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Retrieval Process Development and Enhancements Hydraulic Test Bed Integrated Testing Fiscal Year 1995 Technology Development Summary Report

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Executive Summary

The Retrieval Process Development and Enhancements Program (RPD&E) is sponsored by the U.S. Department of Energy Office of Science and Technology to investigate existing and emerging retrieval processes suitable for the retrieval of high-level radioactive waste inside underground storage tanks. This program, represented by industry, national laboratories, and academia, seeks to understand retrieval processes, including emerging and existing technologies, gather data on these technologies, and relate the data to specific tank problems such that end-users have requisite technical bases to make retrieval. Part of this program has involved the development of the Hydraulics Test Bed (HTB) to evaluate a high-pressure waterjet dislodging system and pneumatic conveyance integrated as a scarifier. In fiscal year (FY) 1994 and FY95, the HTB was completed through a cooperative effort involving the U.S. Department of Energy (DOE), Tanks Focus Area, Pacific Northwest National Laboratory, Westinghouse Hanford Company (WHC), and Quest Integrated, Inc. The HTB provides a facility for testing of waste dislodging and conveyance processes at scales which support engineering development and gathering of process performance data necessary for program decisions about deployment of that process to be made. Although the Hydraulic Test Bed was originally used to test the high-pressure scarifier, the HTB addresses technology needs that drive retrieval requirements at multiple DOE sites, including Oak Ridge National Laboratory (ORNL), Savannah River National Laboratory, and Idaho National Engineering Laboratory (INEL). There is a strong need to validate the mining strategy used to remove waste fields; to measure the dynamic reaction forces, accuracy, repeatability, and maneuverability requirements of end effectors; and to define the requirements for instrumentation and automatic control. There is also a need to evaluate waste retrieval tool performance over various waste types and topography. The Hydraulic Test Bed addresses these needs by providing longer duration, multiple pass tests on large waste simulant fields using a three-dimensional deployment platform. The mission of the HTB is not to develop new technologies, but to support DOE Environmental Management programs, industry, and academia by providing key testing capabilities to allow full-scale cold testing of waste retrieval tools. The HTB will allow DOE retrieval programs to evaluate alternative established and emerging retrieval processes in a standardized, cost-effective, and timely manner.

At the beginning of FY95, the HTB Test Plan was finalized and the procurement of instrumentation was completed. A data acquisition and controls program was written to take data from the sensors and to control various components in the system. The completion of the data acquisition system lead to initial system check-out tests, hardpan testing, sludge testing, and topography waste testing. During late FY95, the construction activities were completed for the HTB and the testing program was initiated through feature testing of the Quest high-pressure scarifier using both sludge and saltcake simulants.

Although not the focus HTB testing during FY95, testing was also conducted to verify the controllability and accuracy of the proximity sensors and control software to maintain a constant stand-off distance. Maintaining a relatively constant stand-off distance is of importance because of constraints

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imposed by the conveyance system. Software was developed to modify the gantry position in real time to maintain a constant stand-off distance on hard and soft simulants and various topography. Two sensors were installed on the shroud at the leading and trailing edge to allow the system to prepare for abrupt changes in topography without collisions. Ultrasonic sensors were used initially for their low cost and adaptability for the high noise, industrial environment. Various commercially available proximity sensors were also evaluated, based on the needs for underground storage tank waste retrieval at DOE sites. This evaluation included an in-depth comparison of radar, ultrasonics, and low-powered laser sensors.

Abbreviations/Acronyms

DOE	U.S. Department of Energy
EM	Environmental Management
E-stops	Emergency stops
GENISAS	General interface for supervisor and subsystems
HTB	Hydraulic Test Bed
IGRIP	Interactive Graphics Robot Instruction Program
INEL	Idaho National Engineering Laboratory
LDUA	Light Duty Utility Arm
MLDUA	Modified Light Duty Utility Arm
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RPM	Real-time path modification
SNL	Sandia National Laboratory
UMR	University of Missouri-Rolla
UST	Underground storage tank

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1.0 Introduction

The Retrieval Process Development and Enhancements Program is sponsored by the U.S. Department of Energy (DOE) Office of Science and Technology to investigate waste dislodging and conveyance processes suitable for the retrieval of high-level radioactive waste. This program, represented by industry, national laboratories, and academia, is testing the performance of a technology of high-pressure waterjet dislodging and pneumatic conveyance integrated as a scarifier as a means of retrieval of waste inside waste storage tanks (Rinker et al. 1994). Waste simulants have been designed to challenge this retrieval process, and this technology has been shown to mobilize and convey the waste simulants at target retrieval rates while operating within the space envelope and the dynamic loading constraints of postulated deployment systems. The approach has been demonstrated to be versatile in dislodging and conveying a broad range of waste forms, from hard wastes to soft sludge wastes, through the use of simple and reliable in-tank components.

The Hydraulic Test Bed (HTB) provides a facility for testing of waste dislodging and conveyance processes at scales which support engineering development and gathering of process performance data necessary for program decisions about deployment of that process to be made. Although originally used to test the high-pressure scarifier, the HTB addresses retrieval process data that drive retrieval requirements at multiple DOE sites, including Oak Ridge National Laboratory (ORNL), Savannah River National Laboratory, and Idaho National Engineering Laboratory (INEL). There is a strong need to validate the mining strategy used to remove waste fields; to measure the dynamic reaction forces, accuracy, repeatability, and maneuverability requirements of end effectors; and to define the requirements for instrumentation and automatic control. There is also a need to evaluate waste retrieval tool performance over various waste types and topography. The HTB addresses these needs by providing longer duration, multiple pass tests on large waste simulant fields using a three-dimensional deployment platform. The primary mission of the HTB is not to develop new technologies, but to support DOE Environmental Management (EM) programs, industry, and academia by providing key testing capabilities to allow full-scale cold testing of waste retrieval tools. The HTB will allow DOE retrieval programs to evaluate alternative established and emerging retrieval processes in a standardized, cost-effective, and timely manner. The capabilities of the HTB include:

- large programmable gantry to implement three-dimensional mining strategies
- waste simulant production procedures and equipment
- standardized testing protocols to evaluate waste retrieval tools, controls, and instrumentation
- waste retrieval balance of plant equipment, including water pumps, air conveyance systems, and material handling equipment.

The HTB will allow DOE retrieval programs to evaluate various alternate retrieval processes in a standardized, cost-effective, and timely manner. The HTB will also assist industry and academia by providing test facilities that they would not otherwise have access to and would prevent them from developing key technologies.

At present, the HTB supports the retrieval programs at the following DOE sites:

- Oak Ridge National Laboratory through prototype testing of the Gunite Tank Treatability Study confined sluicing end effector

- Idaho National Engineering Laboratory through prototype testing of the underground storage tank confined sluicing end effector

- Hanford, through support of Acquire Commercial Technology for Retrieval task and testing of the high-pressure, lightweight scarifier developed by Quest Integrated, Inc.

The HTB testing programs are cost effective for a number of reasons. Preliminary tests are conducted off-site by retrieval tool developers to establish baseline performance trends. This reduces the number of variables that must be considered in the testing matrix and allows the HTB testing programs to focus on mining strategy tests. Also, the experience of end effector developers is used to reduce the design and construction time of HTB systems. And finally, because the HTB is operated by a national laboratory, off-site personnel from academia and industry can participate in testing activities. This also facilitates the involvement of technology end-users.

The HTB investigates deployment strategies for remote retrieval operations inside underground storage tanks. The HTB will use developmental testing of retrieval tools to determine appropriate mining strategies, level of control, and sensor requirements. The primary technical focus areas of the HTB include:

- measurement of dynamic forces

- mining strategy development

- process control and instrumentation

- evaluation of proximity sensors to provide localized distance data for contour following and collision avoidance

- evaluation of waste retrieval tool performance over various wastes types and topography.

A strategy (Bamberger et al. 1993) was developed to guide an analytical/experimental approach to develop a multi-function scarifier dislodger coupled with a pneumatic conveyance system. Based on the strategy, a testing program has been initiated to characterize aspects of waste dislodging and conveyance processes, evaluate process equipment performance, and address integration issues associated with deploying the scarifier by a robotic arm. The mission of the program is to investigate system deployment strategies to determine appropriate mining strategies, level of control, and sensor requirements. This paper will describe the test bed facility and testing program and present initial test results to date.

2.0 System Description

This section provides an overview of the high-pressure scarifier, test facility, and experimental test set-up.

2.1 High-Pressure Scarifier

A promising technology for waste dislodging is a high-pressure waterjet scarifier. High-pressure waterjet technology has been used industrially for many years for mining, cutting, cleaning, and scarification of materials with a broad range of properties. Separate effects and proof-of-concept testing have demonstrated that high-pressure waterjets can effectively dislodge several diverse waste simulants.

The test scarifier article was develop by Quest Integrated, Inc. through collaboration with Pacific Northwest National Laboratory (PNNL). This scarifier consists of high-pressure fluid jets mounted on a rotating body and directed at the waste surface. The three rotating jets require approximately 22.7 liters per minute (6 gal/min) of water at 345 Mpa (50,000 psi). The rotation of the jet carrier is provided by a secondary motion drive, which nominally rotates at 650 rpm. The axis of the secondary motion rotation is normal to the waste surface. The secondary motion drive and jet carrier are contained in a sealed enclosure mounted concentric to and inside the conveyance system inlet shroud. The waterjet assembly is encased in a shroud which contains the dislodged waste and water and directs the collected waste to an air conveyance system.

2.2 Test Facilities

To demonstrate the scarifier in an actual mining operation, a test facility (HTB) has been con-structed to allow longer duration, multiple-pass tests on large waste fields using a versatile gantry style manipulator (Figure 2.1). A gantry was selected for implementing the mining operation due to its inherent rigidity, programmability, and large load capacity demanded by a technology development program. The actual gantry manipulator select, provided by PaR Systems, Inc., includes 4 degrees of freedom to allow rectangular motion plus mast rotation. The control system of the gantry allows sensor data to be used to update the trajectory in real time. This feature allows candidate proximity sensors to be used in the course of an actual mining operation.

The ancillary equipment of the dislodging system includes a high-pressure hose and two high-pressure pumping units. The high-pressure pumps are capable of producing 17.4 liter/min (4.6 gal/min) of water at 345 MPa (50,000 psi). The balance of the conveyance system includes a conveyance line, a wet/dry separator, a collection hopper, and a blower unit.

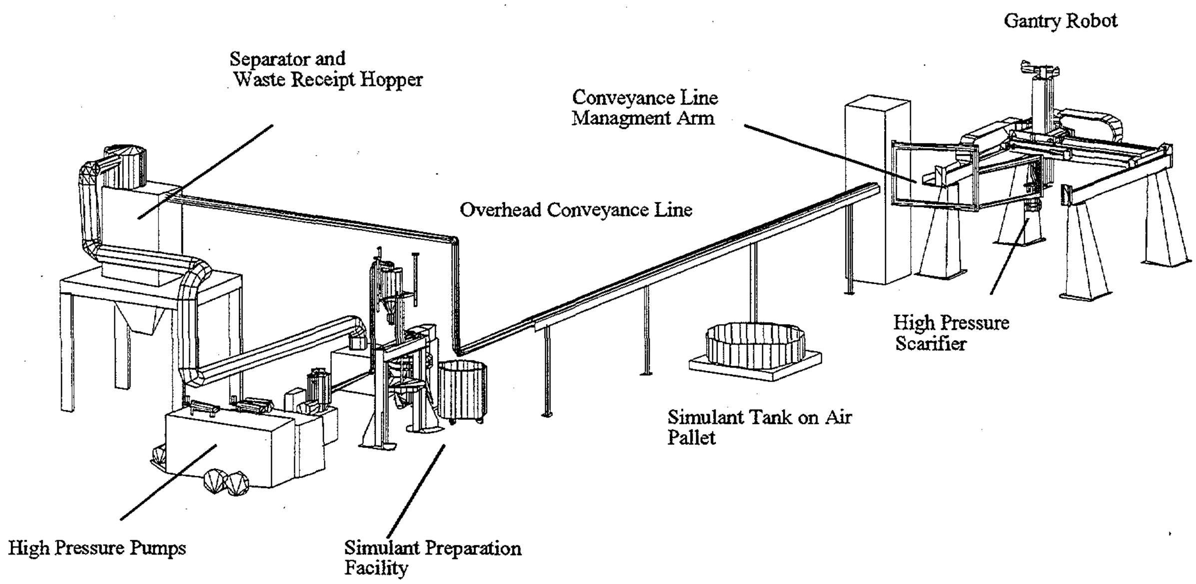

Figure 2.1. Retrieval Process Development & Enhancements Hydraulic Test Bed

As shown in Figure 2.2, the high-pressure hoses, lubrication water hose, and air conveyance line are suspended as a bundle from a trolley, which travels along a beam attached to the perimeter of the gantry. The bundle is allowed to coil and extend to accommodate the motion of the scarifier.

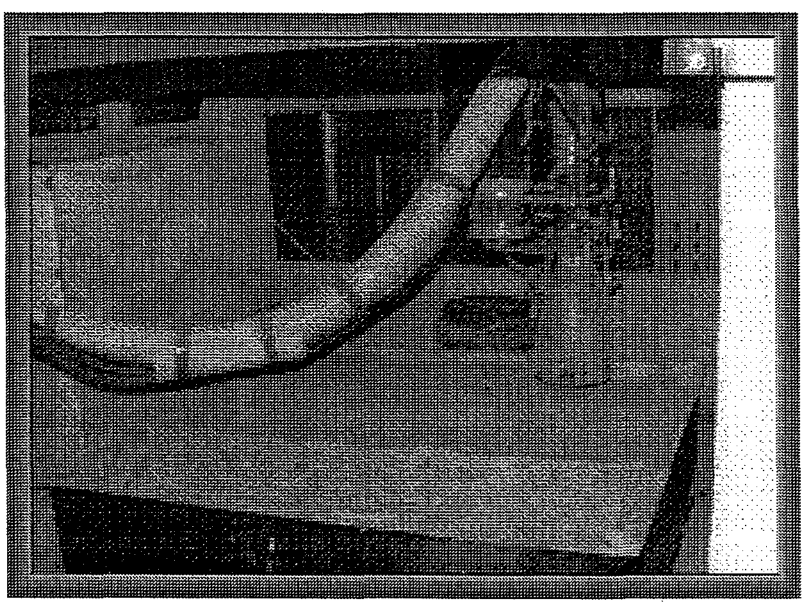

Figure 2.2. Scarifier Installation on the Gantry. High-pressure hoses were attached to the air conveyance line and suspended from a trolley arrangement.

2.3 Instrumentation and Control

An integrated data acquisition and controls system was designed and assembled to record the test data and perform various controls functions (Figure 2.3). The system consists of instrumentation, signal conditioning components, and a computer workstation. These sub-systems are described below.

Adequate instrumentation has been installed on the system to measure retrieval perform-ance and scarifier reaction forces. The instrumentation system consists of:

Waterjet Pressure Transducers: Pressure transducers were installed in the high-pressure water line at the two pump outlets and near the inlet port to the scarifier. These gauges were essential to monitor pump performance, to determine pressure losses, and to insure adequate cutting pressure was available at the scarifier.

Waterjet Flow Meters: Water flowmeters were installed in the high-pressure pumps to determine the flow rate of water in the high-pressure lines.

Lubrication Water Flow Meter: A flow meter was used to measure the amount of water used to lubricate the conveyance line during sludge retrieval. Lubrication ports are provided at the spray ring on the bottom of the scarifier and before the first elbow (Figure 2.4).

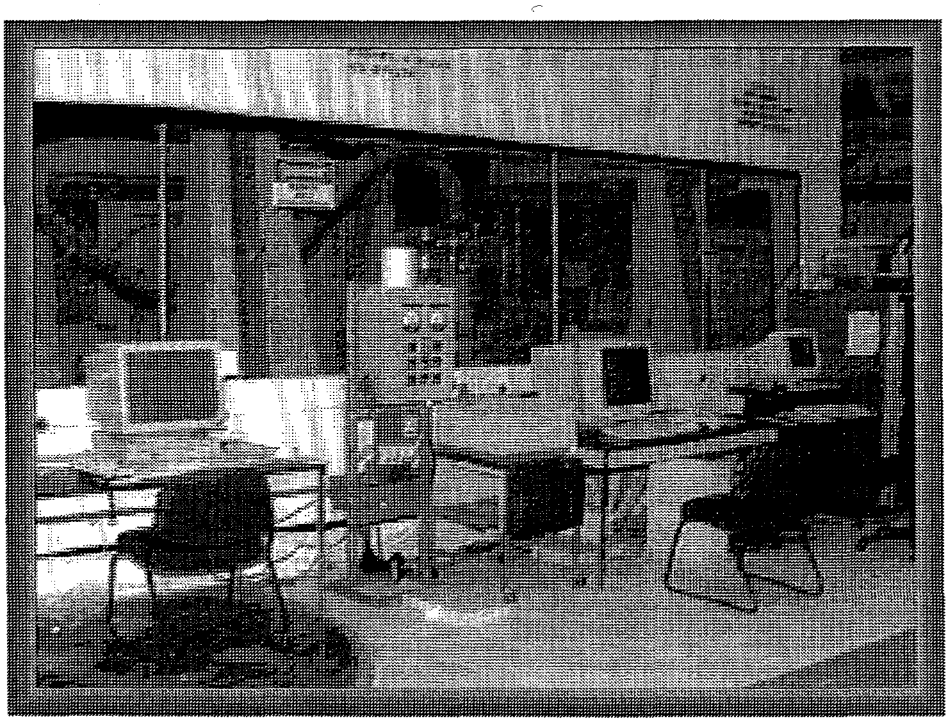

Figure 2.3. Hydraulic Test Bed Data Acquisition Workstation

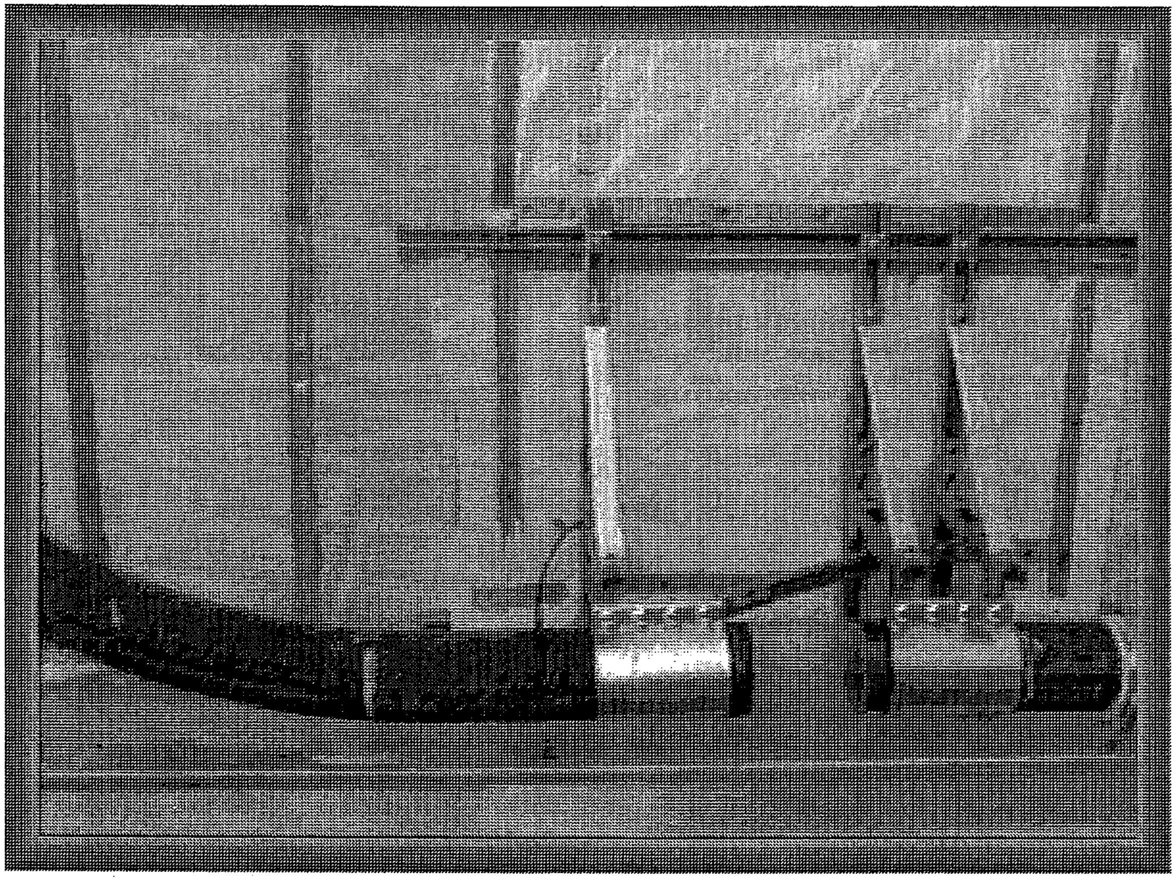

Figure 2.4. Air Conveyance Instrumentation. Pressure taps were installed at various points in the conveyance line to measure pressure drops and to monitor material accumulation.

Conveyance Line Pressure Transducers: A total of four pressure transducers were installed in the 15.2 cm (6 inch) diameter conveyance line to monitor the vacuum pressure along various points in the line. To prevent the pressure ports from being clogged, it was necessary to install the sensors in a special pressurized air line that provided a very small back pressure in the line. This mounting technique was adopted because it has been successfully used in the test fixture during conveyance testing.

Force-Torque Sensor: Figure 2.5 shows the installation of the scarifier on the gantry mast. To measure dynamic forces due to air suction, inertia, and waterjet reaction, the scarifier is attached to a sensor which measures forces and torques along three axis. The sensor is then mounted to a compliant joint, which is attached to the gantry mast and releases in the event of an overload condition.

Forces are isolated from the conveyance line by a flexible bellows between the scarifier outlet and the conveyance line. An adjustable spring is used to "zero out" the steady-state moment and force exerted by the scarifier be providing an alternate load path to the gantry mast.

Scarifier Speed Controller: A tachometer was installed on the scarifier motor shaft to mea-sure the rotational speed of the waterjets. The speed was controlled with a motor speed con-trol system.

Hopper Load Cells: Load cells were installed on the hopper mounting locations to measure the weight of material entering the hopper.

Annubar Air Flow Measuring System: An annubar air flow system was procured from Die-trich's Standard and installed in the conveyance line between the material separator and the blower. The actual sensor measures the pressure drop across various points in a diamond shapes column in the line. This pressure drop has been calibrated with flow rates at a number of configurations. This probe offers significant advantages over other flow measuring ob-structions, such as a pilot tube, because is uses pressure data from a number of radial posi-tions inside the pipe. Included in the system is an absolute pressure transducer and a tem-perature probe. The various measurements are transmitted to a local computer, which calcu-lates air flow and transmits the signals to the main data acquisition computer.

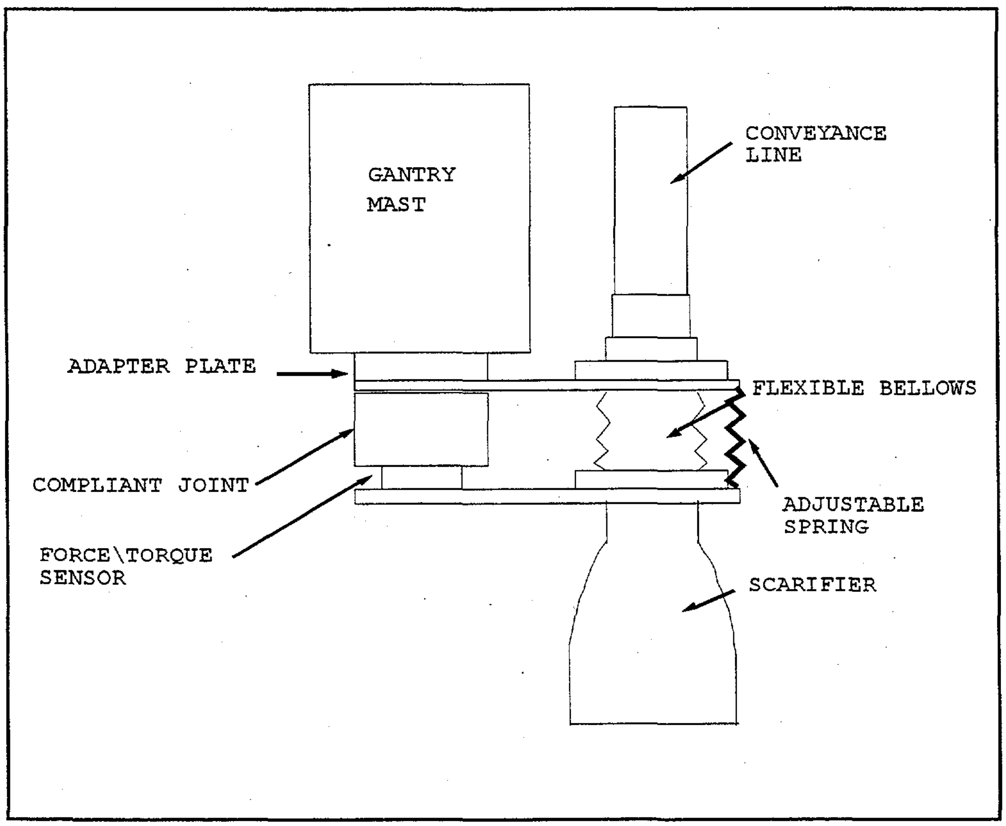

Figure 2.5. Scarifier Attachment to Gantry

The sensors were connected to a National Instruments Labview data conditioning module, which converted the sensor signal to an analogue voltage. This module also provided electrical iso-lation between the data acquisition computer and the sensors, which reduced the risk of electrical overload at the computer. The computer platform was a Pentium-based PC running at 90 MHZ and allowed rapid sampling of instrumentation and process control. Labview data acquisition software was devel-oped to manipulate control valves and equipment emergency stops (E-stops) and monitor key process variables from a central workstation. Labview software for data acquisition was chosen for its excel-lent graphical user interface and because it is used by the Light Duty Utility Arm (LDUA) program. A typical application screen is shown in Figure 2.6.

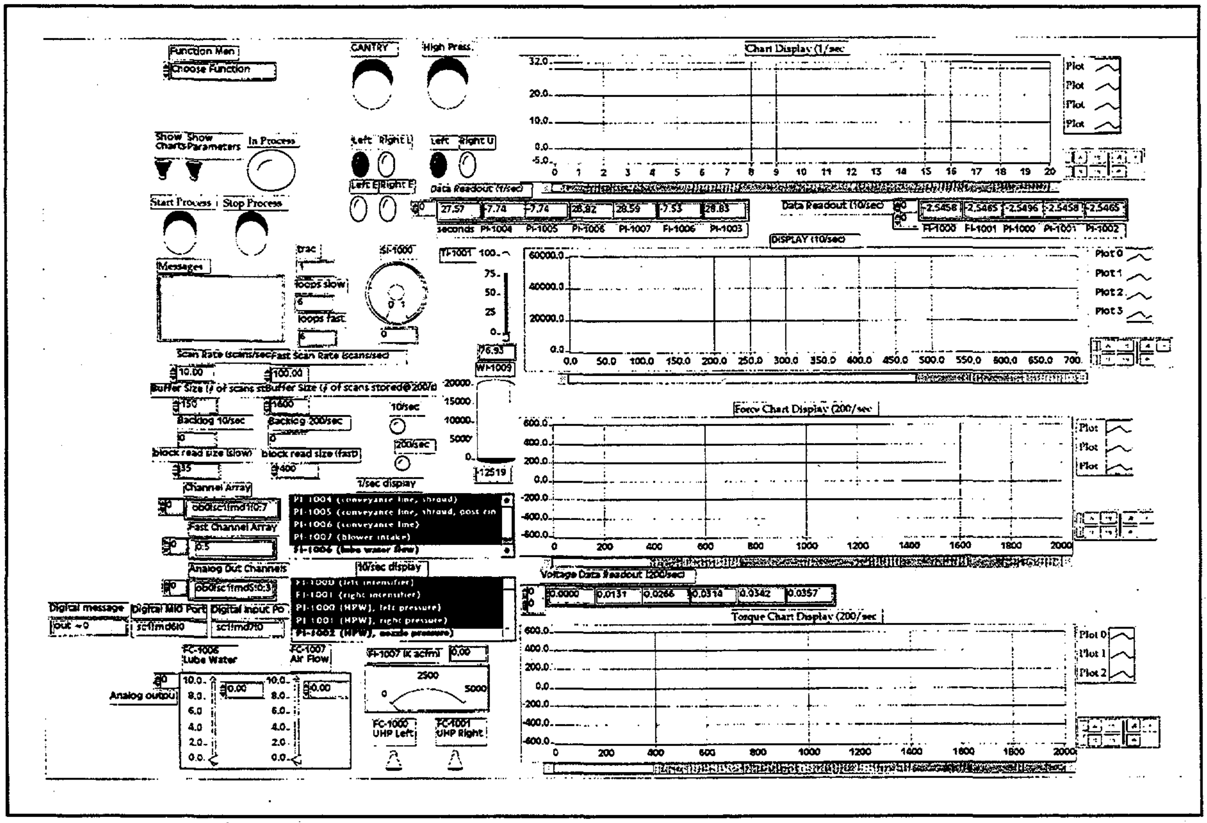

Figure 2.6. Labview User Interface Screen. The graphical interface allowed the user to manipulate control valves and monitor key process parameters from the computer screen.

3.0 Major Accomplishments

- Long Lead Items Procured: Several long lead capital items were procured in FY95, including an annubar air flow measurement system, an uninterruptable power supply, and a high-capacity force torque sensor to measure scarifier forces.

  A new high-capacity DeMarco air conveyance system was installed at the HTB. The procurement for this large system was initiated in FY94. This system was integrated into the control system of the HTB to permit remote operation of the blower and separator system. This new system will allow testing at much higher retrieval rates than previously possible. The system also uses advanced technology for the separation of liquids and solids which promises to be very effective in the retrieval of high-level waste.

- HTB Instrumentation and Controls Systems Completed: At the beginning of FY95, the HTB system instrumentation was selected and procured, along with additional data acquisition hardware and software. The sensors were installed in the system in parallel with system construction, and were calibrated, verified, and operational within two weeks of the completion of the rest of the system. A Labview data acquisition program was written to sample the sensors at the desired frequency and control the valves and emergency system stops through-out the system. A key design criteria in this system was the development of a user friendly graphical interface, which allows the operator to manipulate control valves and equipment E-stops and monitor key process variables from a central workstation. This system will serve as an example for actual tank retrieval control systems. The system also records scarifier reaction forces at up to 200 Hz, which is critical to determining frequency content of the structural disturbances.

- Retrieval Test Completed At HTB: The first retrieval tests were successfully completed at the HTB. The high-pressure scarifier was used to retrieve simulated sludge and saltcake material from test tanks. For the first time, the performance and reaction forces of the scarifier were measured during a three-dimensional mining operation. Personnel from Quest Integrated, Inc. participated in start-up testing to help configure the scarifier for retrieval of sludge and saltcake. Sludge testing focused on optimizing the lubrication water flow and cutting jet pressure while saltcake tests focused on determining air flow requirements to successfully scavenge fractured saltcake and proximity sensor development. For both saltcake and sludge testing, measuring reaction forces during off-normal events and retrieving simulant fields of various topography were key drivers. The testing program will be completed and documented in early FY95.

- Conceptual Design of the HTB to Support Confined Sluicing Prototypes Completed: In preparation for FY96, conceptual design documentation was completed for the HTB facility to support confined sluicing end effector testing next year. This addendum to the HTB conceptual design documentation describes the components, systems, and instrumentation that will be added to the HTB to permit testing of medium pressure sluicing end effectors currently being developed by the University of Missouri-Rolla (UMR). A series of facility drawings were prepared to show utility line routing and the location of major components of the new systems (medium pressure pumps, jet pump, etc). A conceptual design package was completed during mid-September and transmitted to UMR.

4.0 Testing Focus Areas

Table 4.1 provides an overview of the testing program matrix. The first testing segment verified the ability of the proximity sensors to maintain a constant stand-off distance between the scarifier and the waste surface over various challenging topography. Next, the reaction forces at the scarifier interface plate will be measured separately due to suction, inertia, and jet reaction. This will greatly simplify the force data reduction from subsequent testing. Next, mining strategy tests with saltcake and sludge simulants will be conducted to evaluate the effectiveness of mining strategies, forces related to scarifier and conveyance line, and retrieval rate. Performance of the system during off-normal events and the ability of the system to deal with waste topography will also be evaluated. In addition, tests will also be conducted to quantify dislodging efficiency as a function of waste stream properties (amount of material, depth of cut, and surface quality).

Table 4.1. Overview of the Testing Program Matrix

Test Focus	Test Parameters	Key Data Expected
1. Verity instrumentation to maintain a constant stand-off distance	• Surface Roughness • Traverse Velocity • Angle of Incline • Waste Type	Stand-off distance over various waste types and topography in the presence of waterjet spray, high-velocity air, and noise.
2. Reaction forces due to separate effects	• Stand-off Distance • Air flow • Position of Gantry • Traverse Velocity • High-Pressure Water Flow	• Reaction forces due to suction, inertia, jet reaction • Pressure drop in conveyance line
3. Initial system check-out and performance verification (2 tests)	• Simulant type (saltcake and sludge)	• Retrieval rate • Reaction forces • Pressure drop in conveyance line • Air flow rate required to sustain flow
4. Retrieval testing (9 tests)	• Two saltcake recipes • One sludge recipe - kaolin • Mining strategy - serpentine and pit	• Retrieval rate • Reaction forces • Cutting efficiency • Pressure drop in conveyance line • Conveyance line lubrication required

4.1 Mining Strategy Development

A process deployment strategy will be required to cope with changes in the surface contours of the waste. This shall include addressing the problems of capture of dislodged waste and spent water over uneven terrain, avoiding collisions with the waste surface, and procedures for maintaining an effective stand-off distance over an uneven waste surface. Initially, the topography of the waste surface is expected to be irregular. The mining strategy chosen for the retrieval must be such that a high average retrieval rate is maintained. The overall strategy must effectively retrieve waste over the existing topography and tank hardware as well as any topography created by the scarifier itself, including ridges, knobs of harder material, loose chunks, or leftover ribs from previous passes over the surface.

4.1.1 Mining Strategy Functions and Requirements

In order to succeed at removing waste from an underground storage tank, a mining strategy is being developed. The function of the mining strategy is to ensure that mining is conducted in accordance with the following criteria:

- 99% of the waste in the tank must be removed as dictated by agreements in place with state and federal agencies.

- No additional water must remain in the tank once mining is completed.

- The tank, waste removal equipment, personnel, and environment must be protected from damage.

- Water should be recovered at the same rate as it is introduced.

- The strategy must specify the waste removal geometry and path such that an end-effector's required stand-off distance and velocity are observed.

In order to support these functions, the mining strategy must meet the following requirements:

- The mining strategy must minimize the use of gross degrees of freedom of the robotic deployment system (mast elevation and rotation) by using the dexterous portions of the manipulator to implement the mining strategy. Positioning accuracy will be maximized, energy expenditure minimized, and the use of manipulator bracing will be simplified by this requirement. This strategy will dictate dividing the tank into several regions and using the robotic arm to move from region to region while using the shorter dexterous manipulator to implement the mining strategy.

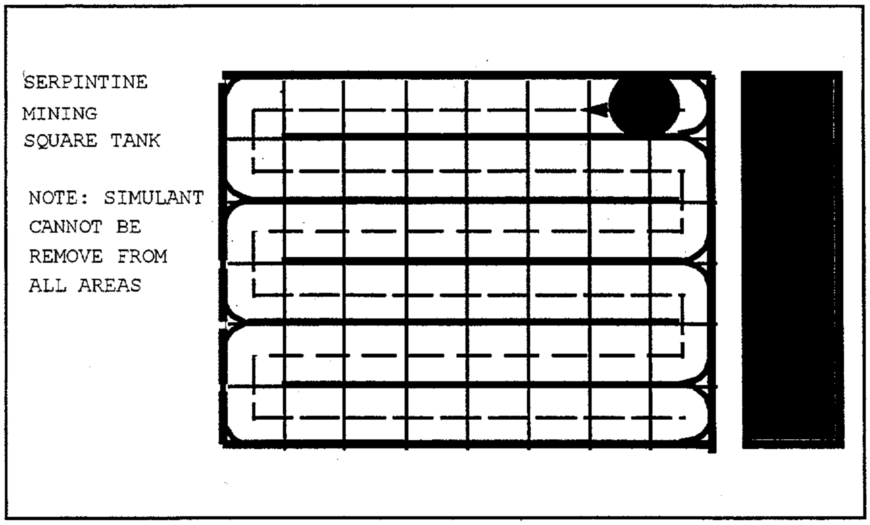

Figure 4.1. Serpentine Mining Strategy

- The mining strategy must minimize sharp corners and backtracking in the waste removal path due to the robot's inability to abruptly change direction without slowing down.
- The mining strategy must manage the supernatant liquid in the tank. The mining strategy must minimize the loss of cutting fluid and collect existing supernate in the tank.
- The mining strategy must avoid repeated motions with frequencies in the range 0.1 to 5 Hz. These frequencies are near the fundamental natural frequency of the robot.
- The mining strategy must maintain a constant linear velocity. This is required to maximize the efficiency of the waste-removal end effectors and to leave the waste surface as clean and smooth as possible.
- The mining strategy must manage hard and soft waste forms, handle variations in topography, and clean the bottom, corner and, sides of tank.

4.1.2 Baseline Strategies

The two baseline strategies illustrated below are being evaluated: serpentine mining and pit mining. In the serpentine mining strategy illustrated in Figure 4.1, the end effector is swept over the waste surface in a regular pattern, removing waste to form horizontal planes. This mining strategy would be the easiest for an operator to implement. In addition, it is the most efficient in terms of cutting rate, since the end effect is cutting waste at all times.

In the pit mining strategy depicted in Figure 4.2, waste is removed gradually in a pattern that forms a pit. The intent of this approach is to use the pit to manage any excess water that escapes the end effector. Using this approach, waste is first removed from the inner section of the region to be excavated. Since the scarifier removes approximately 2.54 cm (1 in) of waste during each pass, several passes will be required to form the initial pit. As retrieval continues, outer rings of material are removed. The waterjets may need to be turned off as the scarifier is moved from one ring to the other to minimize water losses; this limitation will be brought out during testing. This water management strategy can be augmented by using multiple passes for each ring (to improve efficiency) and by angling the scarifier toward the inside of the pit to facilitate drainage. If multiple passes are not taken at each level, this will lead to a very shallow pit that may have less impact on the flow of water than the existing topography of the waste. Pit mining such as this has been proposed by the University of Missouri as the optimal pattern for waste removal, given the constraints listed above. For the initial tests conducted in FY95, the serpentine mining strategy was used, as it was the easiest to implement.

4.1.3 Sludge Mining Strategies

During sludge retrieval, the surface of the sludge field was approximately level and the scarifier left a somewhat indiscernible path. The waterjets apparently agitates the surrounding waste field to the extent that the sharp edges of the cutting path collapsed somewhat. In the case of sludge, it would therefore be difficult to achieve a pit-like mining pattern. However, there is little advantage to using the pit mining strategy for sludge, as excess water is absorbed by the waste, and splatter from the waterjets is minimal, especially when lower water pressure is used (< 220 Mpa). During material removal, the paths were usually spaced 25.4 cm (10 in) apart (the width of the waterjets) although the spacing was sometimes reduced to 15.24 cm (6 in) to accommodate a narrow tank dimension.

4.1.4 Saltcake Mining Strategies

During saltcake retrieval, the scarifier left a very distinct path. The depth of the path was somewhat dependent on the nozzle position selected for the test. If all nozzles were placed at the outer

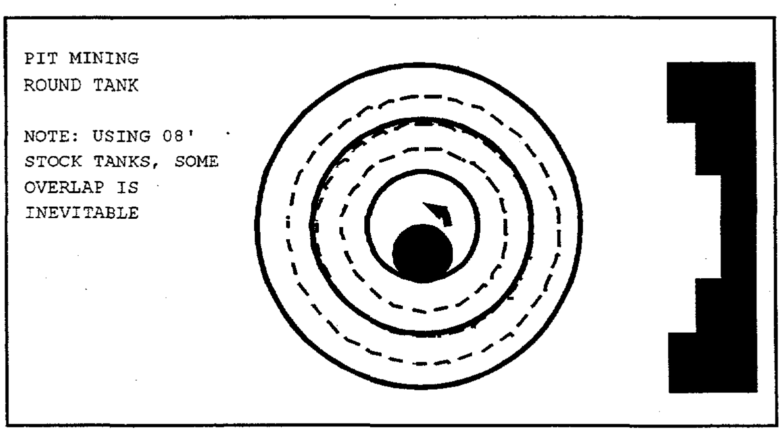

Figure 4.2. Pit Mining Using a Round Tank

most radius of 12.7 cm (5 in), then the depth profile was somewhat concave, with the material removal deeper at the outer edges and shallower at the inner edges. This was used to advantage during initial testing by using a very small path spacing index of 6.35 cm (2.5 in) between the centerline of adjacent passes. If the nozzles were placed in the outer, middle, and inner positions (12.7, 10.2, and 7.6 cm radius), the depth of cut was much more uniform. This was the primary advantage of using nozzles in different diameters.

4.2 Waste Simulant Development

For the initial tests conducted with sludge, a 66% kaolin, 34% water mixture was produced in the simulant production facility adjacent to the HTB. A total of 3400 liters (120 ft^3) of this material (two 1700 liter batches) was produced and pressed out into the simulant tank using a hydraulic ram. This process worked relatively well, although the seal confining the kaolin under the ram action was prone to leakage and damage. The size of the square test tanks was 244 cm (96 in); the material was 30.5 cm (12 in) deep. To characterized the simulant, several samples were taken from the initial material and will be tested for density, water content, and viscosity. Samples were also taken from the test tank after successive retrieval passes; the waterjet penetrated the full depth of the test tank and reduced the viscosity of the remaining kaolin.

For the initial test conducted with saltcake, a 84% dynamate (potassium-magnesium sulfate), 16% water mixture was produced in the simulant production. A large capacity concrete mixer was used to mix the material, which was poured into 8 feet diameter round tanks and leveled. A concrete vibrator was inserted into the mixture at various locations to allow bubbles to escape the material. One 1400 liter batch was produced in this way. This material represents the hardest saltcake material currently proposed by the Simulant Development Subtask. Smaller batches of weaker saltcake material were also produced, using a 88% dynamate (potassium-magnesium sulfate) and 12% water mixture.

4.3 Deployment Instrumentation Development

The deployment instrumentation task began the development and implementation of terrain following methods to control the stand-off distance between the test end effector and the waste surface. The approach to solving this problem was to use non-contact distance measuring sensors in a feedback loop to control the gantry robot over uneven terrain. Testing will verify the controllability and accuracy of the proximity sensors and control software to maintain a constant stand-off distance. Maintaining a relatively constant stand-off distance is of importance because of constrains imposed by the air conveyance system. Parametric testing has shown that the stand-off distance should be 5.08 cm (2 in) nominally with an allowable deviation of +/- 3.8 cm (1.5 in). If the scarifier is too close to the surface, the vacuum may suck the shroud into contact with the waste surface (known as the smooch effect). Conversely, if the scarifier is too far away, the shroud will not be able to effectively contain the dislodged particles. To maintain the correct stand-off distance with the gantry robot control system it is only necessary to vary the position of the vertical mast. For the initial testing the gantry cannot be used to align the scarifier with an angled surface because the robot lacks a wrist necessary to accommodate additional degrees of freedom.

4.3.1 Terrain Following Controls Development

The controls concept was developed around the controls of a terrain following system, using non-contact acoustic sensors to measure the distance from the end effector to the waste surface. Figure 4.3 shows the layout of the system. The sensors being used are ultrasonic acoustic sensors manufactured by MicroSwitch. In order to eliminate the industrial noise generated when operated around industrial machines, the sensor has an operating frequency of 215 kHz.

The sensor feedback signal was transmitted to the controls computer via a 4-20 mA output signal. The sensor data was collected on National Instrument high-speed data acquisition cards. The sensor signals were feed into a proportional-derivative control algorithm to calculate the control output. This signal was sent to the gantry robot over a RS232 serial port at 19,200 baud. The gantry robot allows real-time position control through their real-time path modification (RPM) processor.

This method of modifying the gantry robot's position functions by changing the bias offset position value of the desired joint, in this case the vertical or z-axis. This ensures stability of the robot by leaving the actual robot controller maintaining control of the robot and still allowing position modifications. The control signal was synchronized with the gantry robots controller by a sync pulse signal over the serial line, to ensure real-time control.

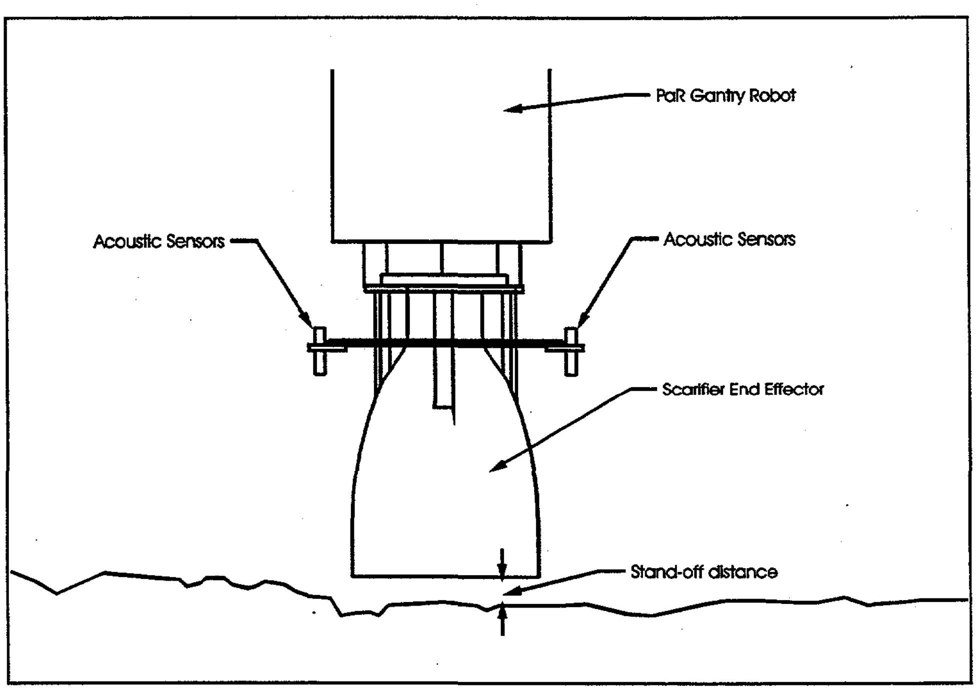

Figure 4.3. Sensor Deployment for Terrain Following Controls

Initial testing of the system was performed on cardboard mockups to prevent damage to the robot and the end effector. Results show the control system could control stand-off distance to an accuracy of approximately 0.25 cm (0.1 in). It was determined that the system was capable of greater accuracy, but electrical noise was induced into the sensor feedback signal and power supply from the operation of the gantry robot's DC motors. When the robot motors are not armed, the feedback signal can measure the position to an accuracy of 0.13 cm (0.05 in). Several steps were taken to resolve this noise issue to no avail.

It was determined that a positioning accuracy of 0.25 cm (0.1 in) was good enough to allow the scarifier waste retrieval system to operate successfully. The desired stand-off distance for the scarifier is 5.08 ± 1.27 cm (2 ± 0.5 in).

The next series of test were performed during actual simulate retrieval operations. The stand-off control system was not operational, because additional testing was necessary to ensure the safe operation of the robot. Initial tests regarding noise from the vacuum system and the high-pressure waterjet system showed no effect on the acoustic sensors. During the test a major problem surfaced. This was the splatter of material caused by the high-pressure waterjets. The piezo sensors require a relatively clean surface to operate effectively. This surface would eventually get covered and prevent the sensor from operating correctly. Another problem with the sensors being used was their size and mounting location.

For these sensors to operate correctly, they needed to be positioned greater than 20.32 cm (8 in) from the lowest point on the end effector and out a distance of at least 5.08 cm (2 in) from the wall of the end effector. This positioning requirement made retrieval tests difficult, because the end effector could not get to within 25.4 cm (10 in) of the tank wall. This sensor positioning could be a potential problem with actual retrieval systems due to the riser diameters and end effector sizes.

To address the issues with the non-contact sensors, a sensors workshop was held to have research scientists with knowledge of non-contact sensor technologies provide solutions to the problem.

4.3.2 Sensor Technology Assessment

A workshop on non-contact sensors was held to evaluate viable technologies which could help address several of the problems previously mentioned. There are four technologies that offer non-contact solutions to measuring distance. These technologies are 1) lasers, 2) acoustics, 3) radar, and 4) Electro-Magnetic coupling.

These technologies were evaluated using the following criteria:

- Environment: The sensor must be relatively insensitive to moisture, temperature fluctuations, industrial noise, air density fluctuations, mechanical vibrations, material build-up and splatter.

- Operational Requirements: The sensor must operate over a very waste with heterogeneous topography and diffuse surface properties. The sensor must operate over surfaces with slopes as steep as 10 degrees and must be able to look ahead and detect a step change in surface height.

- Sensor Characteristics: Other important considerations are radiation hardening capability, size, power requirement, signal output, frequency response, resolution, accuracy, range, and beam width. The sensor must be intrinsically safe to operate in a potentially flammable environment.

Scientists with expertise in the areas of their technologies were then asked to develop white papers to propose a solution to the problem. These white papers are under review and will be combined into a sensor evaluation document to be issued in FY96.

4.4 Control Strategy for HTB

This study was intended to define the control strategy for the HTB and make it as efficient as possible to perform the task of testing end effectors for the various robots being developed for the DOE. To achieve efficiency, the HTB must be able to transfer as much software as possible directly to the retrieval robot, so that it minimizes redundant development of the software. Currently there are two main retrieval robots that are being developed: the LDUA and the Modified Light Duty Utility Arm (MLDUA). In addition, remote vehicles for in-tank deployment are under development, and there is a possibility of deploying waste retrieval end effectors on these remote systems.

The LDUA uses a VME-based low level control system, and Sun SparcStation Unix-based computers for the hardware. GENISAS (General Interface For Supervisor and Subsystems) is used as the communications protocol to talk between the low- and high-level control systems, and it uses Labview as the basis for the high level control software.

The MLDUA is currently scheduled to use the same control architecture as the LDUA, but there is a concern that this control system may not be adequate and that ORNL may have to modify the control architecture.

Ideally, the HTB would have the same hardware to control the system as the retrieval robot that it is doing research for. Unfortunately, the low-level control system is based on a PC bus rather than a VME bus, which is used on all three current retrieval robot designs. Sandia National Laboratory (SNL) has worked with a similar gantry robot system that is built by the same robot manufacturer, and has developed ways to use a VME-based low-level controller which integrates with the current low-level controller. Their work was done in cooperation with PAR Systems, Inc., and uses some hardware upgrades to the low level control system. Also, the high-level control system was built on a IBM PC clone platform, rather than a Sun-based Unix platform as the three retrieval robots are designed to use. All three retrieval robots use the GENISAS control protocol which is continuing to be developed by SNL for use on many systems. This protocol is only available on Unix-based computer systems, and therefore cannot be used with the HTB.

The GENISAS protocol is basically a library of communications functions and control functions that aid in the development of control systems. It relies on TCP/IP network connections to send and receive data to the low-level control system and the various sensors available. The HTB low-level control system will have a network connection that does us TCP/IP network connections for communications to the high-level control system. Therefore the high-level control system will be able to talk in a similar manner to the low-level control system, but it will not be using the GENISAS protocol.

However, the software that is being used to do the high-level control on the LDUA, and possibly the MLDUA, is available also on the PC and has already been purchased for the HTB. All files developed using this software should be directly portable to the retrieval systems, with the exception of any hardware driver routines (such as sensors and end effectors), and network protocols. This will provide some measure of portability for any development that is done using the HTB system.

Under the current hardware configuration, some of the software developed to test end effectors on the HTB will not be portable to the retrieval robots. Device drivers for all sensors, and for the end effectors themselves, will need to be rewritten for the retrieval robots after testing has concluded. All control programming that is developed under Labview will be directly portable to the retrieval robot systems. If any development is done outside of Labview, portability of the C programs could be maintained, as long as function calls were consistent with the functions that would be used in the retrieval robot system.

In order to be completely compatible with the retrieval robots, a substantial hardware and software acquisition would have to be made, and staff would have to be trained on the new hardware. At a minimum, a VME computer system, a Sun SparcStation, and software for the system would have to be acquired. SNL has suggested that they would be willing to train other users in GENISAS and to install their VME-based control system on our HTB since it would not require many changes in their software. This would require at least two weeks of SNL's staff time to install the system, and also PNNL staff time to learn the system.

In summary, during testing of end effectors for the LDUA system and probably the MLDUA system, all development that is done within Labview will be directly applicable to the retrieval robot, after development is complete. Some development will have to be done after testing to write hardware drivers for each of the control systems.

A more compatible system is achievable for the HTB, but would require substantial acquisitions of hardware, as well as considerable staff time to learn the new system. This would, however, reduce the amount of redundant development, since only one set of hardware drivers would be required for each system to be tested. Whether or not this savings would outweigh the cost of the equipment and software upgrades would depend on the number and complexity of end effectors that would be tested over the life of the HTB.

After working with the network option, it has become apparent that there are a few shortcoming in the current control strategy. By design, only one connection through the network is possible to the control computer. Another connection is possible through the RPM option that has also been integrated into the system, but it also can only have one connection. Currently, this connection is being used to keep the stand-off distance of the end effector nearly constant. In order to have multiple points of control an intermediate computer, running a multi-tasking operating system (such as Unix, or VxWorks), would have to be used as a translator. This will be necessary to have one computer commanding the robot and another analyzing the data from the robot controller (joint values, speeds, etc). Conceivably, one computer could be programmed to use both the RPM port and the network port to control the robot, using networked commands from other computers. This is the way that SNL communicates with it's gantry robots.

The network option was installed on the gantry control computer and was tested. This allows any computer on the network to control the Gantry Robot, providing the remote user has the password to log onto the system.

To demonstrate this option, the Gantry Robot was interfaced with the Deneb Robotics software program Interactive Graphics Robot Instruction Program (IGRIP) to first simulate a simple motion, and then download a command to the real robot to perform that movement. IGRIP will then simulate the actual motion of the robot, as the robot moves. Other commands, such as stop, resume, and abort have also been integrated into the control program that operates within IGRIP.

4.5 Test Results To Date

The HTB test facility was completed in August, 1995, which was several months behind the anticipated completion date. Funding reductions, schedule slips due to system design to reflect funding reductions, and construction delays all contributed to delay the construction effort. The facility was completed substantially as envisioned, but the testing scope for FY95 had to be reduced significantly to include system check-out tests and preliminary mining strategy tests using one sludge formula and one saltcake formula. Little time remained to perform an adequate data evaluation in FY95. Therefore, this section will only present preliminary findings, qualitative test impressions, and a limited amount of test data. Depending on the availability of additional funding, the data evaluation tasks will be completed and more testing will be conducted with the scarifier in FY95. The data evaluation phase will include a calculation of the retrieval rates.

4.5.1 System Check-out Test Results

This section will summarize the key findings of the system check-out tests that were conducted before the retrieval tests were initiated.

Pump Performance Before testing was initiated, the water pressure and flow rate supplying the scarifier were measured. In their initial state, the pumps supplied 276 MPa (40,000 psi) water at approximately 15.1 liter/min (4 gal/min). Since the pumps are rated for a maximum of

18.9 liter/min 345 MPa and cutting efficiency is directly related to flow and pressure, determining the cause of the problem became a high priority. The problem was traced to a faulty hydraulic pressure gauge on one of the pumps which was indicating a lower pressure than actual. After this problem was resolved, the pumps provided 17.4 liter/min (4.6 gal/min) at 345 MPa. The 17.4 liters/min flow rate is 31% less than the flow rate of 25.4 liters/min which was used by Quest Integrated, Inc. during the original development of the scarifier. The testing program was continued with the recognition that the retrieval rate of the scarifier would be limited by pump output.

Air Conveyance System Performance The air conveyance system met the design goal of processing 99100 liters (3500 cubic feet) per minute of air at up to 45.7 cm (18 in) of mercury vacuum. The filters inside the separation system had to be rinsed once to remove a fine layer of kaolin on the outer surface. This caused the system to shut done automatically, due to high filter differential pressure, after a long test conducted with saltcake. The high temperature of the high-pressure water raised the air temperature and humidity during saltcake cutting, which no doubt contributed to the problem. The rest of the system components performed without any failures.

4.5.2 Preliminary Sludge Retrieval Test Results

The initial retrieval tests were conducted with a highly adhesive kaolin sludge. The waterjet pressure was initially 276 MPa (40,000 psi). The scarifier generated excessive splatter at this pressure and resulted in material coating the sides of the tank and tent walls. The pressure was reduced to 220 MPa (32,000 psi) and finally to 165 MPa (24,000) in succeeding tests, and the amount of splatter was reduced significantly, while still mobilizing the sludge material. The rotational speed of the waterjets was 1200 rpm, on the recommendation of Quest Integrated, Inc. Quest's testing revealed that the higher rotational speeds resulted in better slurrying action of the scarifier, which reduced the likelihood of shroud plugging. The operating parameters of the scarifier during sludge retrieval test are summarized as follows:

Waterjet rotational speed:	1200 rpm
Traverse speed:	5.1 cm/sec
Waterjet pressure:	165, 220, and 276 Mpa
Waterjet flow rate:	11.4, 15.1, and 17.4 liters/min (respectively)
Lubrication water flow rate:	45.4 liters/min at shroud spray ring

The simulant bed was filled to a depth of approximately 25.4 cm (10 in) of material. To retrieve this material, the scarifier was set initially 2.54 cm (1 in) above the sludge and lowered 2.54 cm (1 in) after each pass. After two passes were completed, the remaining sludge had been "fluffed up" by the waterjets, and the viscosity was significantly reduce. In succeeding passes, the scarifier was lowered 3.8, 5.1, and finally 7.6 cm after each pass without any plugging. The final 5.1 cm (2 in) of sludge was found to be very watery, and this material was removed with the action of the vacuum system only. It was felt that even more aggressive retrieval of the sludge is possible; through follow-on tests next year, the process will be further challenged to determine the maximum retrieval rate.

During these tests, the scarifier annulus was plugged with kaolin on two occasions to the extent that the electric scarifier motor was stalled. The inside of the scarifier annulus was cleaned manually to free the motor, and testing was continues. To avoid shroud plugging, a stand-off distance of 2.54 cm (1 in) was maintained on the initial passes. Plots of the air conveyance flow rate and pressure at various points in the vacuum line are provided in Figures 4.4 and 4.5, respectfully.

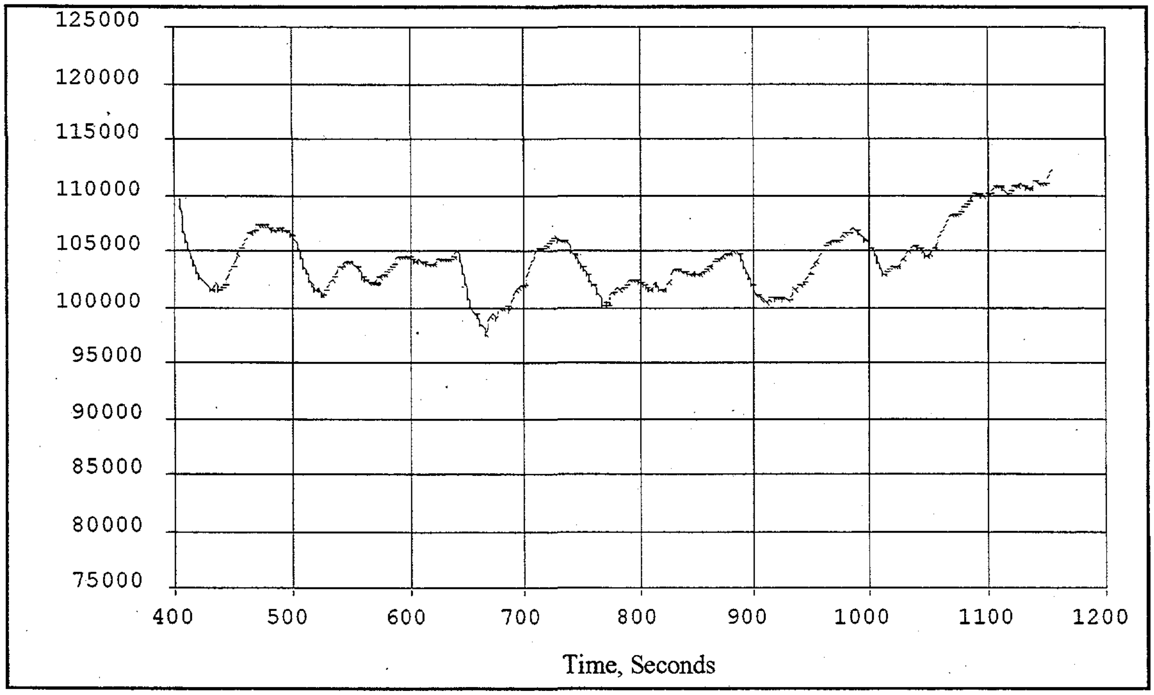

Figure 4.4. Air Flow Rate During Sludge Retrieval

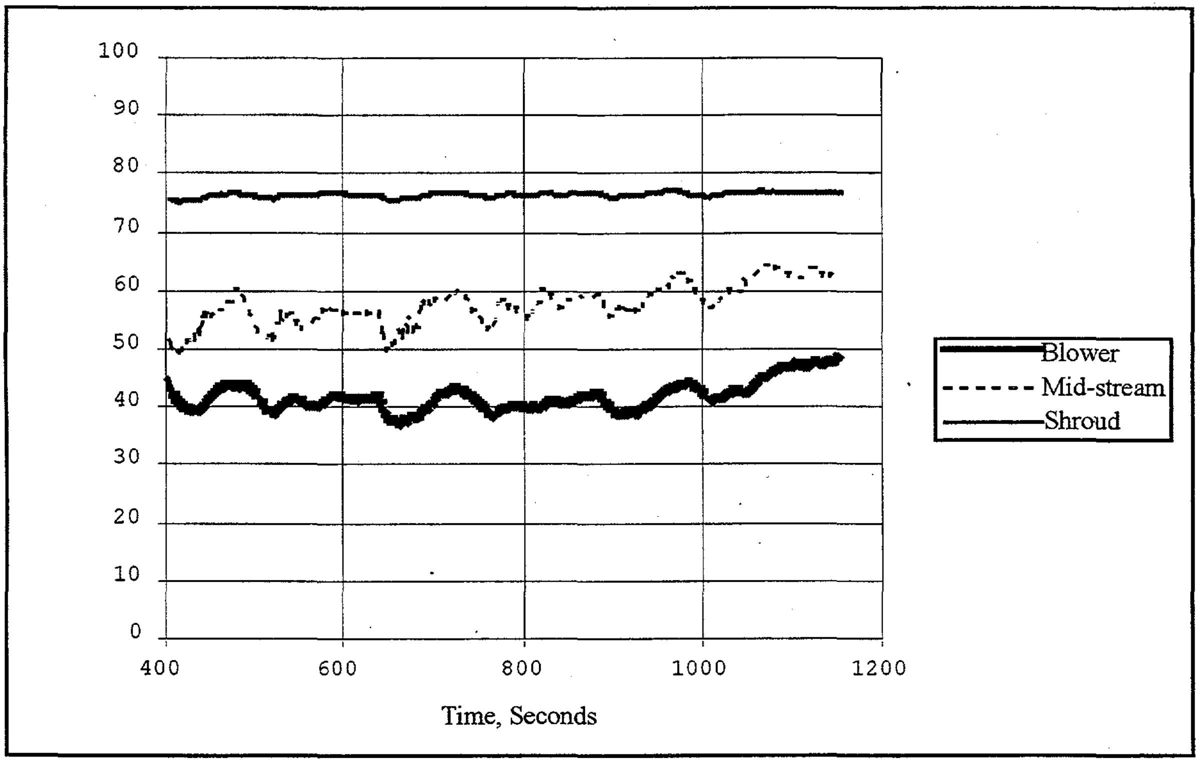

Figure 4.5. Conveyance Line Pressure During Sludge Retrieval

4.5.3 Preliminary Saltcake Retrieval Test Results

The initial saltcake tests were met with limited success. On tests using the highest strength saltcake, the depth of cut was very shallow (< 0.6 cm) and resulted in low retrieval rates. A variety of attempts were made to improve the performance, including varying the speed of rotation and the traverse rate. The problem was finally traced to worn nozzle jewels, which reduced jet coherence and cutting efficiency. After the nozzles were replaced, the cutting efficiency was significantly increased, although it was still somewhat less than expected. The low waterjet flow rate is apparently limiting the cutting efficiency of the scarifier (see Section 4.6.1). The operating parameters of the scarifier during sludge retrieval tests are summarized as follows:

Waterjet rotational speed:	100-750 rpm
Traverse speed:	5.1-10.2 cm/sec
Waterjet pressure:	345 MPa
Waterjet flow rate:	17.4 liters/min

The 17.4 liters/min flow rate is 31% less than the flow rate of 25.4 liters/min which was used by Quest Integrated, Inc. during the original development of the scarifier. Personnel at Quest Integrated,

Inc. are in the process of varying the rotational speed and traverse velocity to optimizing the scarifier performance at this lower flow rate. Testing will continue next year using these optimized values.

Plots of the air conveyance flow rate and pressure at various points in the vacuum line during a saltcake retrieval test are provided in Figures 4.6 and 4.7, respectfully.

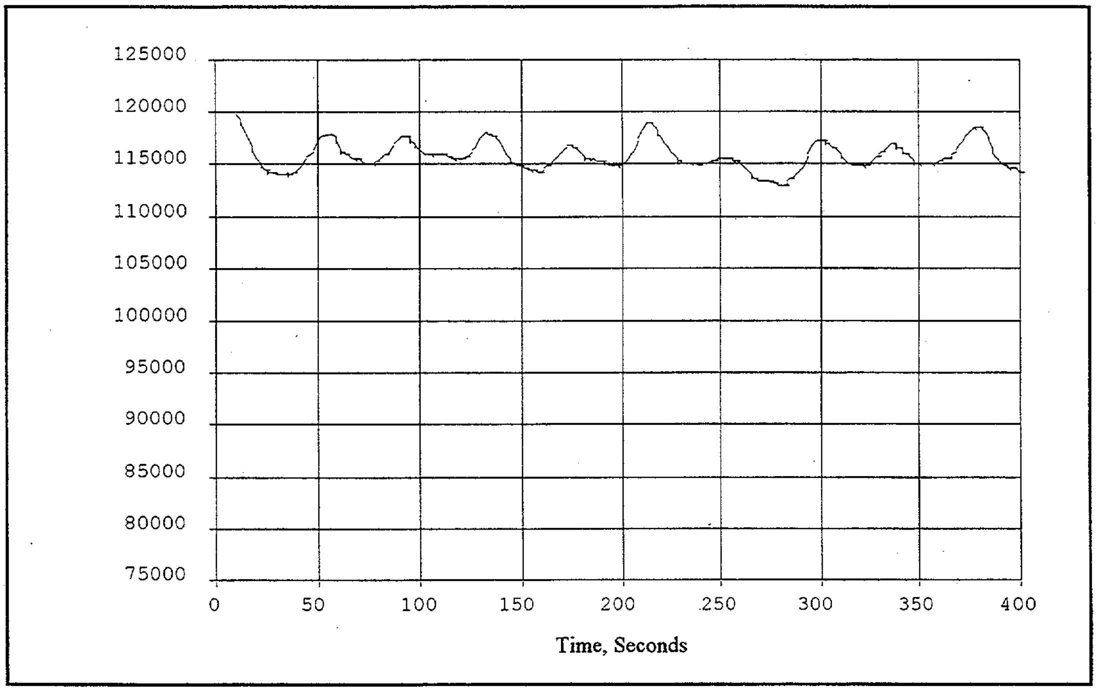

Figure 4.6. Air Flow During Saltcake Retrieval

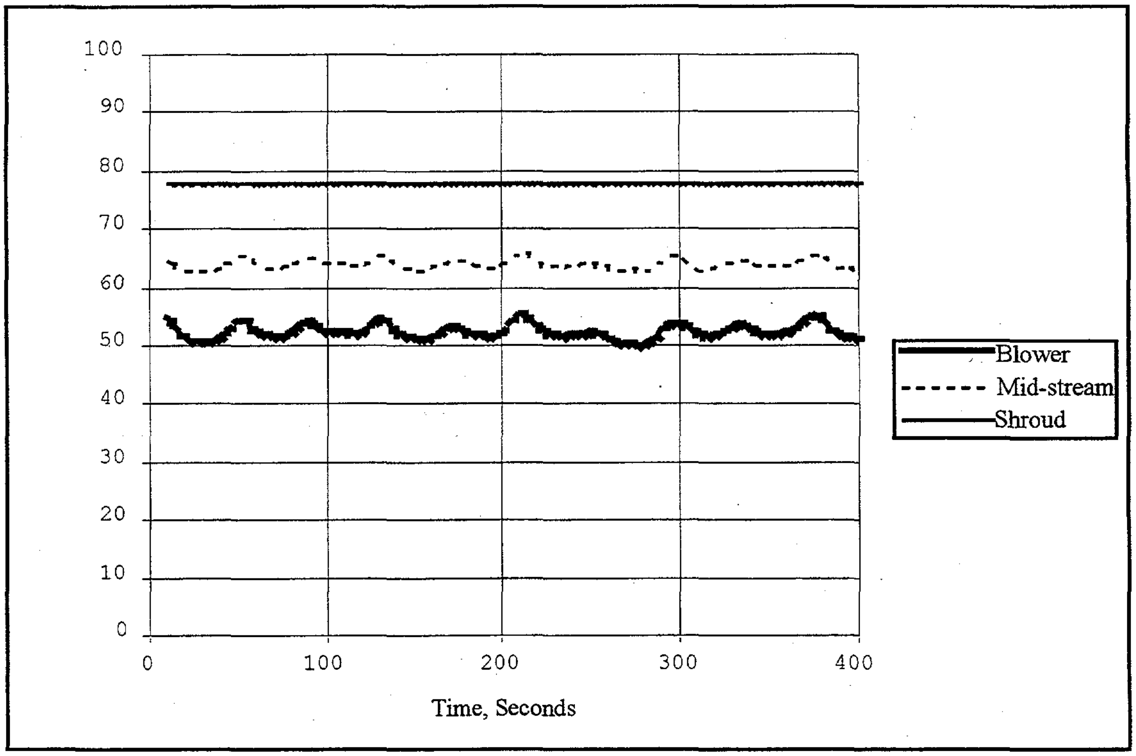

Figure 4.7. Conveyance Line Pressure During Saltcake Retrieval

4.5.4 Preliminary Force Measurement Results

The reaction force of the scarifier was surprisingly low during the majority of the tests. In general, the forces are less then 250 newtons (56 lbs). The forces and moment measurements recorded during a saltcake retrieval test are provided in Figures 4.8 and 4.9, respectfully. Note that the X and Y direction are in the horizontal plane, while Z is aligned with the vertical direction. The suction force of the vacuum system resulted in a reactive load of approximately 220 newtons (50 lbs). The test data was input into a Fourier transform routine to determine the frequency contribution components.

The results indicate a strong 6 Hertz frequency, which corresponds to the waterjet rotational speed of 360 rpm. This is caused either by the action of the jets themselves or, more likely, by an imbalance in the waterjet assembly.

During a final surface cleaning pass in a sludge test, the scarifier inlet was completely blocked by the tank bottom. This situation created a high shroud vacuum pressure and a high vertical reaction force of 2670 newtons (600 lbs). This situation was avoided in successive tests by not allowing the shroud skirt to contact the tank bottom.

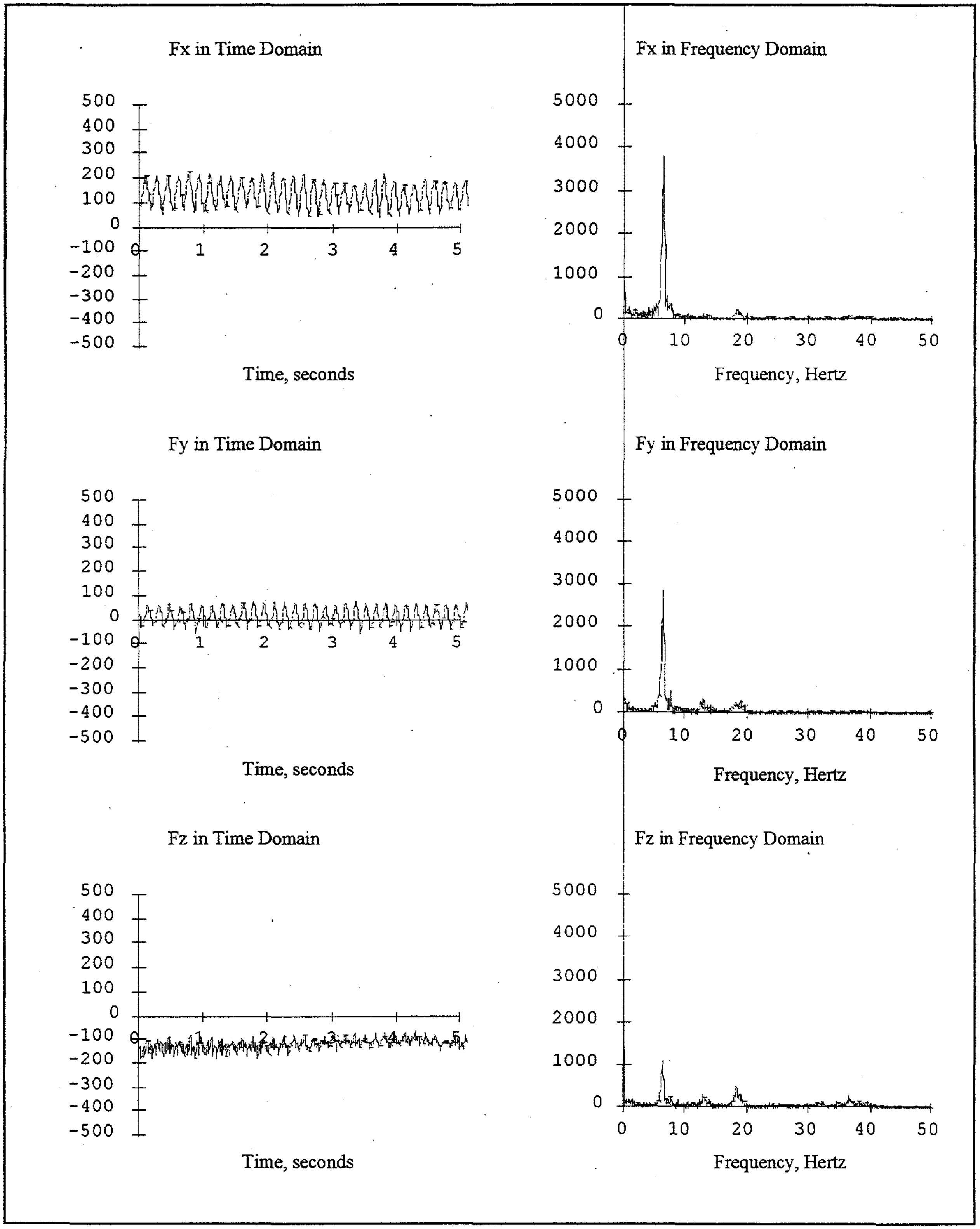

Figure 4.8. Scarifier Force Plots, Saltcake Retrieval

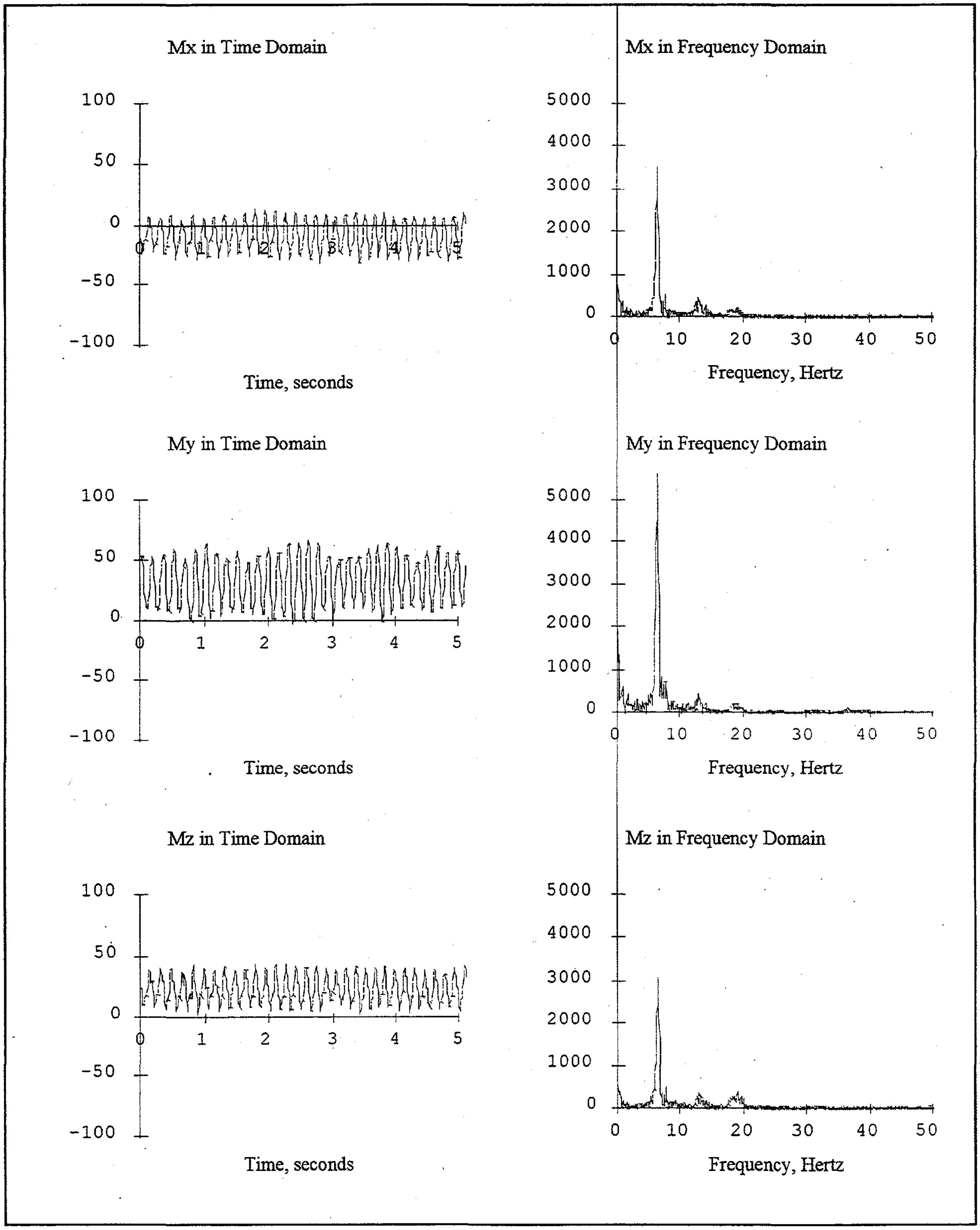

Figure 4.9. Scarifier Moment Plots, Saltcake Retrieval

5.0 Conclusions

The HTB program will continue next year with testing of the ORNL Gunite Tank Treatability Study confined sluicing end effector, INEL confined sluicing end effector, and the high-pressure, lightweight scarifier developed by Quest Integrated, Inc.

The data generated from these tests are essential to allow the completion of definitive system design of actual in-tank components. Testing of full-scale prototype end effectors, cold testing, operations research, and operator training will be considered as long-range uses for the HTB.

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