weight, deflection, and time were recorded (see appendix for raw data and comments). Approximately two minutes was allowed to elapse between each measurement. If significant sinkage occurred between measurements, then the deflection was measured and recorded again for the same load.

Once the test was concluded, the sample was removed from the box, and placed in a stainless steel bowl. The water content was incremented based on the following formula:

Wwater new = (%water/%solid)*Wsolid - Wwater

where:

Wwater new = the mass of water to be added
%water = the desired percentage of water
= mass of water in sample / total mass of sample
%solid = the desired percentage of solid
= mass of solid in sample / total mass of sample
= 100 - %water
Wsolid = total mass of solid in sample
Wwater = current mass of water in sample

The added water was thoroughly mixed by hand, and the test process was repeated.

Test Results:

Each test had its own unique concerns and results. A brief discussion of each of the four test follows.

30% water, 70% solid:

The soil sample was acquired at approximately the desired water level. An initial water content test revealed the sample was actually 31.5% water. Since the sample was at this state for at least two days, it was easily transferred to the wooden box and tamped lightly. The sample rested for one day, and then the test was conducted. The tread sample did not sink to the base of the grouser before the amount of weight became unstable. The test was concluded at this point.

40% water, 60% solid:

This test was the second of the four tests and was the first where water was added to the sample. When the correct mass of water was added, the soil consistency changed rapidly from a relatively solid soil to an unstable mud. After the sample rested for 1.5 days, the consistency appeared to return to a much more cohesive soil. The sample sank past the base of the grousers, but still held a considerable load.

%50 water, 50% solid:
This test also showed a remarkable change in consistency when additional water was added. The consistency immediately after mixing was closer to a frothy liquid than a solid, suggesting the soil had exceeded its liquid limit. After resting for a day, the sample was indeed still predominantly liquid. Water content tests were performed on samples collected from the surface and from the bottom of the box. These tests revealed a definite moisture gradient within the box, varying from 56% solid at the surface to 60% solid at the bottom. Also, a considerable amount of water remained on the surface of the sample and had leaked into the open section of the box. Even so, the tread sample sank considerably into the sample.

%35 % water, 65% solid:
This experiment was the last test conducted. In order to create a water content that was less than the last test, the entire sample was placed into the oven and dried. Then the remaining solid was pulverized, weighed, and mixed with the correct amount of water. This test produced a soil consistency similar to the 30% water test.

Conclusions:

The properties of this sample of soil proved to be very time dependent. A rest period of at least twelve hours was necessary to insure proper distribution of moisture through the soil. Significant sinkage of the tread did not occur until approximately 40% water was introduced, even for loads up to 44 lb. Assuming thirty such tread pieces are in contact with the ground, this load equates to a total of 1320 lb that can be supported by the soil, which is less than the total weight of the robot. additionally, the limit of the useful range of moisture content was shown to be between 40 and 50%.

It is important to note the limitations of the testing procedure. The small quantity of available soil distorted the data. The volume of material set the dimensions of the testing box. The small amount of material meant there was not enough space between the tread sample and the front wall and divider.

When the tread sank a significant amount -- in the 40% water test, for example -- the soil in front and behind the tread sample heaved al the way to the walls of the box. Therefore, the box was directly carrying a portion of the load. Thus, the load carrying ability of the soil may not be as great as was seen; although the effect of the heaving may be neglected.

Another minor problem which made the tests more difficult was the tendency of the box to leak for high moisture levels. As the actual water content measurements show, the leakage made it difficult to produce the desired water percentage.

For future tests, it is important to note that repeated tests cause a steady decrease in the available soil through spillage, hand washing and cleanup. From interim weight measurement, at least 3% of the sample was lost.

Appendix

Soil Sample Data:

Final mass of sample: 2659 g (5.96 lb)

specific weight: 65 lb per cubic ft

Tread Sample Data:

tread sample weight: .90 lb

tread contact area (grouser tips only): 2.4 square in.

tread contact area (at grouser base): 15.6 square in.

Test Data:

see following sheets for actual data and plots

Mud Test 1: 30% water 70% solid

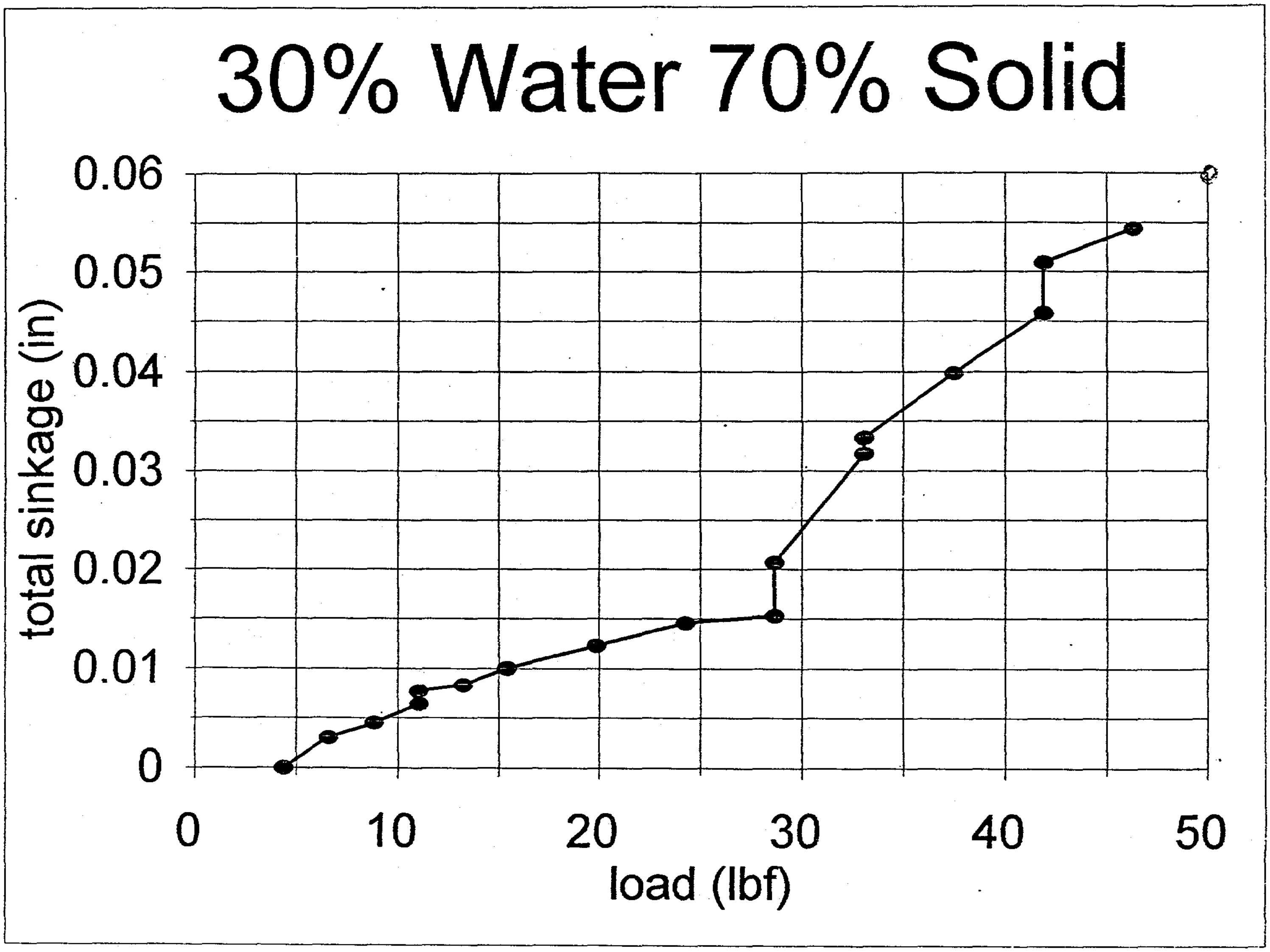
actual moisture content: 31.5% water, 68.5% solid

raw data:

mass (kg)	sinkage (in)	time	notes
2	0	9.53	
3	0.003	9.55	
4	0.0045	9.56	
5	0.0064	9.59	
5	0.0077	10	
6	0.0083	10.01	
7	0.01	10.03	
9	0.0122	10.06	
11	0.0146	10.08	
13	0.0153	10.1	
13	0.0207	10.13	weight correction
15	0.0317	10.15	
15	0.0333	10.16	
17	0.0399	10.17	weight stack fell over
17	0	10.25	weights and dial gauge reset (deflections below are relative)
19	0.006	10.26	base of grouser starts to support right corner
19	0.011	10.27	
21	0.0145	10.28	
21	0.031	10.3	
23	0.0619	10.31	
23	0.067	10.32	
25	0.1685	10.33	stack of weights very unstable

refined data:

mass (kg)	load (lbf)		sinkage (in)	total sinkage (in)	time
2	4.410576		0	0	9.53
3	6.615864		0.003	0.003	9.55
4	8.821152		0.0045	0.0045	9.56
5	11.02644		0.0064	0.0064	9.59
5	11.02644		0.0077	0.0077	10
6	13.231728		0.0083	0.0083	10.01
7	15.437016		0.01	0.01	10.03
9	19.847592		0.0122	0.0122	10.06
11	24.258168		0.0146	0.0146	10.08
13	28.668744		0.0153	0.0153	10.1
13	28.668744		0.0207	0.0207	10.13
15	33.07932		0.0317	0.0317	10.15
15	33.07932		0.0333	0.0333	10.16
17	37.489896		0.0399	0.0399	10.17
17	37.489896		0	0.0399	10.25
19	41.900472		0.006	0.0459	10.26
19	41.900472		0.011	0.0509	10.27
21	46.311048		0.0145	0.0544	10.28
21	46.311048		0.031	0.0709	10.3
23	50.721624		0.0619	0.1018	10.31
23	50.721624		0.067	0.1069	10.32
25	55.1322		0.1685	0.2084	10.33



30% Water 70% Solid
total sinkage (in)
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
load (lbf)

Mud Test 2: 35% water 65% solid

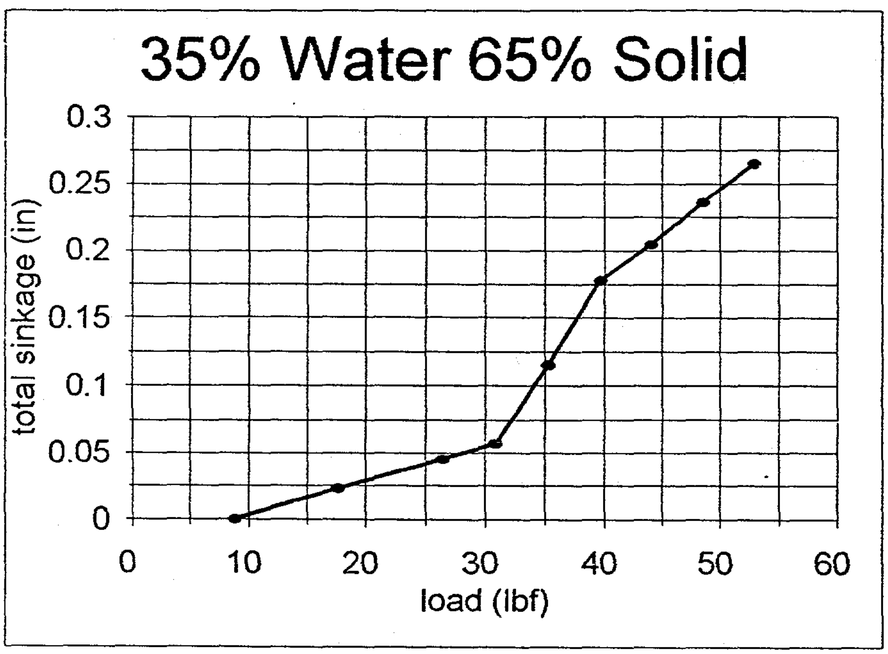
actual moisture content: 31.5% water, 68.5% solid

raw data:

mass (kg)	sinkage (in)	time	notes
4	0	11.39	
8	0.0228	11.47	
12	0.0447	11.48	
14	0.057	11.49	
16	0.1156	11.5	
18	0.1778	11.52	
20	0.2045	11.53	one corner settled to base of grouser
22	0.2358	11.55	
24	0.2646	11.57	

refined data:

mass (kg)	load (lbf)		total sinkage (in)		time
4	8.821152		0		11.39
8	17.642304		0.0228		11.47
12	26.463456		0.0447		11.48
14	30.874032		0.057		11.49
16	35.284608		0.1156		11.5
18	39.695184		0.1778		11.52
20	44.10576		0.2045		11.53
22	48.516336		0.2358		11.55
24	52.926912		0.2646		11.57



Mud Test 3: 40% water 60% solid

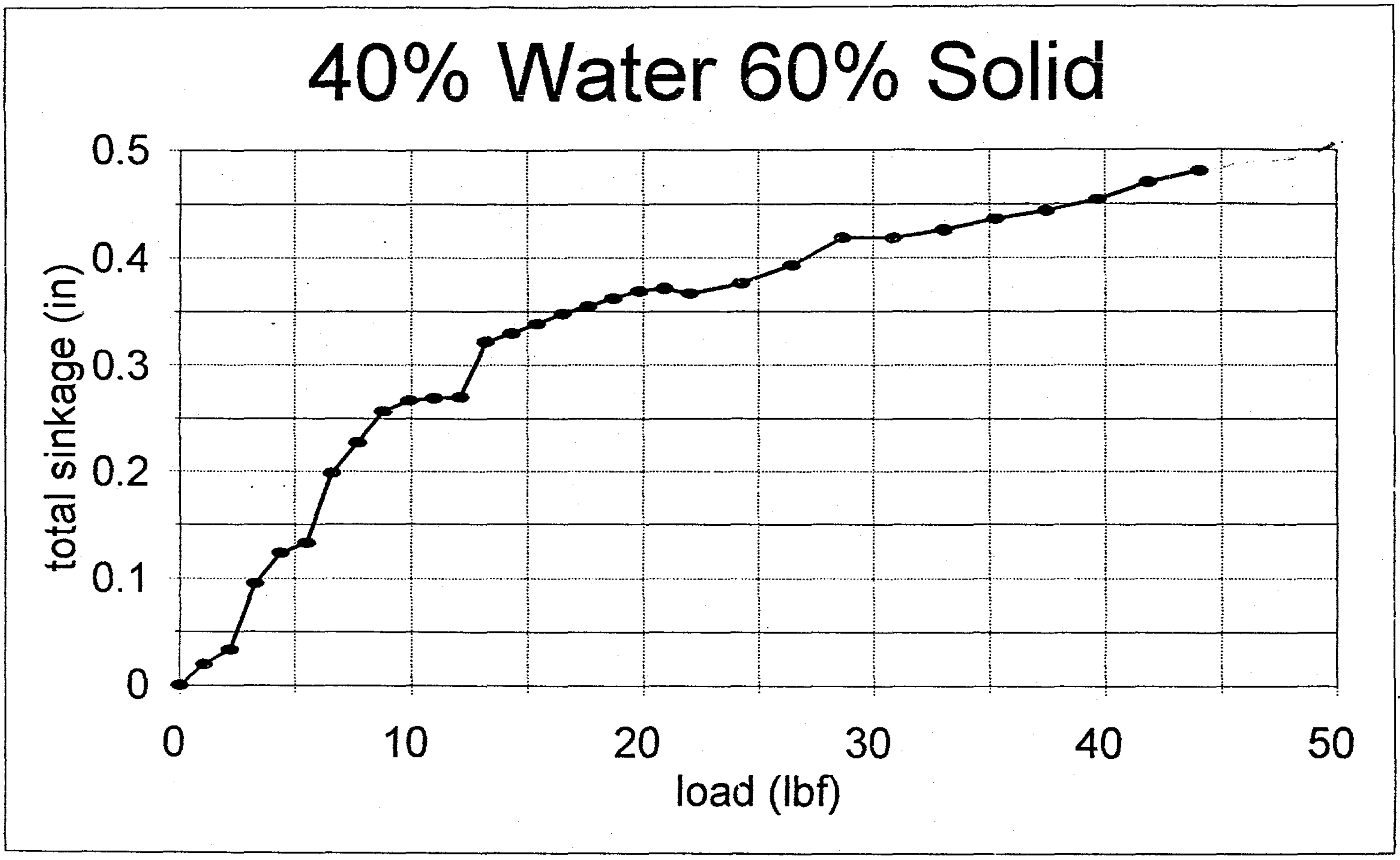
actual moisture content: % water, % solid

raw data:

mass (kg)	sinkage (in)	time	notes
0	0	1.18	
0.5	0.0197	1.18	
1	0.033	1.2	
1.5	0.0957	1.22	
2	0.1238	1.25	
2.5	0.1333	1.27	
3	0.1989	1.28	
3.5	0.2273	1.3	
4	0.2566	1.32	grouser base reached in front
4.5	0.2668	1.34	
5	0.2688	1.36	
5.5	0.2702	1.38	
6	0.3222	1.41	dial gauge adjusted, changed to 4 kg mass
6.5	0.3296	1.43	
7	0.3386	1.45	
7.5	0.3483	1.47	almost completely settled to grouser base
8	0.3547	1.49	
8.5	0.3623	1.51	
9	0.3689	1.53	
9.5	0.3719	1.55	
10	0.3669	1.57	changed to 4 kg mass
11	0.3764	1.59	back end settled
12	0.3929	2.01	
13	0.4185	2.03	
14	0	2.08	dial reset, changed to 4 kg mass, load adjusted
15	0.0072	2.09	one side completely sunk
16	0.0169	2.11	
17	0.025	2.11	
18	0.0354	2.13	
19	0.0508	2.15	
20	0.0616	2.17	

refined data

mass (kg)	load (lbf)		sinkage (in	total sinkage (in)		time
0	0		0	0		1.18
0.5	1.102644		0.0197	0.0197		1.18
1	2.205288		0.033	0.033		1.2
1.5	3.307932		0.0957	0.0957		1.22
2	4.410576		0.1238	0.1238		1.25
2.5	5.51322		0.1333	0.1333		1.27
3	6.615864		0.1989	0.1989		1.28
3.5	7.718508		0.2273	0.2273		1.3
4	8.821152		0.2566	0.2566		1.32
4.5	9.923796		0.2668	0.2668		1.34
5	11.02644		0.2688	0.2688		1.36
5.5	12.129084		0.2702	0.2702		1.38
6	13.231728		0.3222	0.3222		1.41
6.5	14.334372		0.3296	0.3296		1.43
7	15.437016		0.3386	0.3386		1.45
7.5	16.53966		0.3483	0.3483		1.47
8	17.642304		0.3547	0.3547		1.49
8.5	18.744948		0.3623	0.3623		1.51
9	19.847592		0.3689	0.3689		1.53
9.5	20.950236		0.3719	0.3719		1.55
10	22.05288		0.3669	0.3669		1.57
11	24.258168		0.3764	0.3764		1.59
12	26.463456		0.3929	0.3929		2.01
13	28.668744		0.4185	0.4185		2.03
14	30.874032		0	0.4185		2.08
15	33.07932		0.0072	0.4257		2.09
16	35.284608		0.0169	0.4354		2.11
17	37.489896		0.025	0.4435		2.11
18	39.695184		0.0354	0.4539		2.13
19	41.900472		0.0508	0.4693		2.15
20	44.10576		0.0616	0.4801		2.17


40% Water 60% Solid
total sinkage (in)
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
load (lbf)

Mud Test 4: 50% water 50% solid

actual moisture content: varied from 56% solid at surface to 60%solid at bottom

raw data:

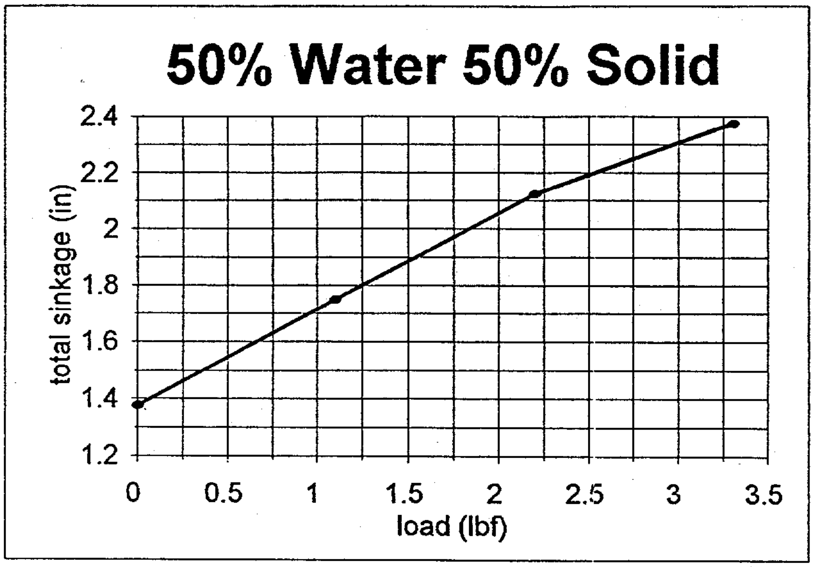
mass (kg)	tread remaining above surface (in)	time	notes
0	1.125	n/a	
0.5	0.75	n/a	
1	0.375	n/a	
1.5	0.125	n/a	

total tread height (in)

2.5

refined data:

mass (kg)	load (lbf)		total sinkage (in)	time
0	0		1.375	n/a
0.5	1.102644		1.75	n/a
1	2.205288		2.125	n/a
1.5	3.307932		2.375	n/a



DOE/MC/32092 – 5630

HOUDINI (TM): RECONFIGURABLE IN-TANK MOBILE ROBOT

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