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ENGINEERING DEVELOPMENT OF A LIGHTWEIGHT HIGH-PRESSURE SCARIFIER FOR TANK WASTE RETRIEVAL

B. K. Hatchell

September 1997

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Prepared for the U.S. Department of Energy
Under Contract DE-AC06-76RLO 1830

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Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 7831;
Prices available from (615) 576-8401.

Available to the public from the National Technical Information Services,
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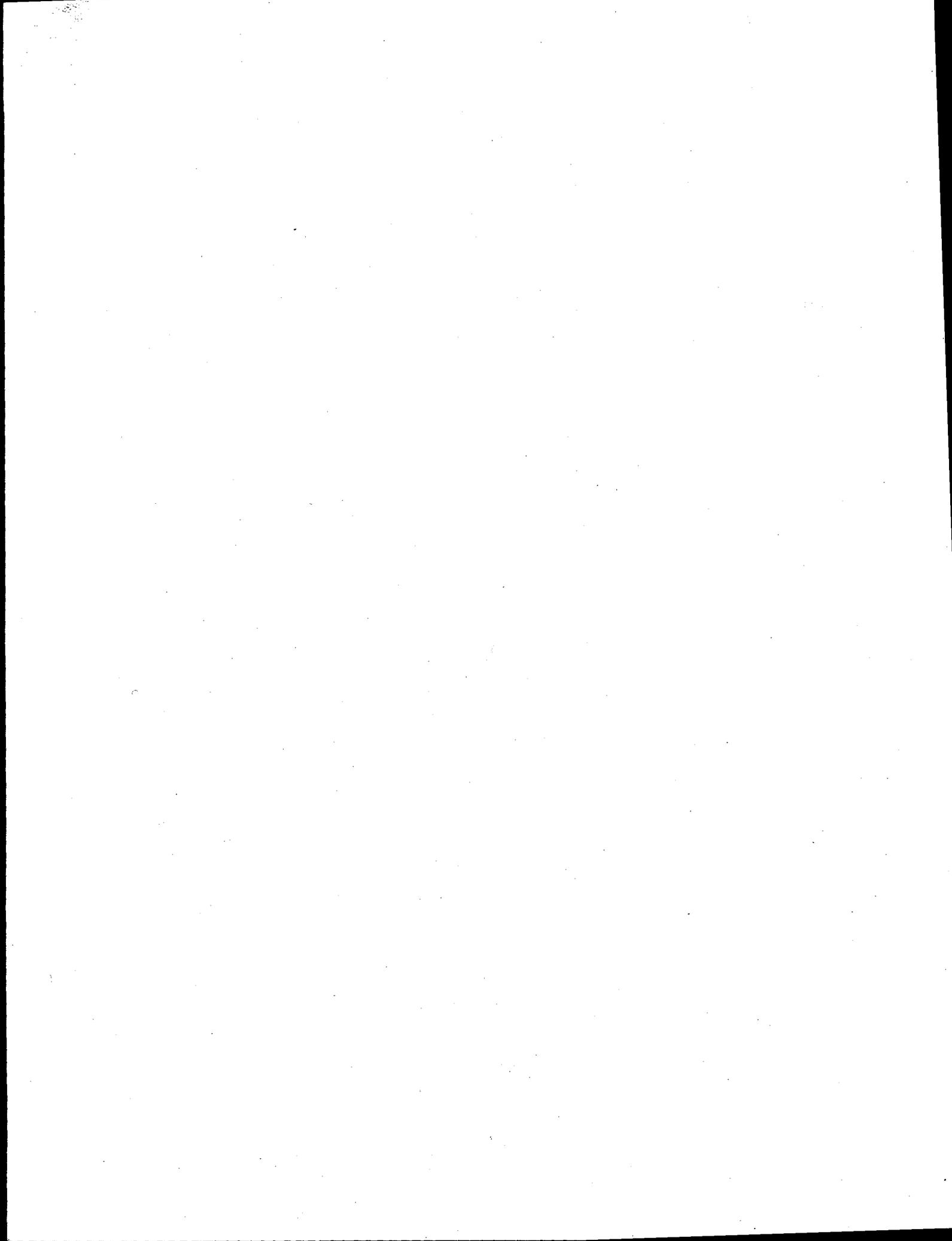
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Executive Summary

The Retrieval Process Development and Enhancements Program (RPD&E) is sponsored by the U.S. Department of Energy Tanks Focus Area 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 provide a technical and cost basis to support site-remediation decisions. Part of this program has involved the development of a high-pressure waterjet dislodging system and pneumatic conveyance integrated as a scarifier. Industry has used high-pressure waterjet technology for many years to mine, cut, clean, and scarify materials with a broad range of properties. The scarifier was developed as an alternate means of retrieving waste inside Hanford single-shell tanks, particularly hard, stubborn waste. Testing of the scarifier has verified its ability to retrieve a wide range of tank waste ranging from extremely hard waste that is resistant to other dislodging means to soft sludge and even supernatant fluid. Since the scarifier expends water at a low rate and recovers most of the water as it is used, the scarifier is well suited for retrieval of tanks that leak and cannot be safely sluiced or applications where significant waste dilution is not acceptable.

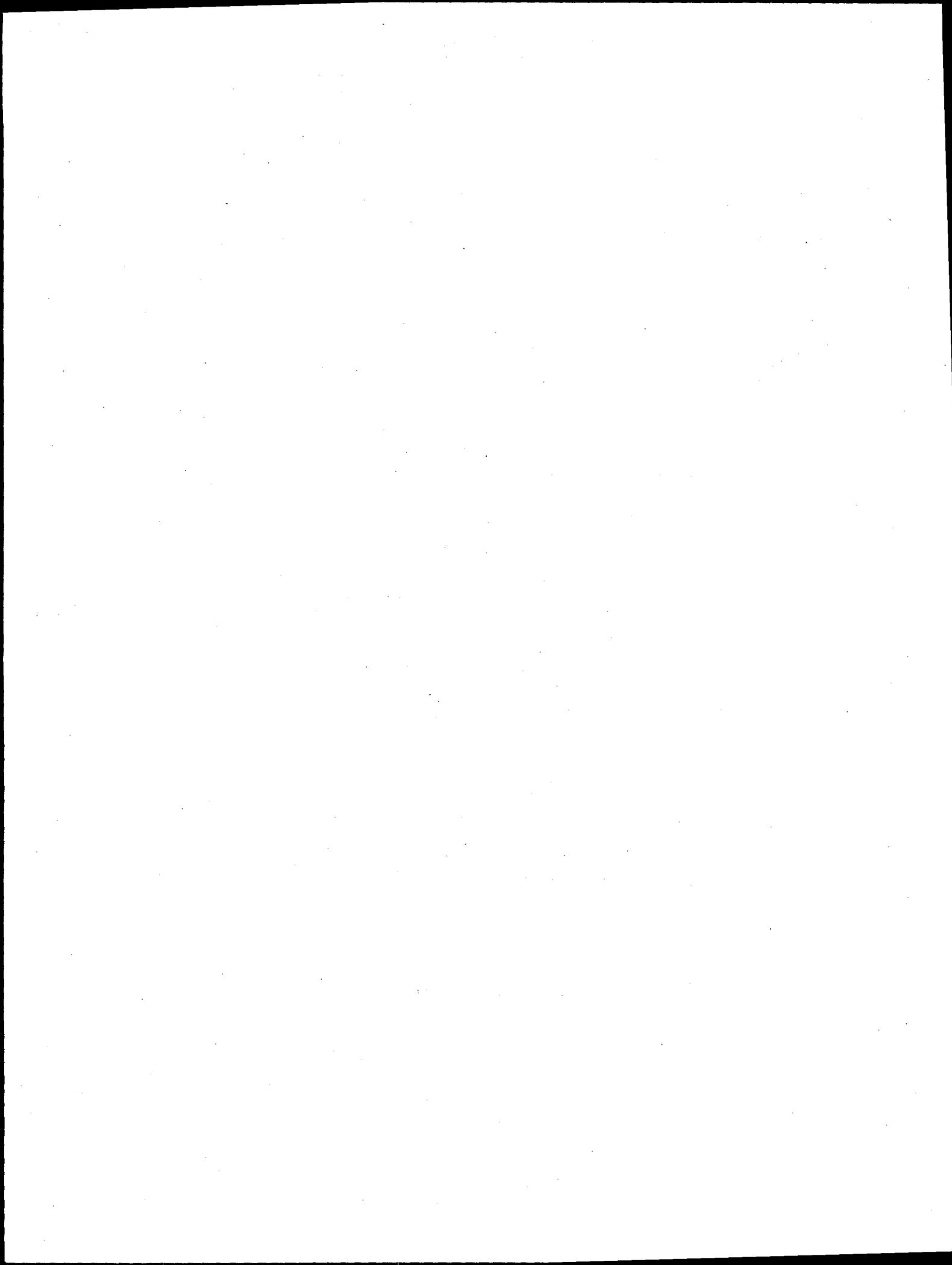
Although the original scarifier was effective, it became evident that a lighter, more compact version that would be compatible with light weight deployment systems under development, such as the Light Duty Utility Arm, was needed. At the end of FY 95, the Light Weight Scarifier (LWS) was designed to incorporate the features of the original scarifier in a smaller, lighter end effector. During FY 96, the detailed design of the LWS was completed and two prototypes were fabricated.

During FY 96, a thorough testing program was initiated to determine the range of applicability within a matrix of hard and soft simulants, determine appropriate mining strategies, and address integration issues associated with deploying the LWS by a robotic manipulator arm or remote crawler. Long duration tests with materials simulating salt cake, hard pan, and sludge waste forms have been conducted to evaluate the effectiveness of mining strategies, end effector reaction forces, and retrieval rates. This document will describe the testing program, present test results, and provide recommendations for future technology development activities. These tests measured the performance of the LWS and validated its compatibility with existing long reach manipulators. Although there are no planned hot deployments of the LWS at this time, it is believed that the LWS will find application at Hanford for hard heal retrieval and at Oak Ridge National Laboratory (ORNL) for gunite removal. It is hoped that this information will provide a basis for field-able end effectors to meet site remediation requirements.



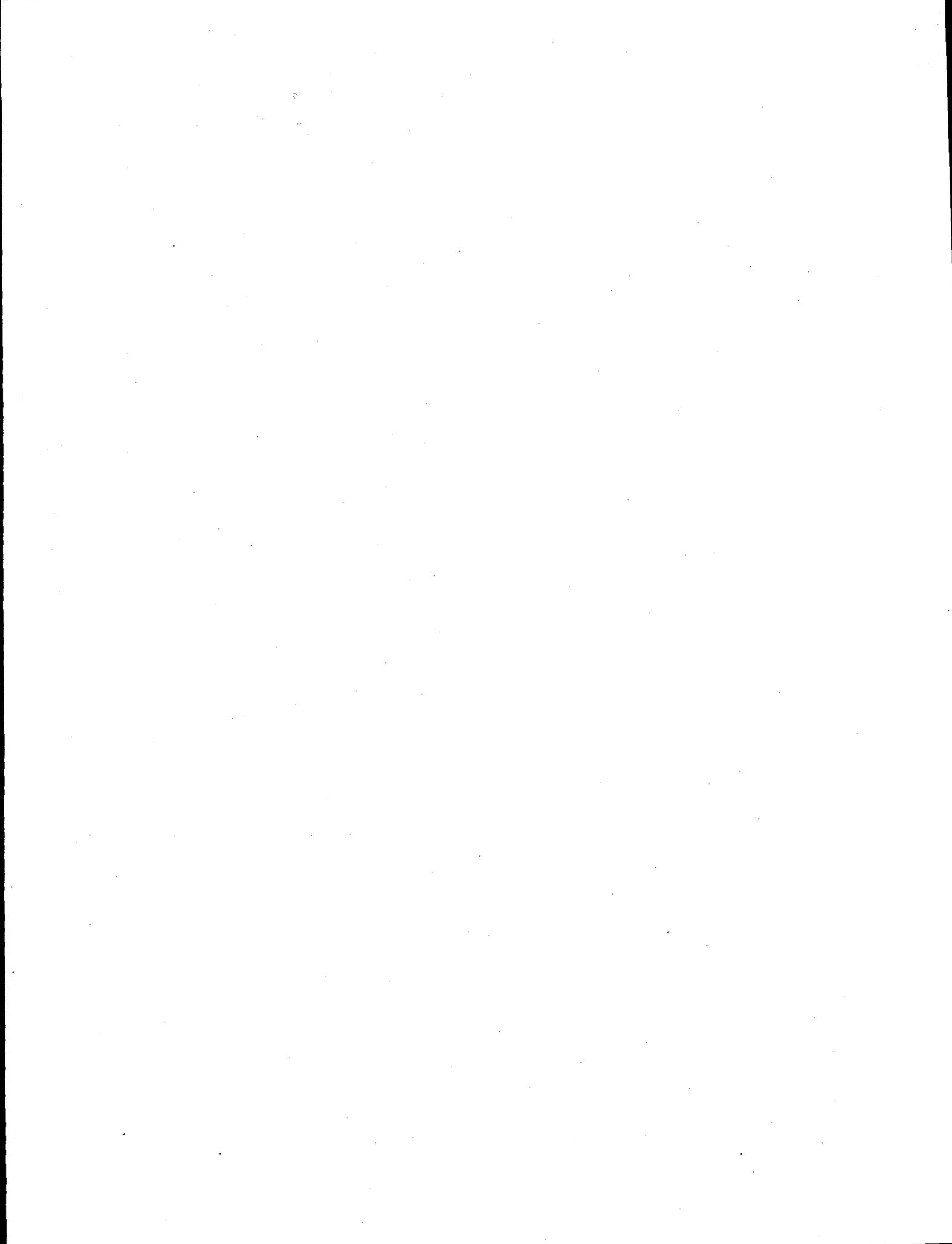
Acknowledgments

The author would like to acknowledge the efforts of engineers and scientists from the Pacific Northwest National Laboratory (PNNL), Waterjet Technology, Inc. (WTI), and University of Missouri at Rolla who contributed to the development, design, and testing of the retrieval end effectors. The author would also like to acknowledge the collaborative efforts and support of personnel from the Department of Energy, Tanks Focus Area, Hanford Tanks Initiative, and Light Duty Utility Arm.



Acronyms

DOE	Department of Energy
HTB	Hydraulic Testbed
HTI	Hanford Tanks Initiative
LDUA	Light Duty Utility Arm
LWS	Light Weight Scarifier
PNNL	Pacific Northwest National Laboratory
RPD&E	Retrieval Process Development and Enhancement
WTI	Waterjet Technology, Inc.



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1.0 Introduction

The Retrieval Process Development and Enhancements Program (RPD&E) is sponsored by the U.S. Department of Energy Tanks Focus Area 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 provide a technical and cost basis to support site-remediation decisions. Part of this program has involved the development of a high-pressure waterjet dislodging system and pneumatic conveyance integrated as a scarifier. Industry has used high-pressure waterjet technology for many years to mine, cut, clean, and scarify materials with a broad range of properties. The scarifier was developed as an alternate means of retrieving waste inside Hanford single-shell tanks, particularly hard, stubborn waste (Rinker 1994). Simulant materials representative of tank waste have been used to test the performance of the scarifier over a wide range of waste types. This technology has been shown to mobilize and convey the waste simulants while operating within the space envelope and the dynamic loading constraints of proposed deployment devices.

Testing of the scarifier has verified its ability to retrieve a wide range of tank waste ranging from extremely hard waste that is resistant to other dislodging means to soft sludge and even supernatant fluid (Hatchell, Rinker, Mullen 1995). Since the scarifier expends water at a low rate and recovers most of the water as it is used, the scarifier is well suited for retrieval of tanks that leak and cannot be safely sluiced or applications where significant waste dilution is not acceptable. The scarifier can also be used for surface decontamination of metal or concrete surfaces. Although the original scarifier was effective, it became evident that a lighter, more compact version that would be compatible with light weight deployment systems under development, such as the Light Duty Utility Arm (LDUA) was needed. At the end of FY 95, the Light Weight Scarifier (LWS) was designed to incorporate the features of the original scarifier in a smaller, lighter end effector (Figure 1.1). During FY 96, the detailed design of the LWS was completed and two prototypes were fabricated.

During FY 96, a thorough testing program was initiated to determine the range of applicability within a matrix of hard and soft simulants, determine appropriate mining strategies, and address integration issues associated with deploying the LWS by a robotic manipulator arm or remote crawler. Long duration tests with materials simulating salt cake, hard pan, and sludge waste forms have been conducted to evaluate the effectiveness of mining strategies, end effector reaction forces, and retrieval rates. This document will describe the testing program, present test results, and provide recommendations for future technology development activities. It is hoped that this information will provide a basis for field-deployable end effectors to meet site remediation requirements.

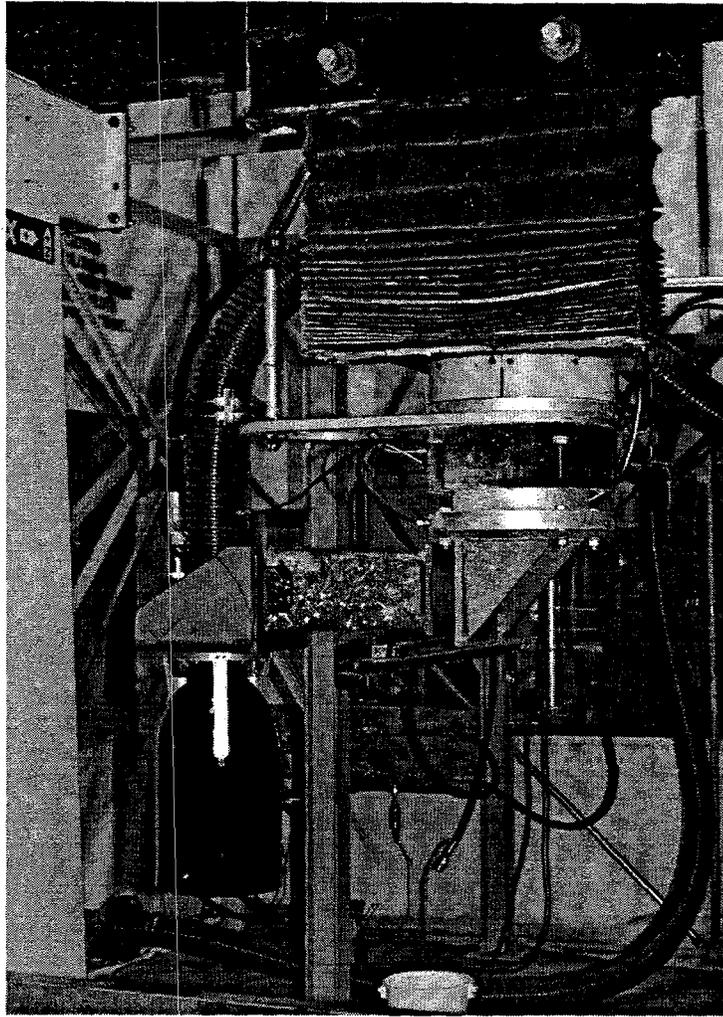


Figure 1.1. Light Weight Scarifier

2.0 Light Weight Scarifier Description

Hydraulic sluicing is the baseline approach to removing the waste inside the Hanford single-shell storage tanks. Local retrieval technologies, such as arm-based systems, are being considered for tanks where net water addition to the tanks would be unacceptable. An alternate technology for waste dislodging and conveyance is a high-pressure waterjet scarifier. The test scarifier was developed through a collaborative effort of Waterjet Technology, Inc. (WTI) and Pacific Northwest National Laboratory (PNNL). The scarifier uses ultra-high pressure water jets (up to 344 MPa or 50,000 psi) as the working fluid to fracture and dislodge the waste. The waterjets provide extreme power density to dislodge waste at low water consumption rates. The scarifier is coupled to an air conveyance system to pneumatically remove the dislodged waste and process water. The waterjets are mounted on a manifold and are rotated by an electric motor to mill a wide channel in the waste material as the scarifier is moved across the surface. At the end of FY 95, the design layout of the LWS was developed to incorporate the features of the original scarifier in a smaller, lighter end effector which retains the pressure capacity of its predecessor.

2.1 Scarifier Design

The LWS uses two ultra-high-pressure water jets to fracture and dislodge the waste. The three waterjets require approximately 22.7 liters per minute (6 gpm) of water at up to 344 MPa (50,000 psi). An electric motor rotates the jet manifold between 0 and 1000 rpm. The ultra-high-pressure waterjets provide extreme power densities on the target and remove material at low water consumption rates. The LWS is coupled with an air conveyance system to pneumatically remove the dislodged waste and water that is used as the cutting fluid. Two waterjets are mounted on a manifold and are rotated by an electric motor to mill a channel in the waste material as the LWS is moved across the surface. The axis of this rotation is normal to the waste surface. A sealed enclosure houses the motor drive. This enclosure is mounted concentric to and inside the annular conveyance inlet shroud, which reduces dispersal of the dislodged waste and water and directs the mobilized waste to the air conveyance system. The scarifier weighs approximately 22.7 kg (50 lbs), is 25.4 cm (10 inches) in diameter, and is approximately 48.3 cm (19 inches) high.

2.2 Ancillary Equipment

The ancillary equipment for the dislodging and conveyance system includes a high-pressure hose and high-pressure pump. Conveyance line, wet/dry separator, a collection hopper, and an air conveyance blower comprise the conveyance system.

2.3 Application

The LWS is being developed for the remediation of tanks containing soft to extremely hard wastes, tanks that leak and cannot be safely sluiced, applications where significant waste dilution is not

acceptable, and for wall scarification and surface decontamination applications. Since the scarifier expends water at a low rate and recovers most of the water as it is used, the scarifier is well suited for retrieval of tanks that leak and cannot be safely sluiced or applications where significant waste dilution is not acceptable. The scarifier can also be used for surface decontamination of metal or concrete surfaces.

2.4 Deployment

The initial scarifier development was based on the assumption that the scarifier would be deployed inside the tank by a remote crawler or a long robotic manipulator (such as the Light Duty Utility Arm) having a significant degree of both structural and operational flexibility. This assumption drove the need to minimize the size and weight of the scarifier and to minimize the periodic forces in the low frequency range. The scarifier could also be deployed inside an underground storage tank by other platforms, such as a cable-driven manipulator or remotely operated crawler.

2.5 Demonstration

High-pressure water jet technology has been used by industry for many years for mining, cutting, cleaning, and scarifying materials with a broad range of mechanical properties. Waterjet-based scarifiers have been used successfully in a variety of decontamination and decommissioning applications in commercial nuclear power plants. Industry has developed scarifiers to clean metals and to remove surface layers of radiation contaminated concrete. Proof-of-concept testing has demonstrated that high-pressure water jets can effectively dislodge several diverse waste simulants (saltcake, sludge, and gunite).

During FY 97, the LWS was also featured in integrated retrieval tests with remote manipulators. The LWS was selected as a featured technology for the Hanford Tanks Initiative (HTI) and was tested with the GreyPilgrim EMMA manipulator at the National Institute of Science and Technology. Using this first-of-a-kind cable driven deployment system, saltcake and sludge simulant were successfully dislodged and conveyed with the LWS (Figure 2.1). Proof-of-principle integrated testing was also conducted to evaluate the performance of the LDUA/LWS retrieval system at PNNL. The LWS was attached to the LDUA gripper and the system was used to retrieve simulants representing dried sludge and granular saltcake waste types. The LDUA was operated remotely through the use of two video cameras. Tests were conducted using manual operation and by executing programmed trajectories, which was necessary to precisely remove a pattern in the waste. These tests confirmed that the LDUA has the structural capacity to maneuver the LWS during waste retrieval while managing the conveyance and high-pressure hoses. From these tests, it is clear that maintaining minimal stand-off distance throughout the retrieval process is critical if the material is to be scavenged efficiently. At PNNL, a request for internal Laboratory Directed Research and Development funds was made to address this and other remote operation issues.

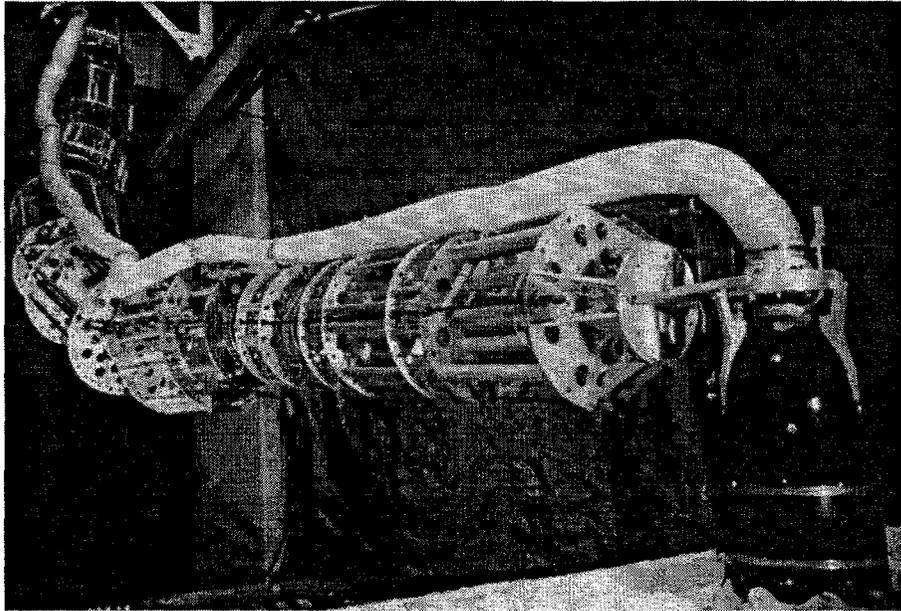


Figure 2.1. EMMA Arm with LWS and Conveyance Hose

2.6 Testing Focus Areas

To characterize the scarifier in terms of certain aspects of waste dislodging and conveyance processes, evaluate process equipment performance, and address integration issues associated with deploying the scarifier with a long manipulator arm. The mission of the program was to investigate waste retrieval systems, and determine appropriate mining strategies, level of control, and sensor requirements.

Short duration scoping tests were conducted at WTI using a compact test bench to determine the optimum operating parameters for retrieval. The system included a 1-axis positioning system that provided 183 cm of travel at speeds up to 2300 cm/min. The motion was monitored using a tachometer with a digital readout. A tent enclosure was used to contain the debris and aerosol that was generated during testing. For tests at WTI, the conveyance system consisted of a 18.6 kW (25 hp) blower, and a cyclone to separate liquids and solids from the air flow. The cyclone had no moving parts and separates the liquids and solids from the air flow by inducing swirl to the air. This type of separation was adequate for the centrifugal type blower, but would not achieve adequate separation of fine particles to be used prior to a positive displacement blower. The centrifugal blower used for testing was capable of moving 85000 liters/min (3000 ft³/min) with 5.0 kPa (1.47 inches Mercury) vacuum. Instrumentation at WTI was installed to measure jet pressure, water flow rate, and shroud pressure.

The objectives for the work performed at WTI were to verify design concepts and determine the performance of the LWS using a matrix of simulants. Small scoping tests were performed to determine the range of applicability of the LWS to establish successful operating pressures, rotational speed, and traverse speeds for each simulant type. Testing was conducted with a full suite of test materials so that

the LWS could be evaluated against alternative retrieval technologies. Test variables included nozzle diameter (0.45-1.02 mm or 0.018-0.040 inch), pressure (68.9-379.2 MPa or 10,000-55,000 psi), stand-off distance (1.27-8.89 cm or 0.5-3.5 inches), scarifier rotational speed (600-1200 RPM) and traverse rate (17.8-1524 cm/min or 7-600 in/min).

A larger test facility denoted the Hydraulic Test Bed (HTB) was constructed at PNNL to allow longer duration, multiple pass tests on large waste fields using a versatile gantry-style manipulator (Hatchell, Smalley, Tucker 1995). The gantry system provides a horizontal work space of 243 cm by 305 cm at speeds up to 5500 cm/min. A passive two-link arm was used to support the conveyance line and high-pressure hoses in the vicinity of the LWS (Figure 2.2). The ancillary equipment for the dislodging system includes a high-pressure hose and high-pressure pump. The capacity of the pump was 94.6 liters/min (25 gallons/min) at 68.9 MPa (10,000 psi). The conveyance system consisted of a 10.16-cm (4-inch) diameter line, a wet/dry separator, a collection hopper, and an air conveyance blower unit. The blower, driven by a 56 kW (75 hp) motor, had a maximum flow rate of 36800 liters/min (1300 ft³/min) at a vacuum of 61.0 kPa (18 inches Mercury). The length of line from shroud to separator was 7.01 meters (23 ft), and from separator to blower was 6.09 meters (20 ft). The conveyance line included a lift of 4.67 meters (15.3ft).

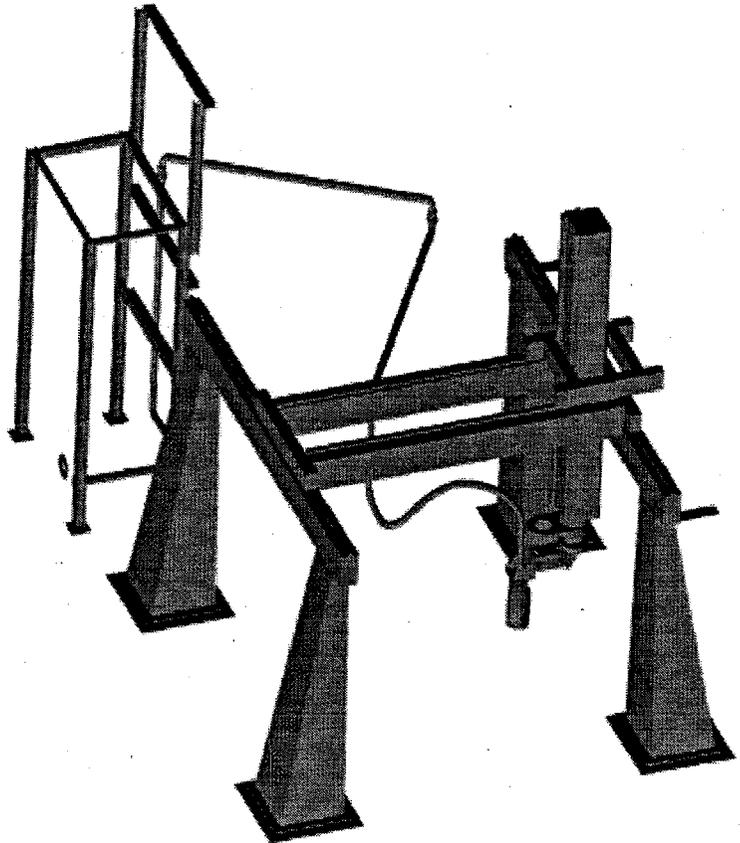


Figure 2.2. Scarifier and Conveyance Line Management Arm Installed on Gantry Robot

The objectives of the retrieval tests at PNNL were to determine long duration retrieval performance, to evaluate the LWS for alternate uses (including boring holes for instrument insertion), to measure steady state and dynamic reaction forces, and to evaluate alternate mining strategies for material removal. Instrumentation installed on the HTB system to measure retrieval performance and scarifier reaction forces consisted of:

Waterjet Pressure Transducer: A pressure transducers was installed in the high-pressure water line near the inlet port to the scarifier to insure that adequate cutting pressure is available at the scarifier.

Waterjet Flow Meter: A high-pressure water flow meter was installed in the high-pressure line.

Conveyance Line Pressure Transducers: Two pressure transducers were installed in the conveyance line to monitor the vacuum at various points in the line. The transducers were located at the shroud and at one point downstream. The pressure port at the shroud was actually just above the shroud, at the beginning of the cylindrical system. The intermediate pressure point was approximately 9 meters downstream from the shroud. To prevent the sensor ports from being clogged, it was necessary to install the sensors in a special pressurized air line that provided a small amount of back pressure.

Force-Torque Sensor: To measure dynamic forces due to air suction, inertia, and waterjet reaction, a sensor which measures forces and torques along three axes was attached to the scarifier mounting beam. At the beginning of each test, the sensor was "zeroed" to eliminate steady state offset due to the weight of the end effector and loading from the hoses.

Scarifier Speed Controller: A tachometer was installed on the scarifier motor shaft to measure the rotational speed of the waterjets. The speed was controlled with a closed-loop system using Hall Effect sensors for armature position feedback.

Hopper Load Cells: Load cells were installed on the hopper mounting locations to measure the weight of process water and waste simulant entering the hopper.

The sensors were connected to a National Instruments Labview™ data conditioning module, which converted the sensor signals to analog voltages. This module also provided electrical isolation 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, which allowed rapid sampling (up to 200 Hz) of instrumentation and process control signals. Virtual instrumentation and controls devices were developed to control valves and equipment emergency stops and to monitor key process variables from a graphical user interface.

The test data and results are discussed in detail in the following sections of this report. The results are divided into three sections: dynamic reaction force information, process information (pressures, flow rates), and performance parameters (retrieval rates, sensitivities, lessons learned).

3.0 Reaction Forces

This section contains scarifier dynamic forces due to separate effects (suction only, jet thrust only) and during retrieval. It was important to measure reaction forces of the scarifier to establish a loading envelope that must be supported by robotic manipulators during deployment. To measure dynamic forces, the scarifier was attached to a force-torque sensor which measured forces and torques along three axis (Figure 3.1). Note that the X and Z directions of the sensor were in the horizontal plane, while Y was aligned with the vertical direction. Vertical reaction forces are typically caused by waterjet thrust, suction, and impacts with the surface, while horizontal reaction forces are primarily caused by impacts with the surface and rotational imbalances.

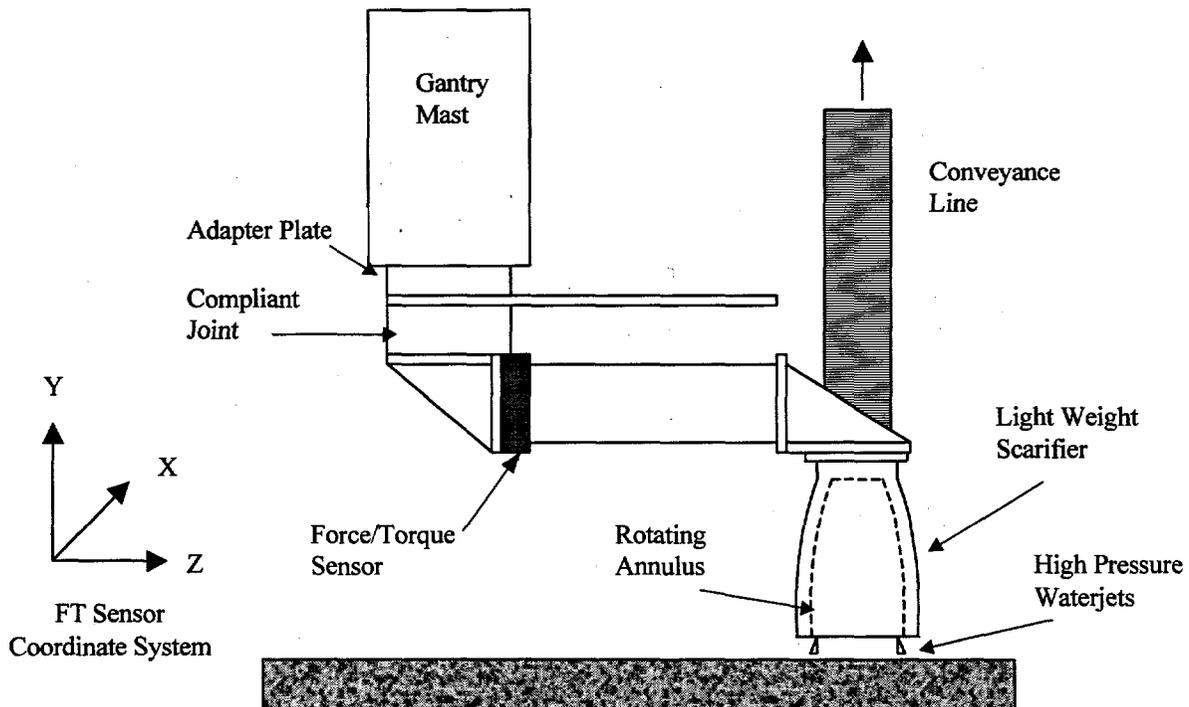


Figure 3.1. Scarifier Attachment to Gantry

3.1 Due To Suction vs. Stand-Off Distance

Tests were conducted to measure the reaction forces due to suction at the scarifier vs. stand-off distance. Suction creates significant forces in the vertical direction, as well as a large moment about the x-axis. These results are provided in Figures 3.2 and 3.3, respectively. As the stand-off distance decreases, the inlet area decreases, which results in a lower shroud pressure and higher suction forces. When the stand-off distance was reduced to 10 mm or less, large suction forces resulted. Suction-induced reaction forces can be mitigated with vacuum control valves in the system to limit the vacuum that can be created at the shroud.

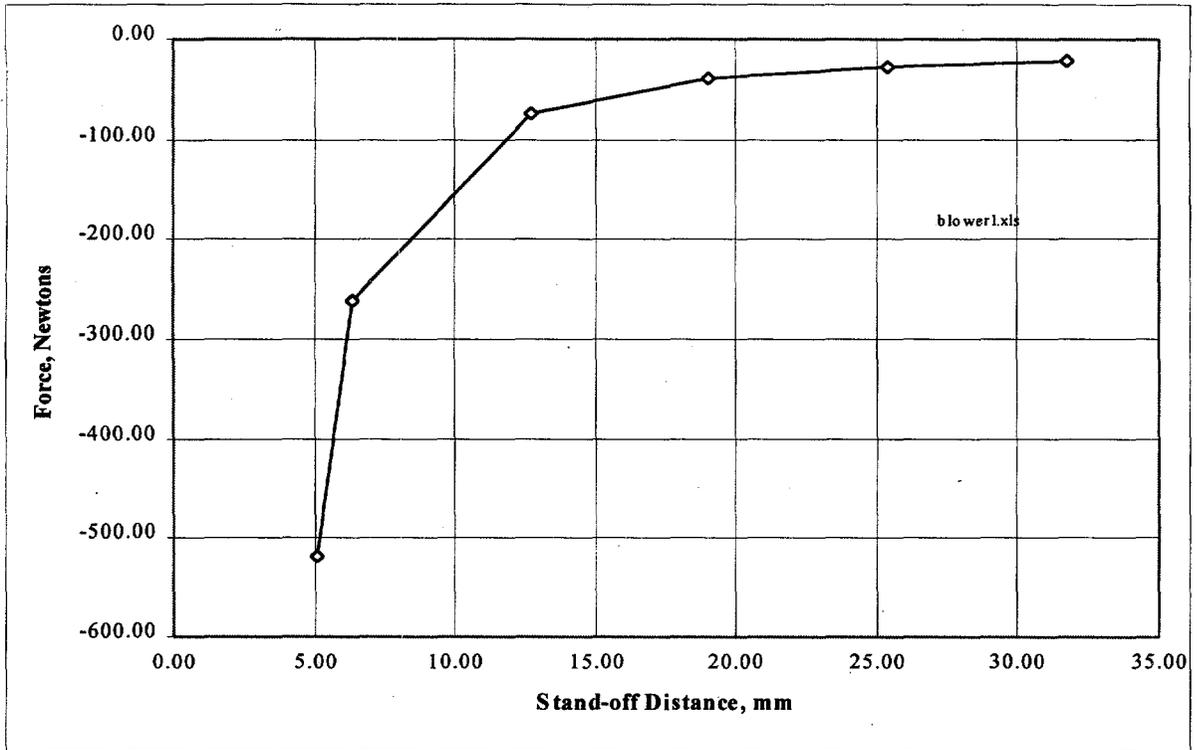


Figure 3.2. Suction Force (vertical direction) vs. Stand-off Distance

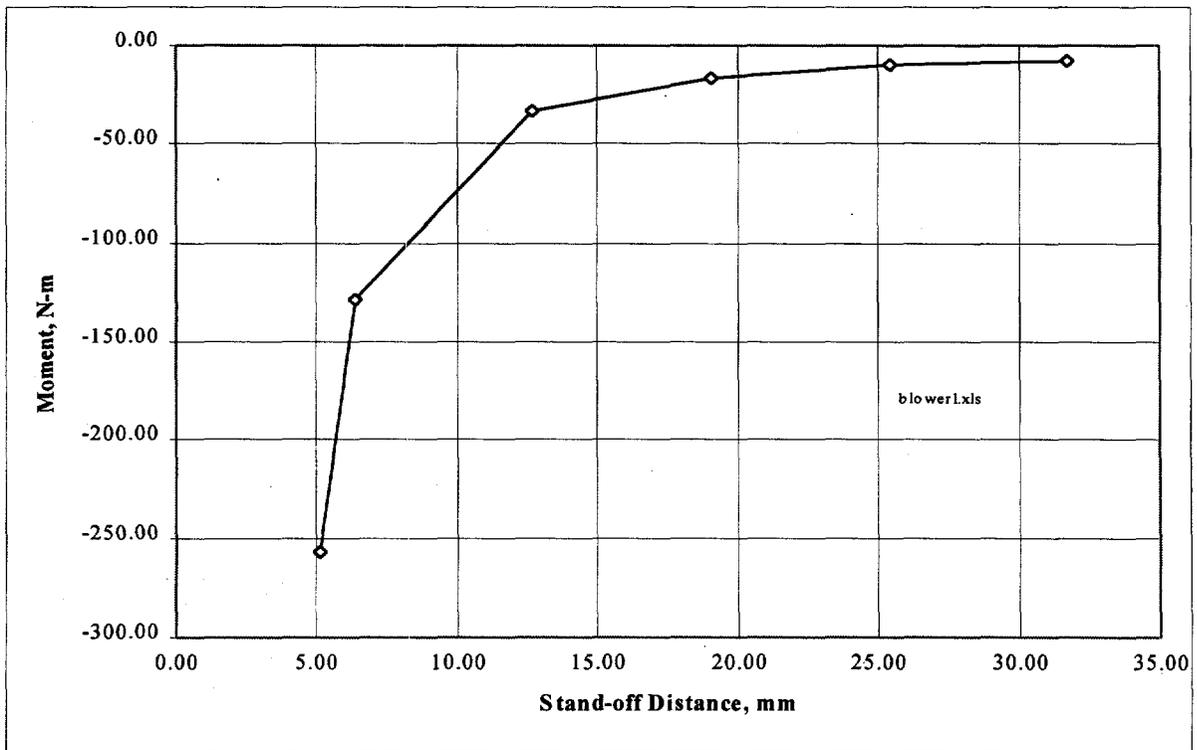


Figure 3.3. Moment due to Suction Force vs. Stand-off Distance

3.2 Due To Jets vs. Jet Pressure

The acceleration of fluid through orifices generates a reaction force in the opposite direction to flow. Figure 3.4 provides the vertical reaction force of the scarifier versus waterjet pressure.

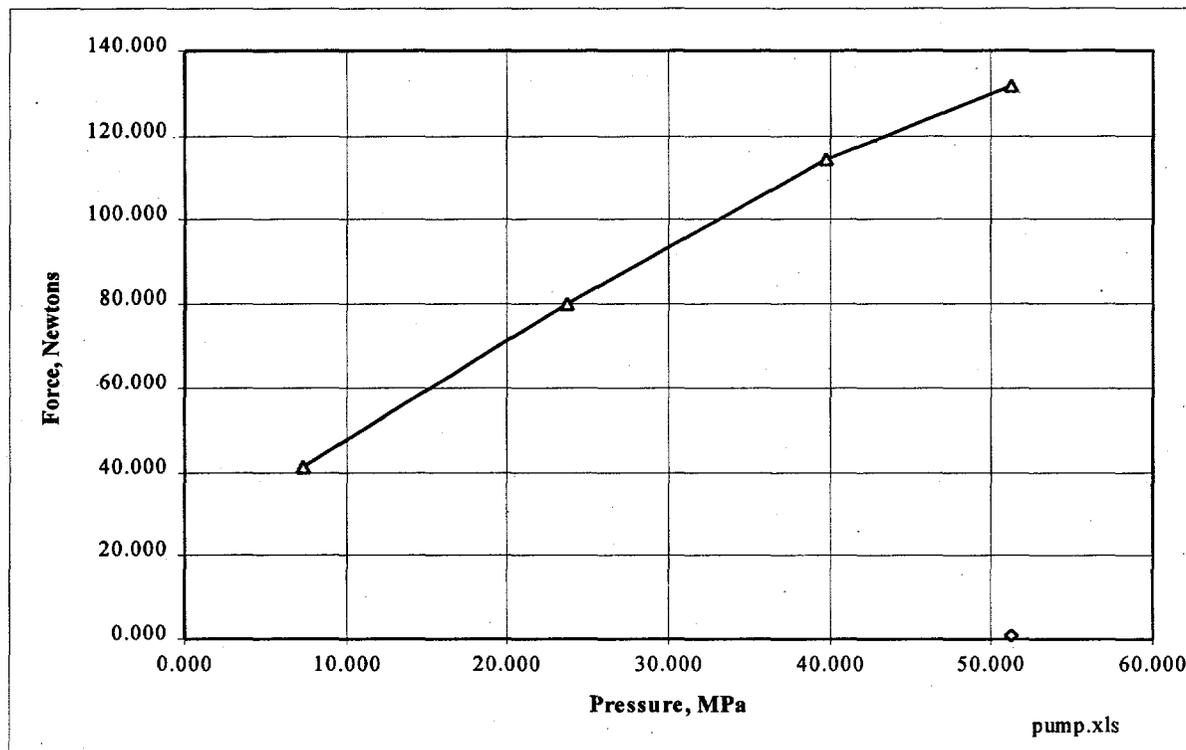


Figure 3.4. Vertical Reaction Force vs. Waterjet Pressure

3.3 During Retrieval

In addition to operational performance, dynamic reaction forces were analyzed to determine the compatibility of the scarifier with remote deployment systems, such as the Light Duty Utility Arm. This data can be used to support decisions regarding the application of the scarifier (or similar) technologies and will allow design and validation of deployment system design and actual in-tank components. Since high-pressure scarifiers are being considered for remediation of Hanford Tanks, there was keen interest in this information from several industrial vendors wishing to propose retrieval concepts to the Hanford Tanks Initiative.

Reaction force data during retrieval tests was examined to determine the effect of waste type and waterjet pressure on end effector reaction forces. Two analyses were performed on each data set. First, a moving average filter was applied to verify that the average values were representative. Second, a spectral analysis was performed using the Mathcad™ implementation of real-data fast Fourier transform. Appendix A contains average, maximum, and minimum force and moment levels and resonance

frequencies for tests with salt cake, sludge, and hard pan. Peak reaction forces were less than 250 Newtons (absolute) during these tests (see Table 3.1). Reaction forces were higher during retrieval of harder materials (saltcake and hardpan) indicating collisions with the waste govern the force magnitudes. The moving average force levels varied throughout the tests. This could have been caused by variations in stand-off distance which strongly affects the suction force. A peak frequency response occurred at the speed of rotation, which was caused by slight imbalance of the rotating parts. Other possible sources of resonance include pressure pulsations from the pumps and mechanical vibration caused by gantry movement. It should be noted that the gantry robot used to position the scarifier was very stiff; the use of a more compliant deployment device could have resulted in much lower reaction forces.

Table 3.1. Maximum Reaction Forces During Retrieval

Simulant	Test Parameters	Maximum Force Level
Granular Saltcake Composition #4 Compressive Strength 55 kPa	Rotation Speed: 650 RPM Traverse Speed: 762 cm/minute Water jet pressure: 23.8 MPa (3450 psi) Flow Rate: 17.7 liters/min (4.67 gpm) Path width: 17.8 cm (7 inches)	150
Sludge Shear Strength 3.5 kPa	Rotation Speed: 775 RPM Traverse Speed: 762 cm/minute Water jet pressure: 8.3 MPa (1200 psi) Flow Rate: 10.7 liters/min (2.82 gpm) Path width: 17.8 cm (7 inches)	160
Hardpan/Dried Sludge Composition #2 Shear Strength 200 kPa	Rotation Speed: 775 RPM Traverse Speed: 762 cm/minute Water jet pressure: 21.0 MPa (3050 psi) Flow Rate: 16.4 liters/min (4.32 gpm) Path width: 17.8 cm (7 inches)	275
Saltcake Composition #2 Compressive Strength 10MPa	Rotation Speed: 600 RPM Traverse Speed: 762 cm/minute Water jet pressure: 54.8 MPa (7950 psi) Flow Rate: 26.9 liters/min (7.11 gpm) Path width: 17.8 cm (7 inches)	275

4.0 Process

This section contains data pertaining to the process of dislodging and conveyance, including line pressures and flow rates. This information is needed to understand the relationship between fluid process parameter and performances measures.

4.1 Conveyance Line Pressure vs. Stand-Off

Various stand-off distances were tested to determine the relationship between inlet area and shroud pressure (Figure 4.1). Note that atmospheric pressure is approximately 100 kPa. The shroud pressure is 95 kPa and relatively constant for stand-off distances greater than 15 mm; below this threshold, shroud vacuum increases rapidly. If the shroud is allowed to contact a flat surface, large suction forces will be generated that may be greater than the capacity of deployment manipulators. This could lead to structural damage, or a stuck position until the suction is relieved. Suction-induced reaction forces can be mitigated with vacuum control valves in the system to limit the vacuum that can be created at the shroud.

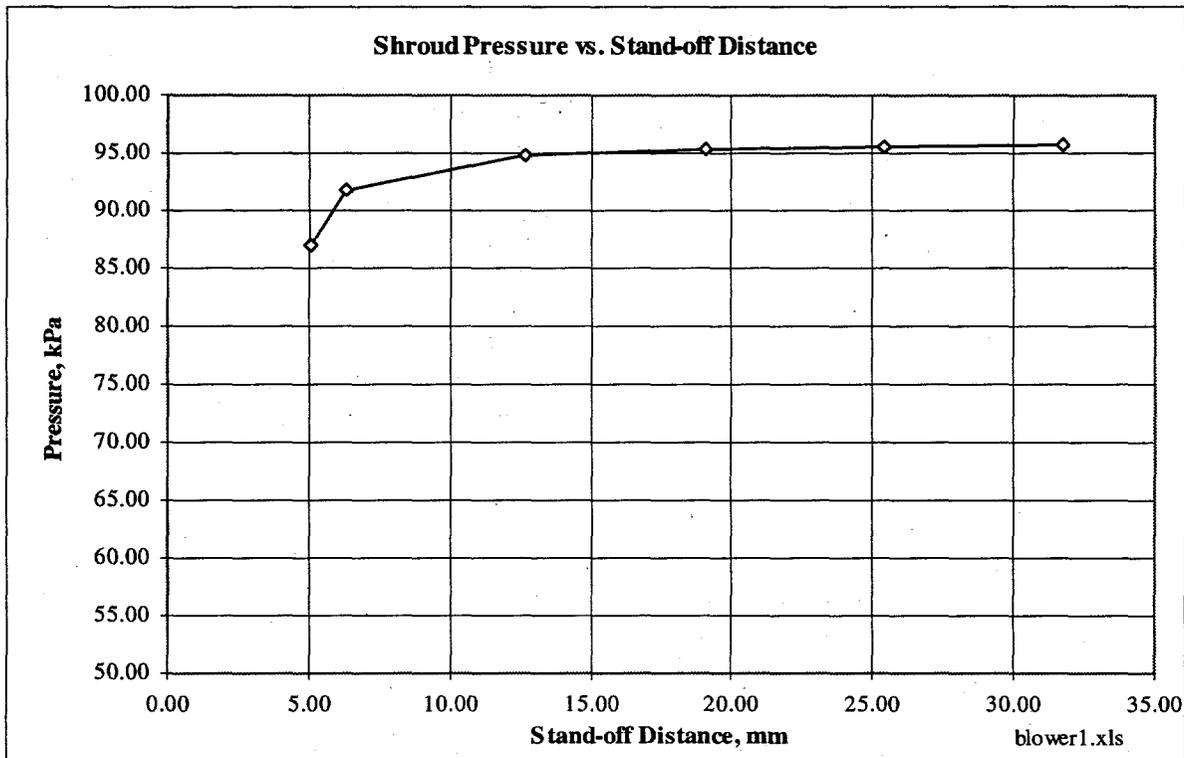


Figure 4.1. Shroud Pressure vs. Stand-off Distance

4.2 Conveyance Line Pressures During Retrieval

Figures 4.2 and 4.3 provide conveyance line pressure at the shroud and one intermediate point during typical retrieval test with granular saltcake, sludge, hardpan, and saltcake. The shroud pressure during all tests was fairly constant at 95 kPa. Since this is shroud pressure with an unrestricted inlet, this indicates that the shroud inlet is not being restricted during retrieval. The downstream conveyance line pressure varied more during the retrieval of sludge, indicating the conveyance line was partially blocked by sludge periodically.

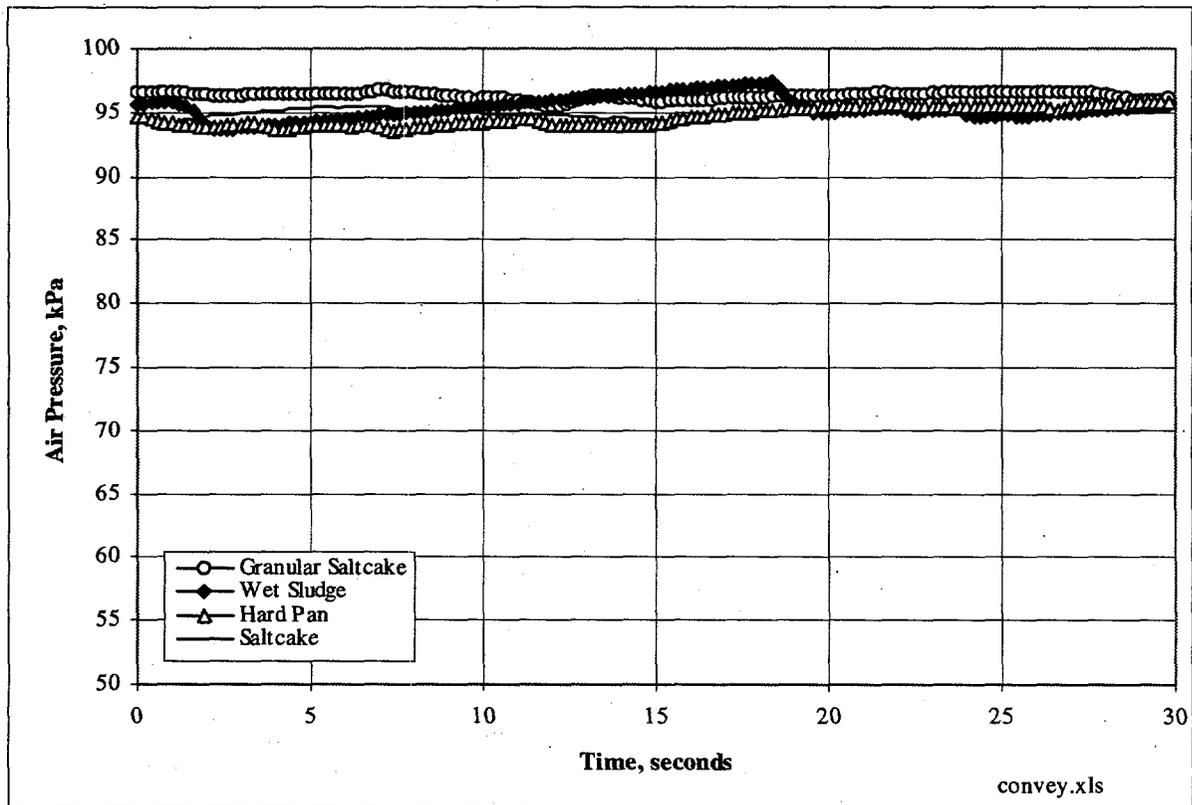


Figure 4.2. Shroud Pressure During Retrieval

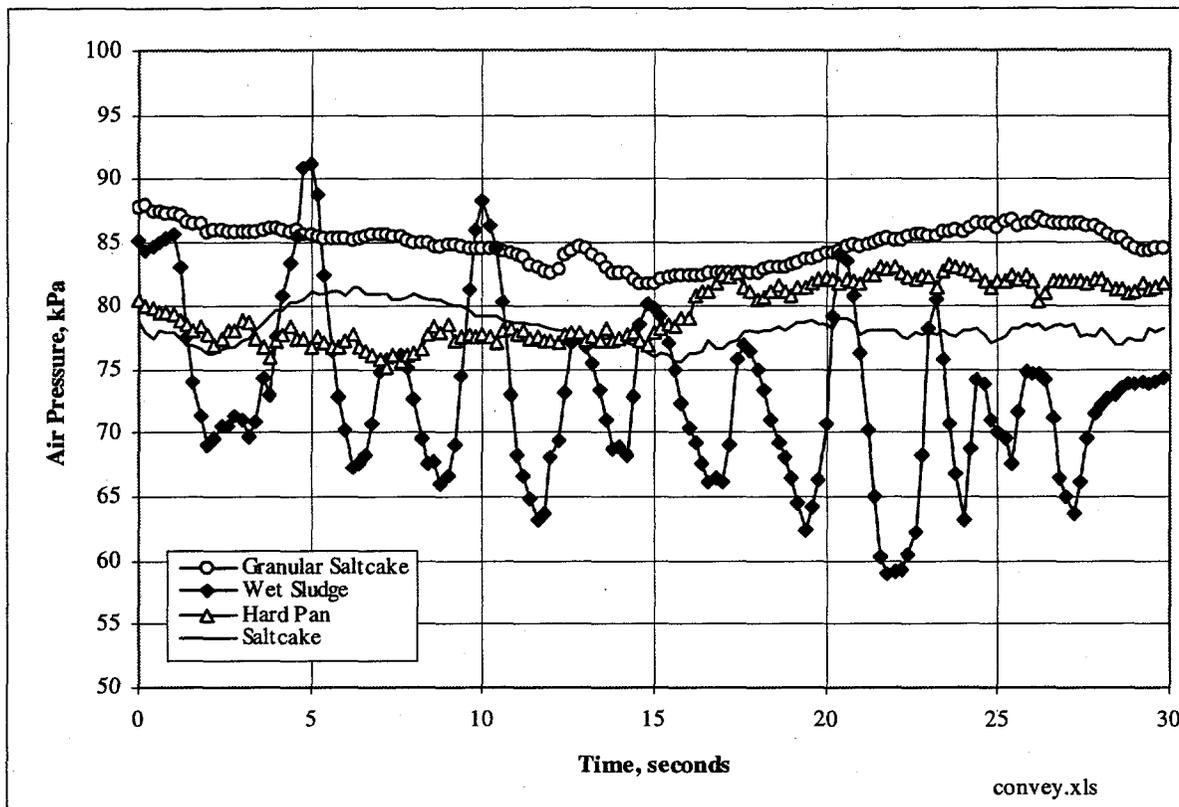


Figure 4.3. Downstream Conveyance Line Pressure During Retrieval

4.3 Flow Rate And Pressure Drop vs. Pump Operating Pressure

Tests were conducted to determine the relationship between flow rate and operating pressure (Figure 4.4). For this pressure range, pressure increases in a fairly linear fashion with flow rate. Water consumption and material dilution rates were computed by using this data.

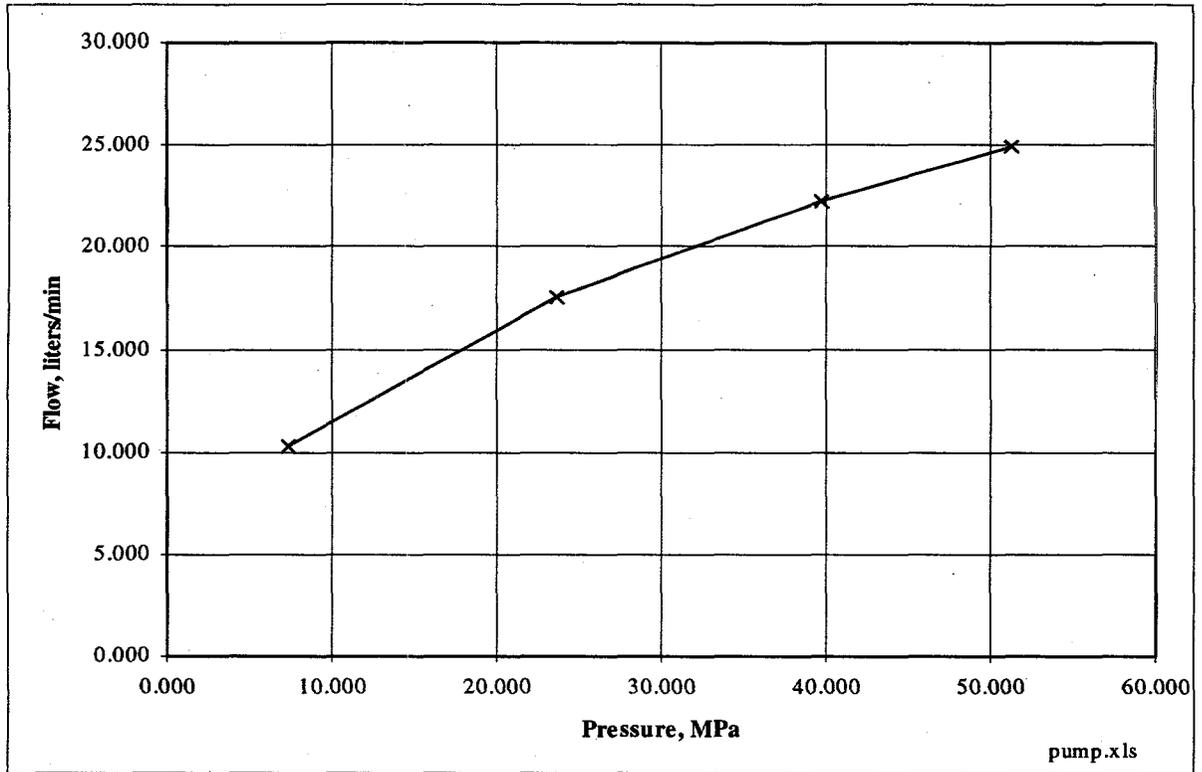


Figure 4.4. Scarifier High Pressure Water Flow Rate vs. Operating Pressure

5.0 Performance

This section contains data pertaining to the performance of the scarifier, including retrieval rates and optimum process parameters.

5.1 Simulant Types

Waste dislodging and conveyance processes will require system qualification tests using radioactive waste materials or simulated waste. Testing with radioactive waste has disadvantages involving the limited volume of material available, significant hazards to personnel, and high cost to run the tests. The use of simulated waste is promoted to overcome these disadvantages. However, the application of simulants is not without its difficulties. Characterization of waste inside Hanford underground storage tanks is very limited and may not span all relevant waste properties. Until such time that physical characterization data becomes available for the actual tank wastes, the simulant properties must be carefully designed to expose the limitations of the process and span the range of properties expected to be critical to the processes studied. Simulants have been designed to capture the essential characteristics of hard saltcake and sludges (Powell 1996). Saltcake recipes typically contain a water/dynamate^(a) or water/dynamate/silica mixture, while sludge recipes contain a water/kaolin or water/bentonite mixture. Hardpan recipes include kaolin and plaster of paris. It is expected that these recipes will bound the critical properties of the actual sludge in the tank.

Table 5.1 provides the simulants used during the testing program. Testing of the LWS was conducted with the same suite of test materials used by the Hanford HTI program so that the LWS could be evaluated against competing retrieval technologies.

It was believed that the LWS would retrieve all simulants bounding the material properties believed to be in the Hanford tanks by selecting appropriate operating pressure. Since testing at PNNL was conducted at lower pressure, the testing focused on retrieval of softer materials. Consequently, a weaker saltcake recipe (#2) was chosen.

(a) Dynamate is a trade name for Potassium Magnesium Sulfate ("K-Mag").

Table 5.1. Simulants Used During the Testing Program

Simulant	Material Strength	Density
Granular Saltcake Composition #4	Compressive Strength 55 kPa	1.20 g/cm ³
Sludge	Shear Strength 3.5 kPa	1.65 g/cm ³
Hardpan/Dried Sludge Composition #2	Shear Strength 200 kPa	1.65 g/cm ³
Saltcake Composition #1 (WTI only)	Compressive Strength 21MPa	2.25 g/cm ³
Saltcake Composition #2 (PNNL only)	Compressive Strength 10MPa	1.94 g/cm ³

5.2 Mining Strategies Tested and Compared

A process deployment strategy will be required to cope with changes in the surface contours of the waste. This strategy will include addressing the 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 must maintain a high average retrieval rate, including the time required to position the end effector. The overall strategy must effectively retrieve waste over the existing topography and tank hardware, as well as over any topography created by the scarifier itself, including ridges, knobs of harder material, loose chunks, or leftover ribs from previous passes over the surface.

5.2.1 Mining Strategy Functions

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.

5.2.2 Mining Strategy Requirements

To support these functions, the mining strategy must meet the following requirements:

The mining strategy must minimize the use of mast elevation and rotation by using the dexterous portions of the manipulator to implement the mining strategy. This requirement will maximize positioning accuracy, minimize energy expenditure, and simplify the required manipulator bracing. This strategy will dictate dividing the tank into several regions and retrieving waste from each region sequentially.

- Because of the robot's inability to change direction abruptly without slowing down, the mining strategy must minimize sharp corners and backtracking in the waste removal path.
- The mining strategy must manage the supernatant liquid in the tank. It 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 of 0.1 to 5 Hz. These frequencies span the fundamental natural frequency of some proposed deployment devices.
- 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, corners, and sides of the tank.

5.2.3 Baseline Strategies

The scarifier was generally used to remove thin layers of material (0.2-4 cm). It is not intended to be submerged deeply into materials, but rather to remove uniform layers successively. Testing with the LWS at PNNL was conducted with a serpentine path in which the end effector was swept over the waste surface in a regular pattern, removing waste in 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 effector is cutting waste at all times. For saltcake and hardpan testing, the hard shroud of the scarifier was placed as close as possible to the surface of uncut material, while the rubber boot accommodated any unevenness. For sludge testing, it was possible to submerge the scarifier head slightly below the surface of the sludge, as the scarifier was able to clear a path ahead of itself. The waterjets cut channels in the material 17.8 cm (7 inches) wide, which dictated a distance between

adjacent passes of 17.8 cm. During sludge retrieval, the surface of the sludge field was approximately level and the scarifier left a somewhat indiscernible path. The waterjets apparently agitated the surrounding waste field to the extent that the sharp edges of the cutting path collapsed somewhat. Excess water was absorbed by the waste, and splatter from the waterjets was minimal, especially when lower water pressure was used.

Saltcake was also retrieved using the serpentine mining path, although at a very slow rate. Pumping pressures were limited to 68.9 MPa (10,000 psi) at the testbed, and prior testing has validated that at least 206.7 MPa (30,000 psi) is required for adequate saltcake dislodging rates. Rather than focus on bulk retrieval of saltcake, the test engineers focused on water containment during retrieval, which is a critical issue for deployment in leaky tanks. It was found that, even at 68.9 MPa waterjet pressure, containment of the process water was a challenge for the retrieval system, and most of the cutting water is not contained within the shroud. The traverse speed and dwell time was modified to reduce the amount of water lost, and it was found that the amount of water lost could be minimized by using a short dwell time followed by a rapid traverse. During this process, a ridge is created by the waterjets which serves to deflect the water up into the conveyance line.

Even though retrieval rates were low, inconsistent simulant reactions from the saltcake were noted. The saltcake material did not cut evenly, and tended to develop pockets as the retrieval progressed. Water tended to escape through these pockets in the simulant. When the material was cut, the resulting particle size was very small (approximately the size of a grain of sand). A layer of saltcake particles was found throughout the test area, indicating that some of the material is being lost.

Methods for boring holes in saltcake retrieval were also attempted. A grid of rings was produced in a saltcake field to generate large chunks of material approximately 2 cm in size. This effort was partially successful; material non-homogeneity prevented consistent fracturing of the material in the same place. Nonetheless, a large hole 50 by 50 by 18 cm deep was created this way.

5.3 Retrieval Performance from Scoping Tests at WTI

A total of 40 tests on saltcake composition 1 were performed by WTI. Peak retrieval rates in the range of 20.5 liters/min were achieved with a small stand-off distance (1.27 cm) and high traverse rate (762 cm/min) using 345 Mpa (50,000 psi) waterjets. Testing with granular rock salt simulant yielded a retrieval rate of 122 liters/min using 206.8 MPa (30,000 psi) nozzle pressure and a traverse rate of 1524 cm/min. Hardpan simulant was also retrieved at high efficiencies using 68.9 MPa pressure. These tests demonstrated that the LWS was capable of dislodging material at high rates; however, it was noted that the ability of the retrieval system to scavenge dislodged particles and water needs to be improved either by altering the way in which the LWS was used, or by modifying its design.

5.4 Retrieval Performance from Long Duration Tests at PNNL

Prior to testing at PNNL, Waterjet Technology recommended a set of near-optimum operating pressures, rotational speed, and traverse speed for each simulant type, based on their bench scale testing. This information greatly accelerated the progress of the testing program.

A wide range of materials, ranging from sticky sludge to hard saltcake, were successfully retrieved by the LWS, demonstrating the versatility of the system. The retrieval goal for the LWS was 28.3 liters/min (1 ft³/min) with a 2.54-cm (1-inch) depth of cut; this goal was reached for sludge, hardpan, and granular saltcake simulants. The maximum capacity of the LWS may be even higher; however, the budget for the task limited the number of iterations that could be attempted. Test parameters and initial test results are provided in Table 5.2. Before the onset of bulk retrieval testing, the waterjet pressure required to cut through 2.54 cm of material was determined. Figure 5.1 provides waterjet penetration results for hardpan and shows that at least 18 kPa is required to cut through 2.5 cm of material. Higher pressures for deeper cutting lead to inadequate retrieval (the dislodged material is out of the range of the conveyance system) and more splatter. In the case of sludge, retrieval with high-pressure (55 Mpa) waterjets resulted in the entire sludge lifting up and plugging the conveyance shroud.

Retrieval of hardpan was made more difficult because the material tends to fragment into clumps, which sometimes were too large for the retrieval inlet and were pushed around by the waterjets. At times, the shroud collided with these chunks, resulting in large reaction forces. This problem was minor but would have to be dealt with before deployment.

Prior to the completion of testing at PNNL, a demonstration of the LWS and other retrieval systems being developed and tested by the RPD&E team was held for personnel from DOE Richland Office. The demonstrations focused on technology development and "paper to product" site support that is the key to successful deployment and were very well received.

Although the scarifier was effective in retrieving a broad range of waste, design enhancements would improve performance in a number of areas.

Retrieval of water: The LWS conveyance system cannot retrieve large amounts of standing water quickly without slugging. The vacuum capacity of the blower is inadequate to support a large water column. A shroud attachment is needed to retrieve water while entraining air to improve performance and eliminate slugging.

Stand-off: Maintaining a tight stand-off distance (1 cm) is critical for maximum conveyance, due to the limited range of the conveyance system. It was difficult at times to maintain a close stand-off distance during remote operations. This issue can be solved by developing a sensor to measure the stand-off, or by designing more a compliant shroud.

Table 5.2. Light Weight Scarifier Test Parameters and Retrieval Results

Simulant	Test Parameters	Volume Retrieved, liters (ft ³)	Retrieval Rate, liters/min (ft ³ /min)
Granular Saltcake Composition #4 Compressive Strength 55 kPa	Rotation Speed: 650 RPM Traverse Speed: 762 cm/minute Water jet pressure: 23.8 MPa (3450 psi) Flow Rate: 17.7 liters/min (4.67 gpm) Path width: 17.8 cm (7 inches)	357 (12.6)	34.4 (1.22)
Sludge Shear Strength 3.5 kPa	Rotation Speed: 775 RPM Traverse Speed: 762 cm/minute Water jet pressure: 8.3 MPa (1200 psi) Flow Rate: 10.7 liters/min (2.82 gpm) Path width: 17.8 cm (7 inches)	357 (12.6)	34.4 (1.22)
Hardpan/Dried Sludge Composition #2 Shear Strength 200 kPa	Rotation Speed: 775 RPM Traverse Speed: 762 cm/minute Water jet pressure: 21.0 MPa (3050 psi) Flow Rate: 16.4 liters/min (4.32 gpm) Path width: 17.8 cm (7 inches)	357 (12.6)	34.4 (1.22)
Saltcake Composition #2 Compressive Strength 10MPa	Rotation Speed: 600 RPM Traverse Speed: 762 cm/minute Water jet pressure: 54.8 MPa (7950 psi) Flow Rate: 26.9 liters/min (7.11 gpm) Path width: 17.8 cm (7 inches)	85 (3)	low < 1 liters/min

Water Containment: The conveyance system is not able to contain the waterjets during retrieval of hard materials, such as saltcake. It was found that, even at 68.9 MPa waterjet pressure, containment of the process water was a challenge for the retrieval system, and most of the cutting water is not contained within the shroud. Several design changes could improve water containment, including 1) the use of a higher capacity blower, 2) improving inlet design to separate the waterjets from the air conveyance annulus, and 3) redirecting the jet angle toward the center of the shroud.

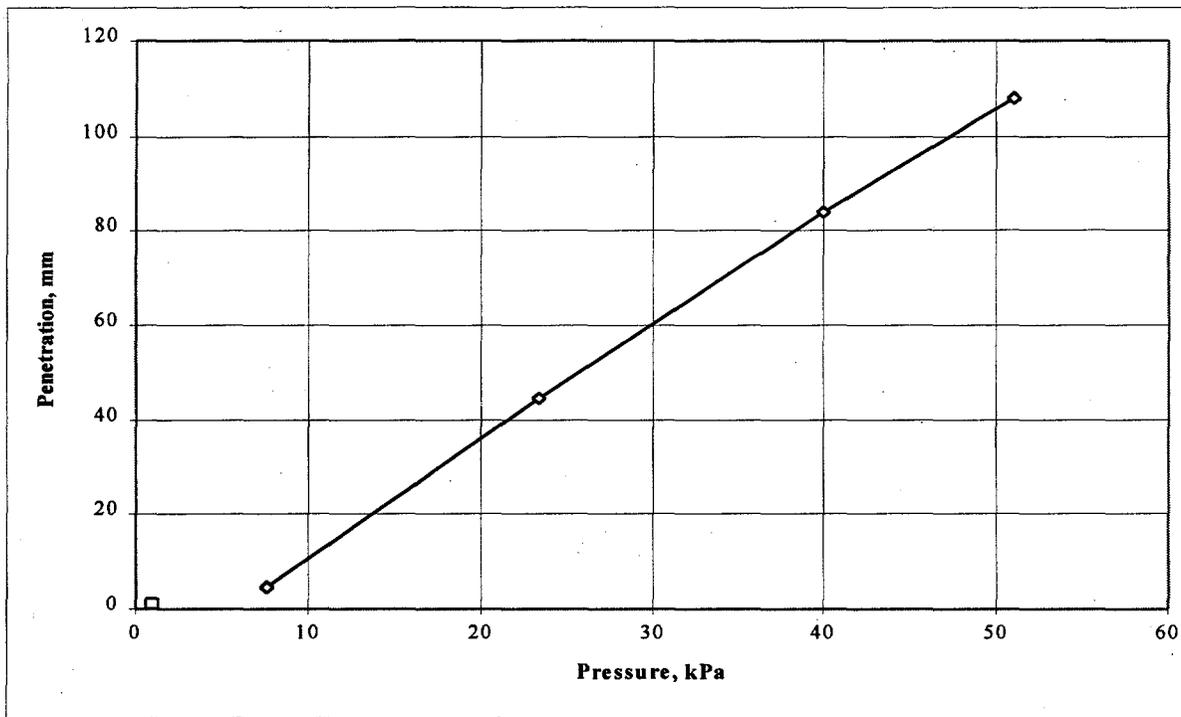


Figure 5.1. Waterjet Penetration in Hard Pan vs. Pressure

6.0 Conclusions

A wide range of materials, ranging from sticky sludge to hard saltcake, were successfully retrieved by the LWS, demonstrating the versatility of the system. The retrieval goal for the LWS was 28.3 liters/min (1 ft³/min) with a 2.54-cm (1-inch) depth of cut; this goal was reached for sludge, hardpan, and granular saltcake simulants. The maximum capacity of the LWS may be even higher; however, the scope for the task limited the number of iterations that could be attempted. Through funding of the LDUA program, proof-of-principle integrated testing was conducted to evaluate the performance of the LDUA and the LWS retrieval system at PNNL. The LWS was attached to the LDUA gripper and the system was used to retrieve simulants representing dried sludge and granular saltcake waste types. The LDUA was operated remotely through the use of two video cameras. Tests were conducted using manual operation and by executing programmed trajectories, which was necessary to precisely remove a pattern in the waste. These tests measured the performance of the LWS and validated its compatibility with an existing long reach manipulator. Although there are no planned hot deployments of the LWS at this time, it is believed that the LWS will find application at Hanford for hard heal retrieval and at ORNL for gunite removal.

7.0 References

Hatchell, B. K., J. T. Smalley, and J. C. Tucker. 1995. *Retrieval Process Development and Enhancements Hydraulic Test bed Integrated Testing FY95 Technology Development Summary Report*. PNNL-11105, Pacific Northwest Laboratory, Richland, Washington 99352.

Hatchell, B. K., M. W. Rinker, and O. D. Mullen. 1995. "Hazardous Waste Retrieval Strategies using a High Pressure Water Jet Scarifier." *8th American Water Jet Conference*, 617-628.

Powell, M.R. 1996. *Initial ACTR Retrieval Technology Evaluation Test Material Recommendations*. PNNL-11021, Pacific Northwest Laboratory, Richland, Washington 99352.

Rinker, M. W., O. D. Mullen, and B. K. Hatchell. 1994. *Waste Dislodging and Conveyance Testing Summary and Conclusions to Date*. PNL-10095, Pacific Northwest Laboratory, Richland, Washington.

Appendix A

Harmonic Forces Generated by the Light Weight Scarifier

LWS Frequency Analysis - Granular Saltcake Retrieval

Operating Conditions

End Effector	Light Weight Scarifier	
Sampling Frequency:	200	Hz
Simulant Type	Granular Saltcake #4	
Traverse Speed	12.7	cm/sec
Rotational Speed	650	RPM
Stand-off Distance	0-2.5	cm
Water Jet Pressure	23.8	MPa
Water Jet Flow	17.7	liters/min
Cutting Nozzle Size	1.14	mm

Summary of Results: Reaction forces were less than 150 Newtons. Real-time force variations possibly caused by variation in stand-off distance, which changed the suction force. Frequency response at 11 Hz corresponds to speed of rotation (650 rpm); response at 22 Hz is a higher harmonic of the 11 Hz response.

Initialize Force and Moment Vectors

```

data := READPRN(lws07)      m := rows(data)      n := cols(data)      m = 2.19*104      n = 10

Fxt := data<1> .4.4482      Fyt := data<2> .4.4482      Fzt := data<3> .4.4482      Convert from lbs to Newtons
τxt := data<4> .1.3558      τyt := data<5> .1.3558      τzt := data<6> .1.3558      Convert from ft-lbs to N-m
    
```

Set up data window

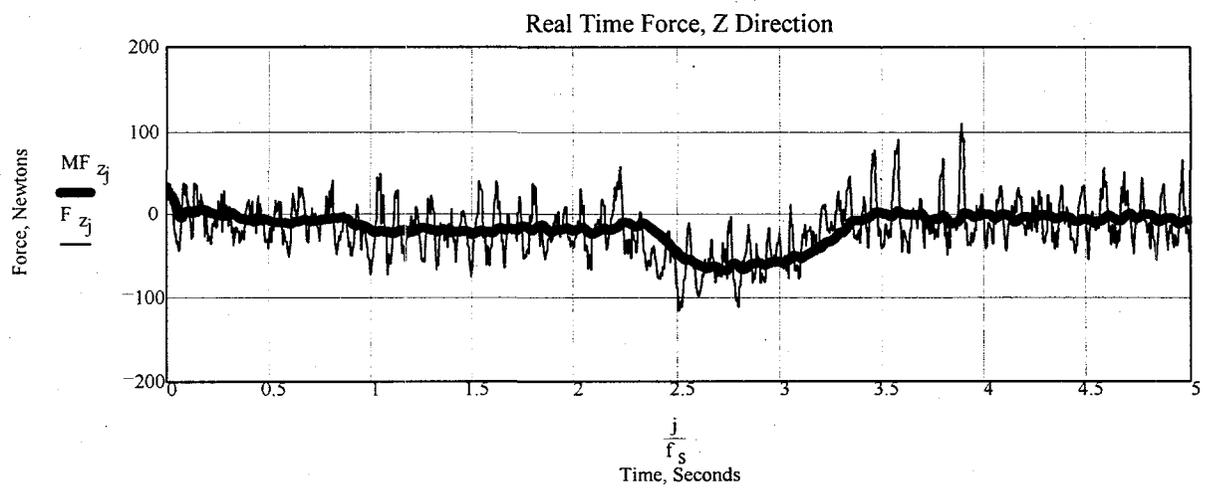
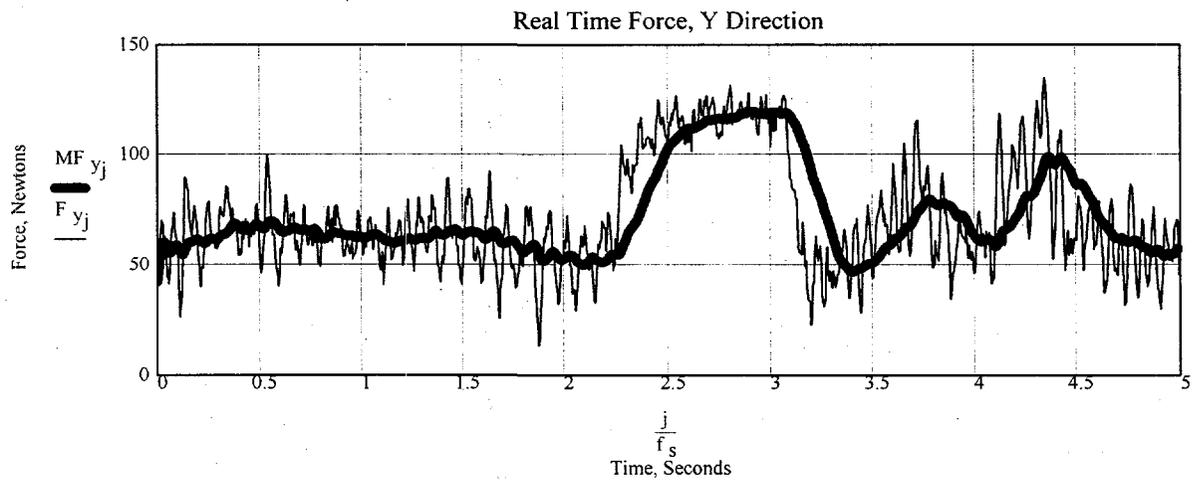
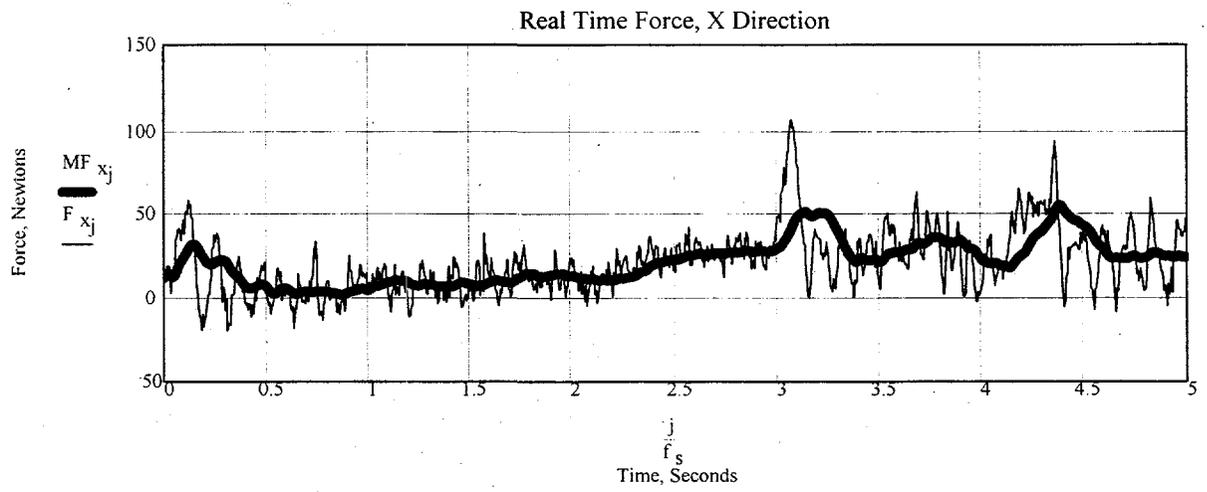
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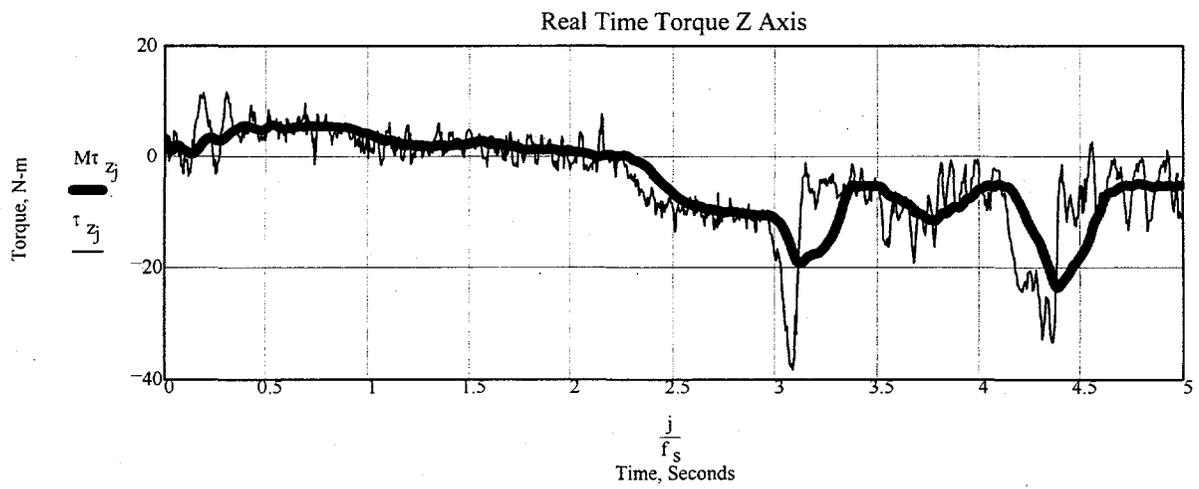
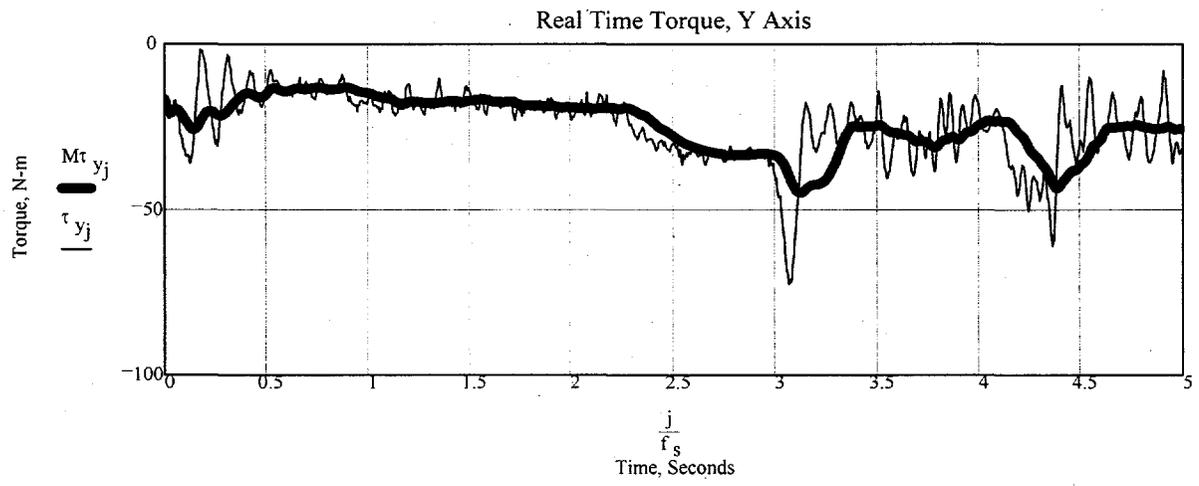
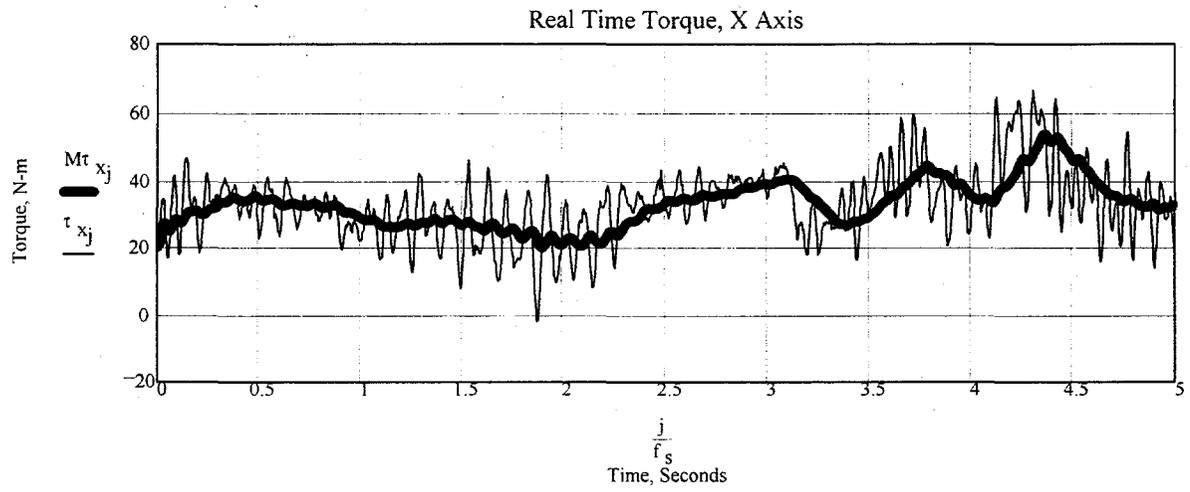
start := 5500      Start row for window
end := 15400      Data row not included at end
count := 210      Note: Count must be some power of two. Count must be greater than Nnew.
count = 1.024*103
N := rows(Fxt) - end      N = 6.5*103
i := start..(N - 1)      j := 0..N - start - 1
fs := 200      Sampling frequency in Hertz
Fxj := Fxtj+start      Fyj := Fytj+start      Fzj := Fztj+start
τxj := τxtj+start      τyj := τytj+start      τzj := τztj+start
Nnew := rows(Fx)      Nnew = 1*103
    
```

C := 50 Define number of points in moving average

```

MFx := movavg(Fx, C)      MFy := movavg(Fy, C)      MFz := movavg(Fz, C)
Mτx := movavg(τx, C)      Mτy := movavg(τy, C)      Mτz := movavg(τz, C)
    
```





Calculate average, max, and min for each data set. Remove the average for FFT analysis

$\max(F_x) = 106.45$	$\min(F_x) = -19.47$	$\text{mean}(F_x) = 21.37$	Newtons
$\max(F_y) = 134.96$	$\min(F_y) = 13.36$	$\text{mean}(F_y) = 72.09$	Newtons
$\max(F_z) = 108.98$	$\min(F_z) = -115.66$	$\text{mean}(F_z) = -17.15$	Newtons
$\max(\tau_x) = 66.79$	$\min(\tau_x) = -1.91$	$\text{mean}(\tau_x) = 33.06$	N-m
$\max(\tau_y) = -1.62$	$\min(\tau_y) = -72.34$	$\text{mean}(\tau_y) = -24.18$	N-m
$\max(\tau_z) = 11.8$	$\min(\tau_z) = -38.26$	$\text{mean}(\tau_z) = -4.1$	N-m

$$F_{x \text{ mean}} := \text{mean}(F_x) \quad F_{y \text{ mean}} := \text{mean}(F_y) \quad F_{z \text{ mean}} := \text{mean}(F_z)$$

$$\tau_{x \text{ mean}} := \text{mean}(\tau_x) \quad \tau_{y \text{ mean}} := \text{mean}(\tau_y) \quad \tau_{z \text{ mean}} := \text{mean}(\tau_z)$$

$$F_x := F_x - F_{x \text{ mean}} \quad F_y := F_y - F_{y \text{ mean}} \quad F_z := F_z - F_{z \text{ mean}}$$

$$\tau_x := \tau_x - \tau_{x \text{ mean}} \quad \tau_y := \tau_y - \tau_{y \text{ mean}} \quad \tau_z := \tau_z - \tau_{z \text{ mean}}$$

Calculate FFT's

$$\text{pad} := 0..[(\text{count} - N_{\text{new}}) - 1]$$

$$\text{padman}_{\text{pad}} := 0$$

$$Fp_x := \text{stack}(F_x, \text{padman})$$

$$Fp_y := \text{stack}(F_y, \text{padman})$$

$$Fp_z := \text{stack}(F_z, \text{padman})$$

$$\tau p_x := \text{stack}(\tau_x, \text{padman})$$

$$\tau p_y := \text{stack}(\tau_y, \text{padman})$$

$$\tau p_z := \text{stack}(\tau_z, \text{padman})$$

$$F_{\text{spec}_x} := \text{fft}(Fp_x)$$

$$F_{\text{spec}_y} := \text{fft}(Fp_y)$$

$$F_{\text{spec}_z} := \text{fft}(Fp_z)$$

$$\tau_{\text{spec}_x} := \text{fft}(\tau p_x)$$

$$\tau_{\text{spec}_y} := \text{fft}(\tau p_y)$$

$$\tau_{\text{spec}_z} := \text{fft}(\tau p_z)$$

$$K := \text{length}(F_{\text{spec}_x})$$

$$F_{\text{spec}_f_x} := \frac{F_{\text{spec}_x}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$F_{\text{spec}_f_y} := \frac{F_{\text{spec}_y}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$F_{\text{spec}_f_z} := \frac{F_{\text{spec}_z}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

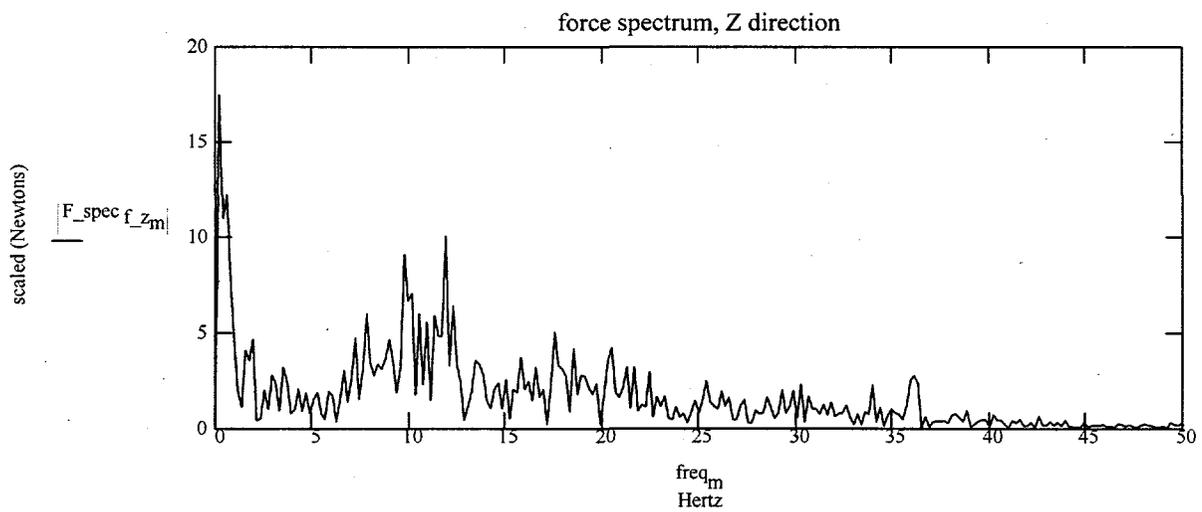
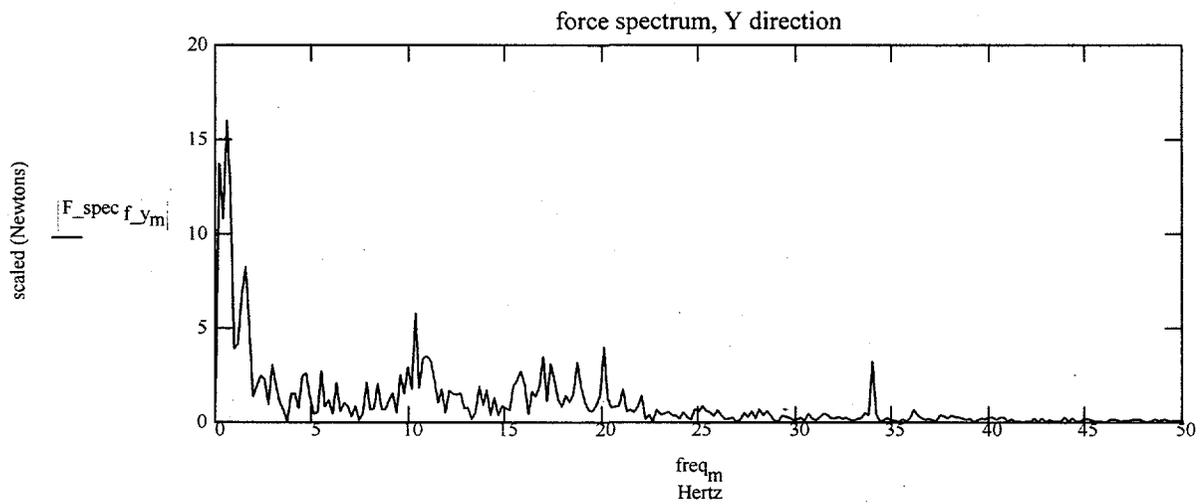
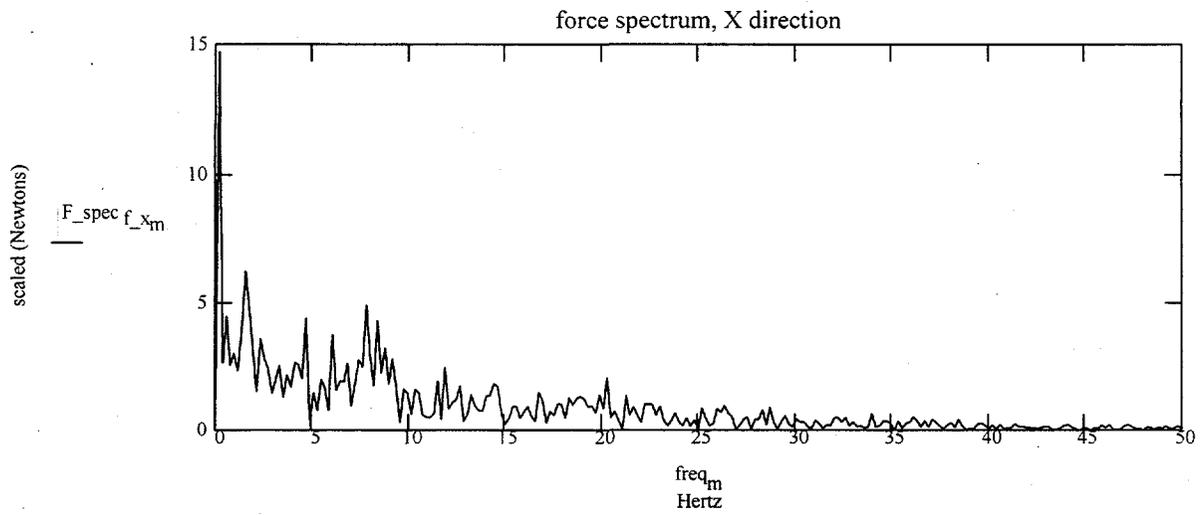
$$\tau_{\text{spec}_f_x} := \frac{\tau_{\text{spec}_x}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

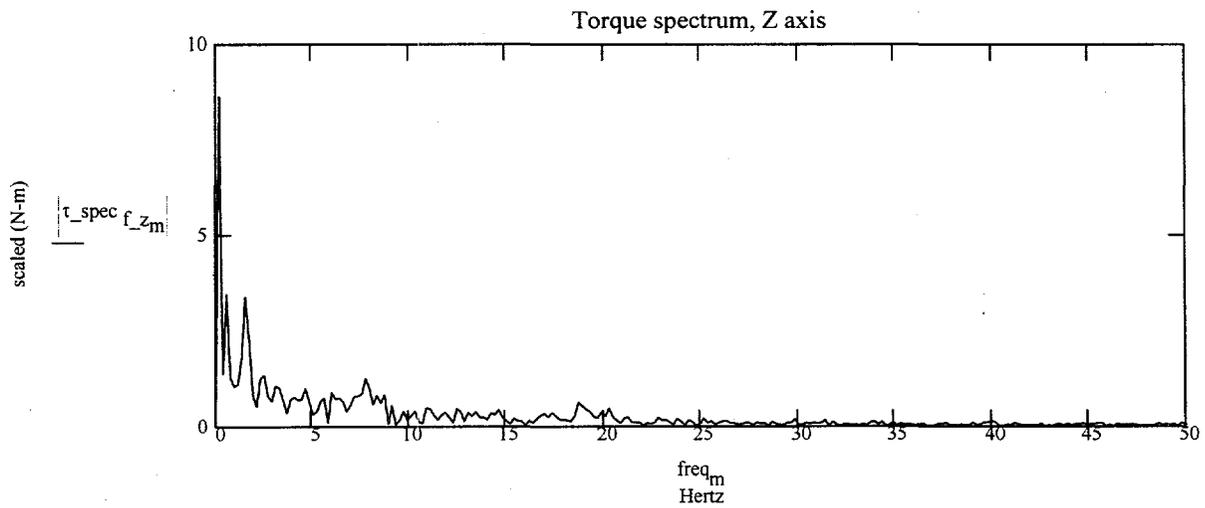
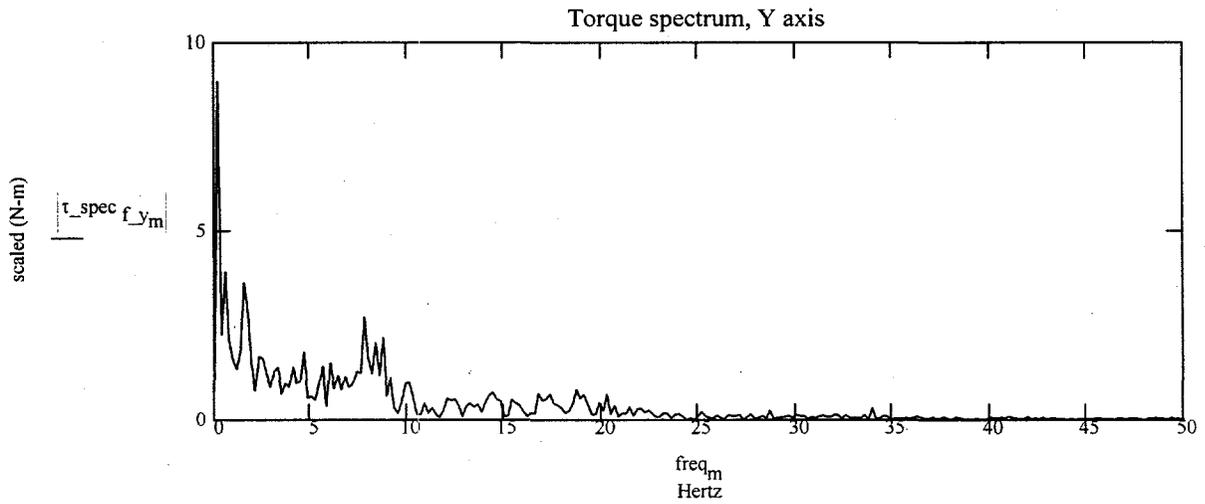
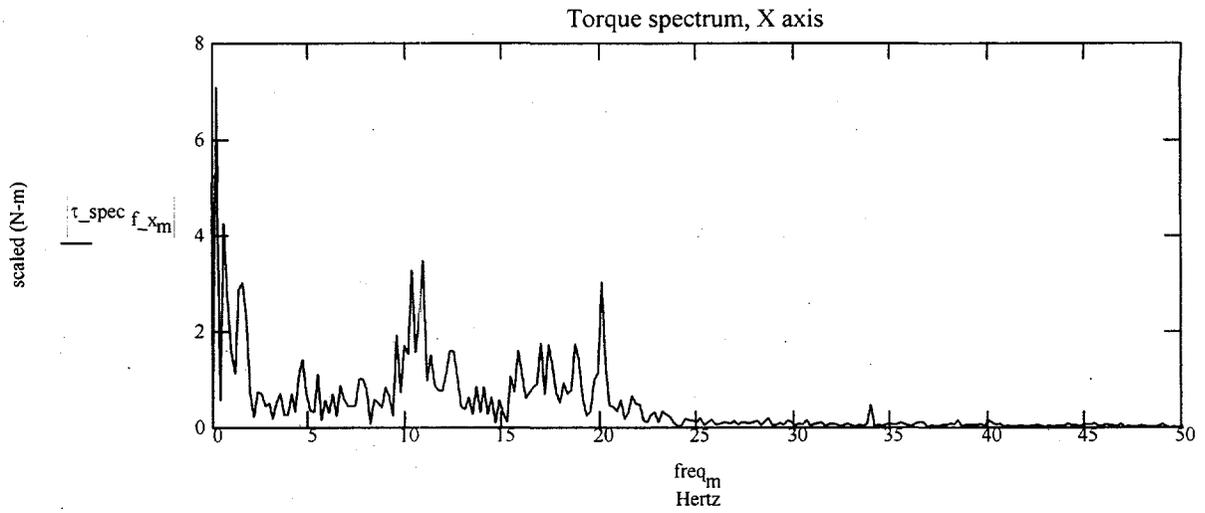
$$\tau_{\text{spec}_f_y} := \frac{\tau_{\text{spec}_y}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$\tau_{\text{spec}_f_z} := \frac{\tau_{\text{spec}_z}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$m := 0..(K - 1)$$

$$\text{freq}_m := m \cdot f_s \cdot \frac{1}{\text{count}}$$





LWS Frequency Analysis - Sludge Retrieval

Operating Conditions

End Effector	Light Weight Scarifier	
Sampling Frequency:	200	Hz
Simulant Type	Sludge	
Traverse Speed	12.7	cm/sec
Rotational Speed	762	RPM
Stand-off Distance	0-2.5	cm
Water Jet Pressure	8.3	MPa
Water Jet Flow	10.7	liters/min
Cutting Nozzle Size	1.14	mm

Summary of Results: Reaction forces were less than 160 Newtons. Real-time force variations possibly caused by variation in stand-off distance, which changed the suction force. Frequency response at 13 Hz corresponds to speed of rotation (762 rpm).

Initialize Force and Moment Vectors

```

data := READPRN(lws17)      m := rows(data)      n := cols(data)      m = 7.0735*104 n = 10
Fxt := data<1> .4.4482      Fyt := data<2> .4.4482      Fzt := data<3> .4.4482      Convert from lbs to Newtons
τxt := data<4> .1.3558      τyt := data<5> .1.3558      τzt := data<6> .1.3558      Convert from ft-lbs to N-m
  
```

Set up data window

```

start := 8000      Start row for window
end := 61735      Data row not included at end
count := 210      Note: Count must be some power of two. Count must be greater than Nnew.
count = 1.024*103
  
```

```

N := rows(Fxt) - end      N = 9*103
  
```

```

i := start..(N - 1)      j := 0..N - start - 1
  
```

```

fs := 200      Sampling frequency in Hertz
  
```

```

Fxj := Fxtj+start      Fyj := Fyjtj+start      Fzj := Fzjtj+start
  
```

```

τxj := τxtj+start      τyj := τyjtj+start      τzj := τzjtj+start
  
```

```

Nnew := rows(Fx)      Nnew = 1*103
  
```

```

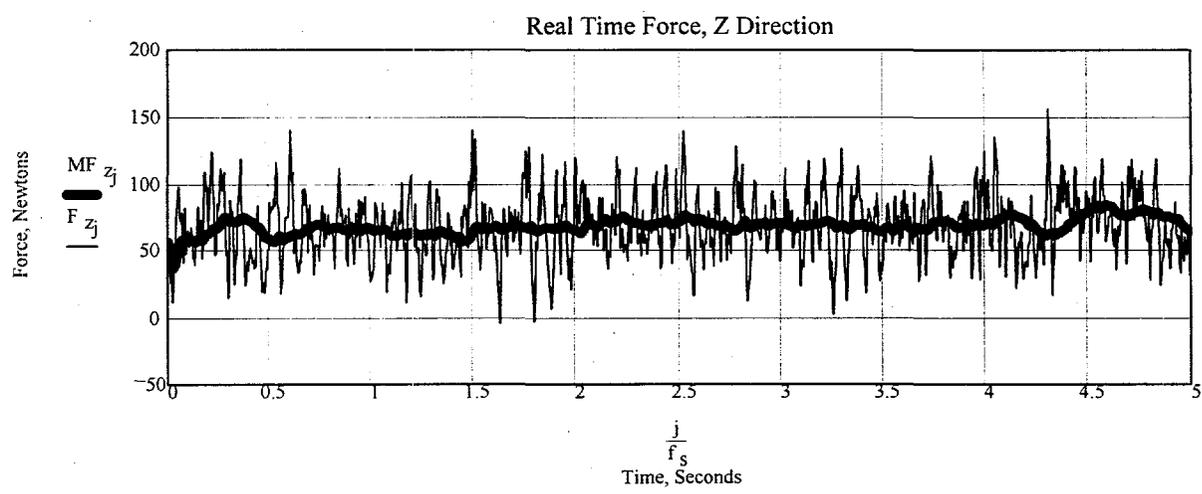
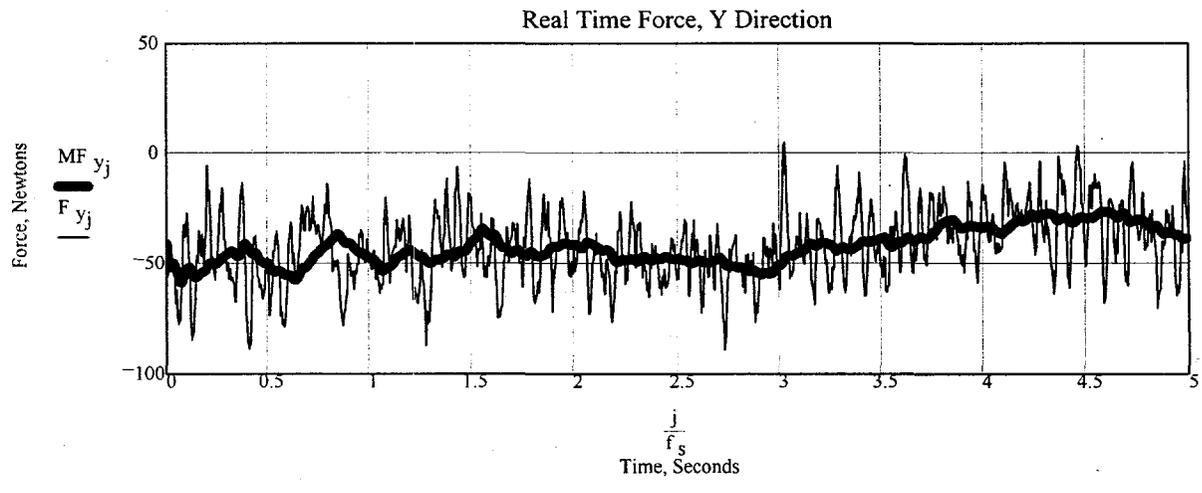
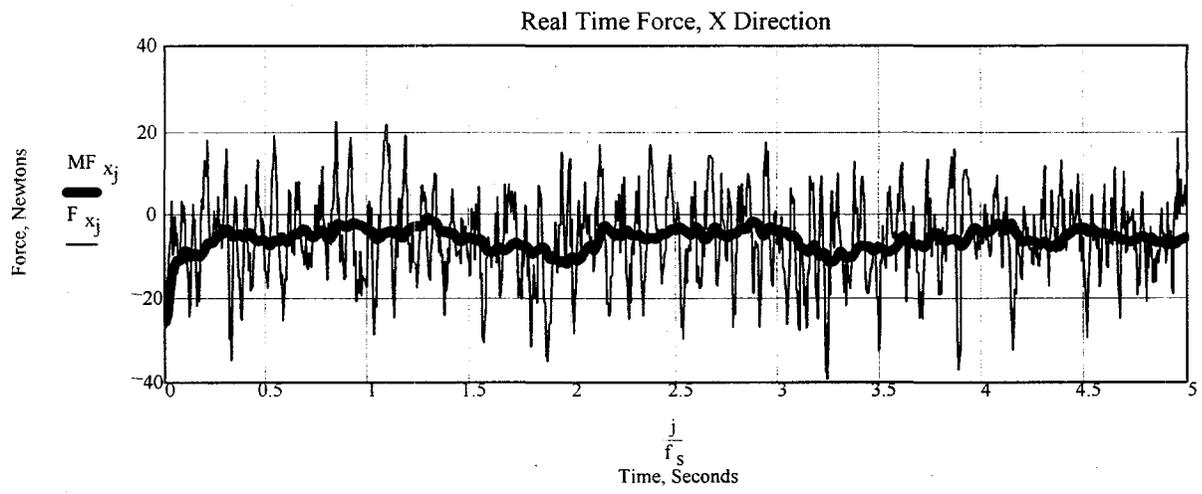
C := 50      Define number of points in moving average
  
```

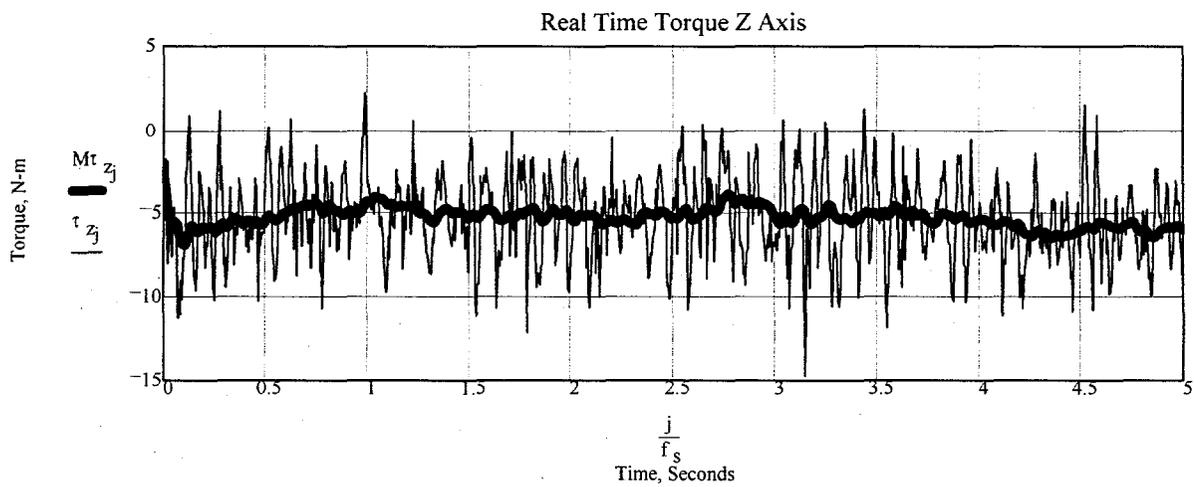
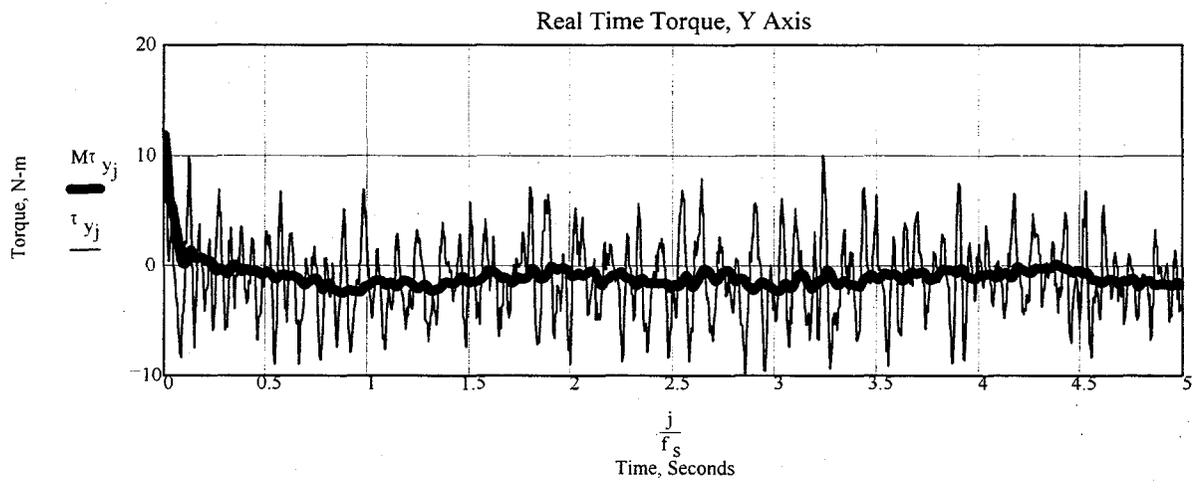
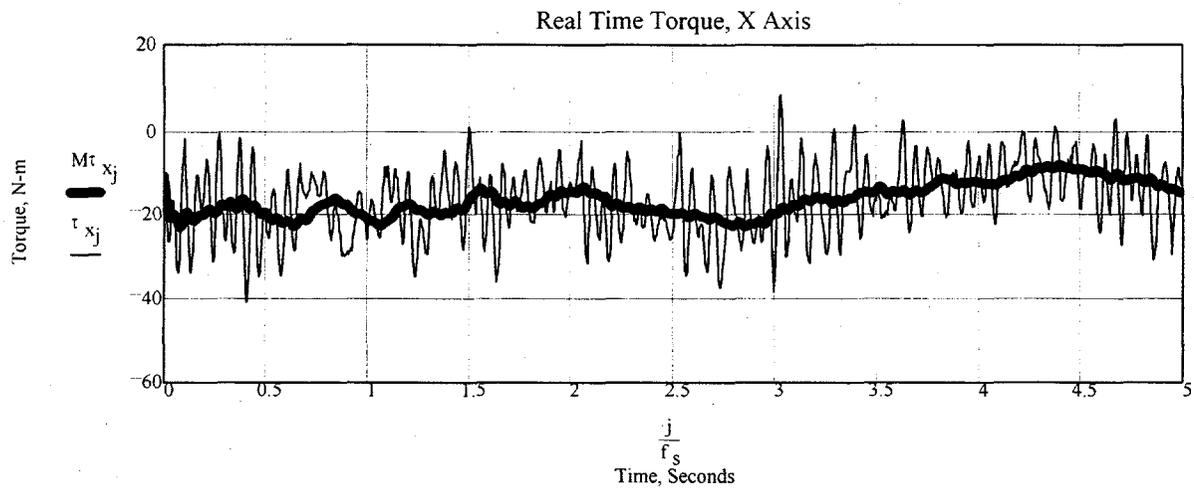
```

MFx := movavg(Fx, C)      MFy := movavg(Fy, C)      MFz := movavg(Fz, C)
  
```

```

Mτx := movavg(τx, C)      Mτy := movavg(τy, C)      Mτz := movavg(τz, C)
  
```





Calculate average, max, and min for each data set. Remove the average for FFT analysis

$\max(F_x) = 22.24$	$\min(F_x) = -39.26$	$\text{mean}(F_x) = -5.65$	Newtons
$\max(F_y) = 5.05$	$\min(F_y) = -89.02$	$\text{mean}(F_y) = -42.12$	Newtons
$\max(F_z) = 155.89$	$\min(F_z) = -4.48$	$\text{mean}(F_z) = 67.83$	Newtons
$\max(\tau_x) = 8.45$	$\min(\tau_x) = -40.77$	$\text{mean}(\tau_x) = -16.27$	N-m
$\max(\tau_y) = 12.07$	$\min(\tau_y) = -9.9$	$\text{mean}(\tau_y) = -1.1$	N-m
$\max(\tau_z) = 2.22$	$\min(\tau_z) = -14.72$	$\text{mean}(\tau_z) = -5.26$	N-m

$$F_{x_mean} := \text{mean}(F_x) \quad F_{y_mean} := \text{mean}(F_y) \quad F_{z_mean} := \text{mean}(F_z)$$

$$\tau_{x_mean} := \text{mean}(\tau_x) \quad \tau_{y_mean} := \text{mean}(\tau_y) \quad \tau_{z_mean} := \text{mean}(\tau_z)$$

$$F_x := F_x - F_{x_mean} \quad F_y := F_y - F_{y_mean} \quad F_z := F_z - F_{z_mean}$$

$$\tau_x := \tau_x - \tau_{x_mean} \quad \tau_y := \tau_y - \tau_{y_mean} \quad \tau_z := \tau_z - \tau_{z_mean}$$

Calculate FFT's

$$\text{pad} := 0..[(\text{count} - N_{\text{new}}) - 1]$$

$$\text{padman}_{\text{pad}} := 0$$

$$Fp_x := \text{stack}(F_x, \text{padman}) \quad Fp_y := \text{stack}(F_y, \text{padman}) \quad Fp_z := \text{stack}(F_z, \text{padman})$$

$$\tau p_x := \text{stack}(\tau_x, \text{padman}) \quad \tau p_y := \text{stack}(\tau_y, \text{padman}) \quad \tau p_z := \text{stack}(\tau_z, \text{padman})$$

$$F_spec_x := \text{fft}(Fp_x) \quad F_spec_y := \text{fft}(Fp_y) \quad F_spec_z := \text{fft}(Fp_z)$$

$$\tau_spec_x := \text{fft}(\tau p_x) \quad \tau_spec_y := \text{fft}(\tau p_y) \quad \tau_spec_z := \text{fft}(\tau p_z)$$

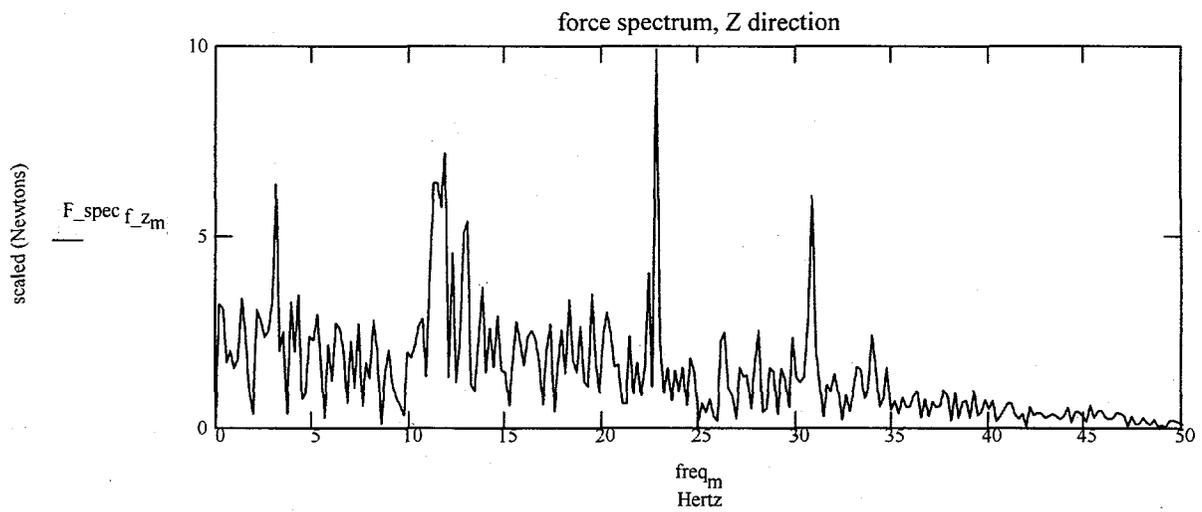
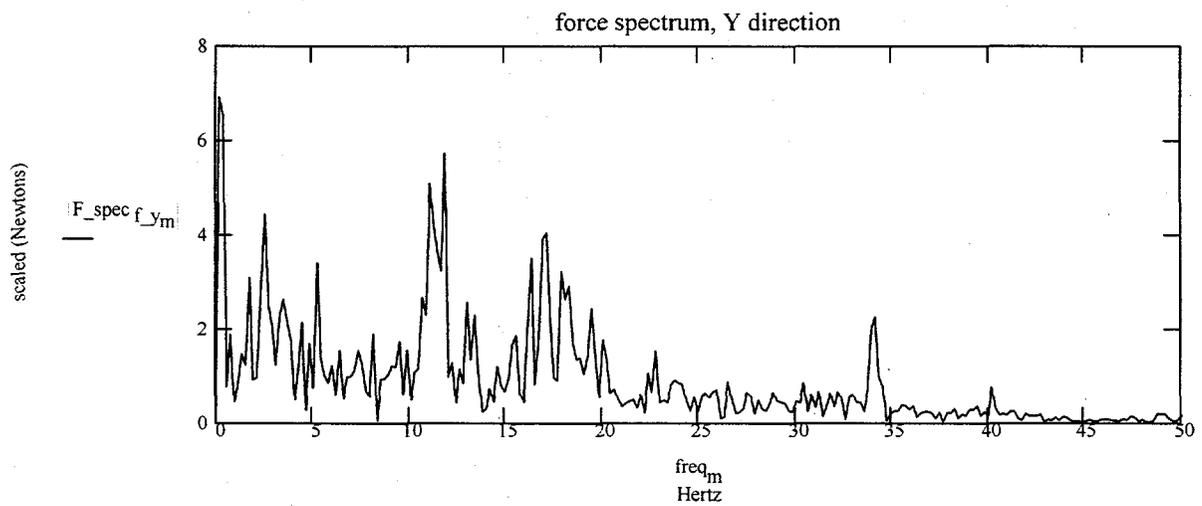
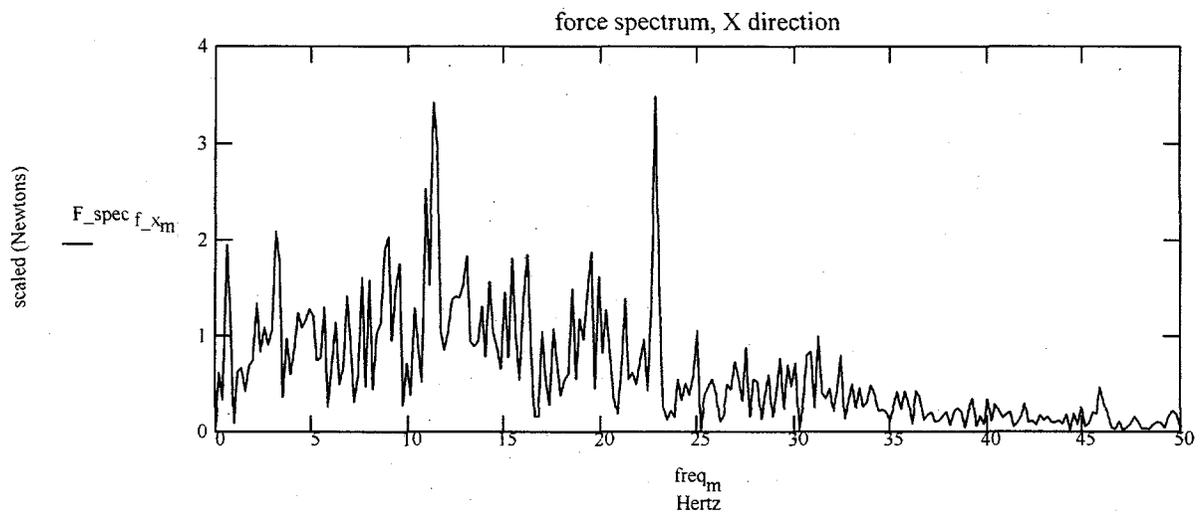
$$K := \text{length}(F_spec_x)$$

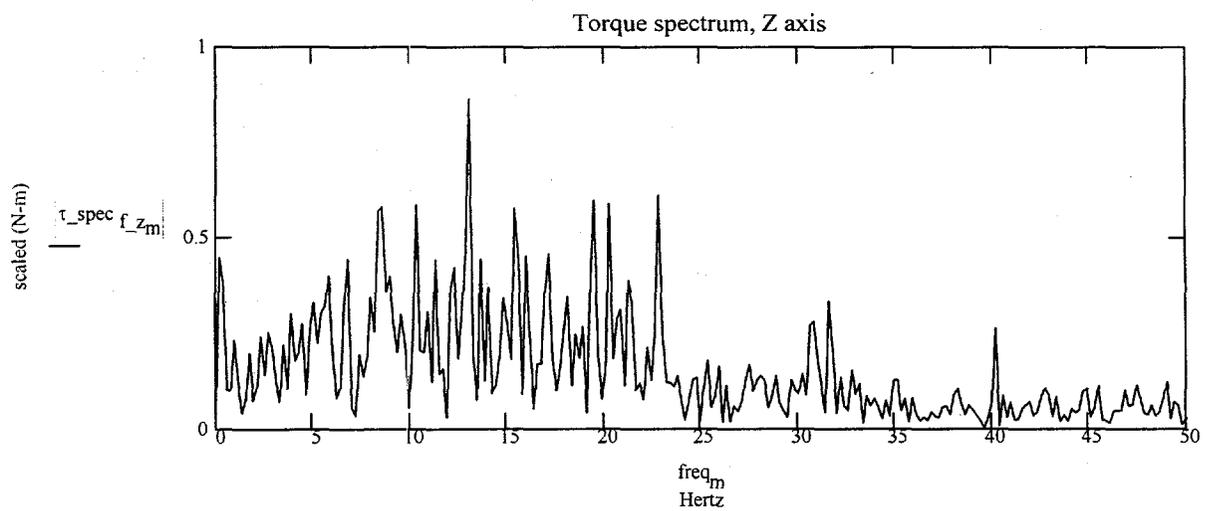
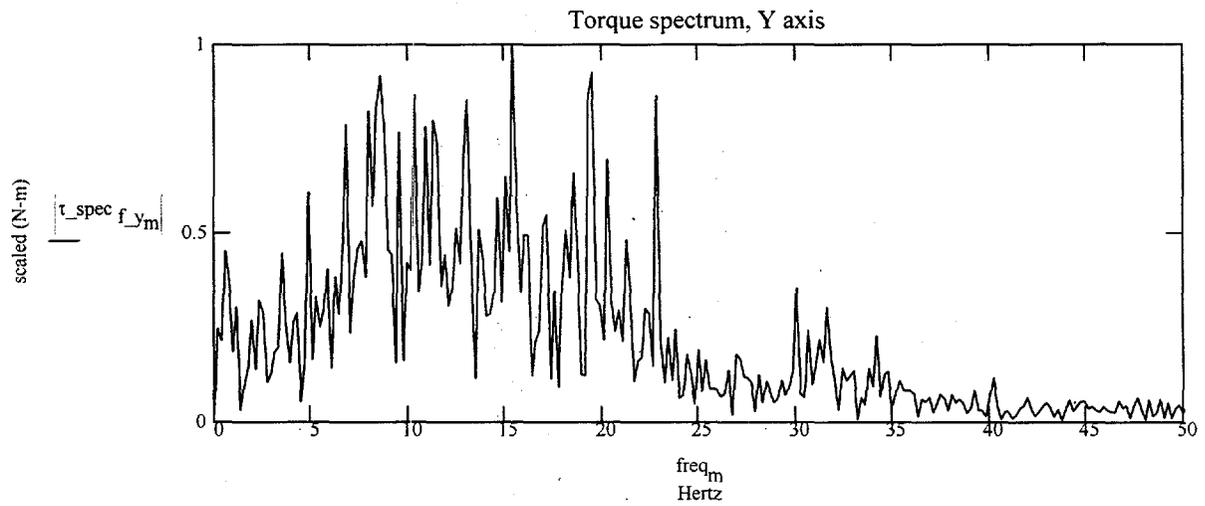
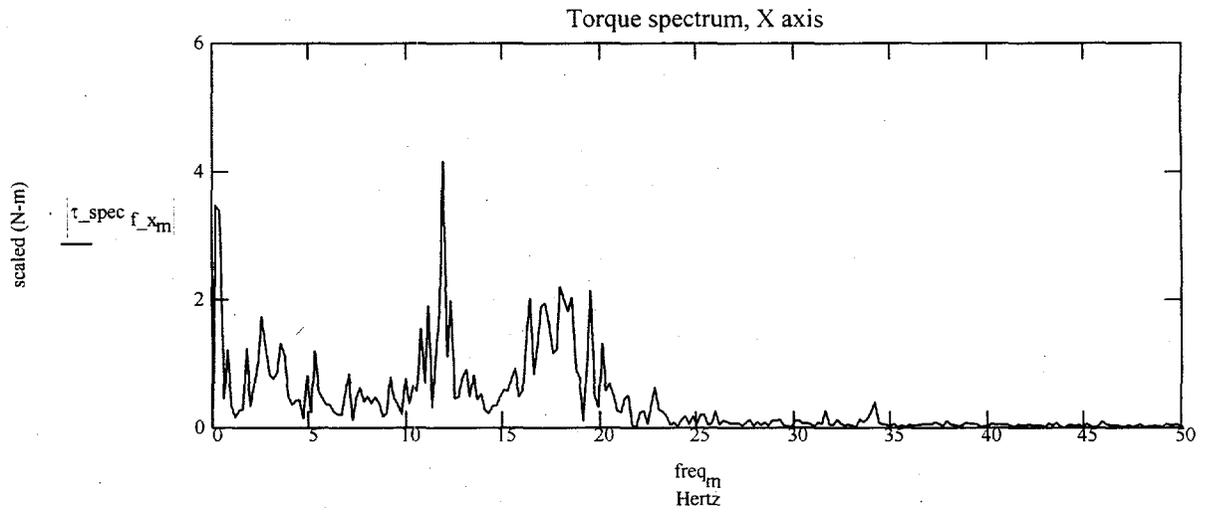
$$F_spec_f_x := \frac{F_spec_x}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad F_spec_f_y := \frac{F_spec_y}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad F_spec_f_z := \frac{F_spec_z}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$\tau_spec_f_x := \frac{\tau_spec_x}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad \tau_spec_f_y := \frac{\tau_spec_y}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad \tau_spec_f_z := \frac{\tau_spec_z}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$m := 0..(K - 1)$$

$$\text{freq}_m := m \cdot f_s \cdot \frac{1}{\text{count}}$$





LWS Frequency Analysis - Hard Pan Retrieval

Operating Conditions

End Effector	Light Weight Scarifier	
Sampling Frequency:	200	Hz
Simulant Type	Hardpan #2	
Traverse Speed	12.7	cm/sec
Rotational Speed	762	RPM
Stand-off Distance	0-2.5	cm
Water Jet Pressure	21.0	MPa
Water Jet Flow	16.4	liters/min
Cutting Nozzle Size	1.14	mm

Summary of Results: Reaction forces were less than 275 Newtons. Real-time force variations possibly caused by variation in stand-off distance, which changed the suction force. Frequency response at 13 Hz corresponds to speed of rotation (762 rpm).

Initialize Force and Moment Vectors

```

data := READPRN(1ws23)      m := rows(data)      n := cols(data)      m = 1.621*104  n = 10
Fxt := data<1> .4.4482      Fyt := data<2> .4.4482      Fzt := data<3> .4.4482      Convert from lbs to Newtons
τxt := data<4> .1.3558      τyt := data<5> .1.3558      τzt := data<6> .1.3558      Convert from ft-lbs to N-m
    
```

Set up data window

```

start := 2000      Start row for window
end := 13210      Data row not included at end
count := 210      Note: Count must be some power of two. Count must be greater than Nnew.
count = 1.024*103
    
```

```

N := rows(Fxt) - end      N = 3*103
    
```

```

i := start..(N - 1)      j := 0..N - start - 1
    
```

```

fs := 200      Sampling frequency in Hertz
    
```

```

Fxj := Fxtj+start      Fyj := Fytj+start      Fzj := Fztj+start
    
```

```

τxj := τxtj+start      τyj := τytj+start      τzj := τztj+start
    
```

```

Nnew := rows(Fx)      Nnew = 1*103
    
```

```

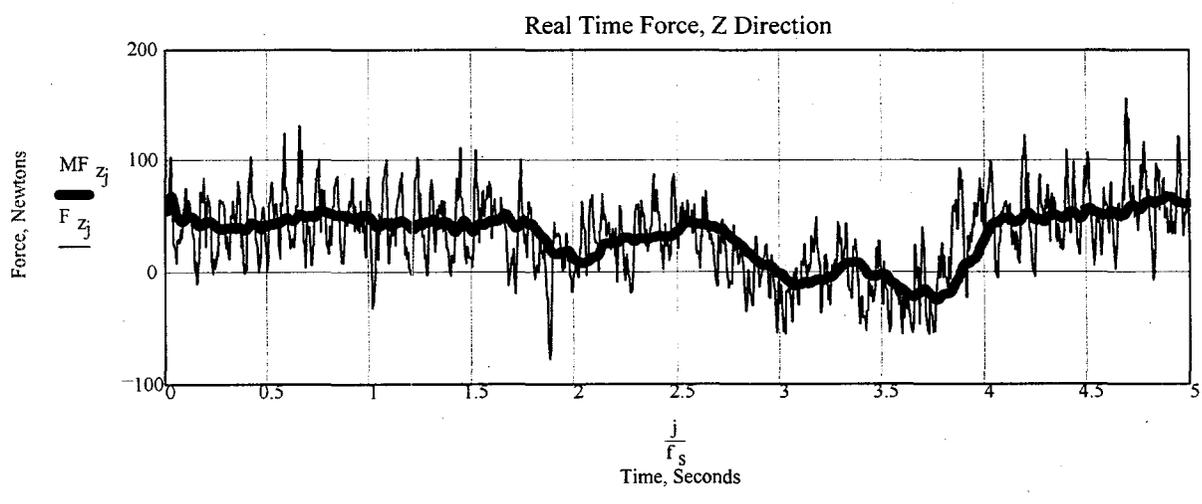
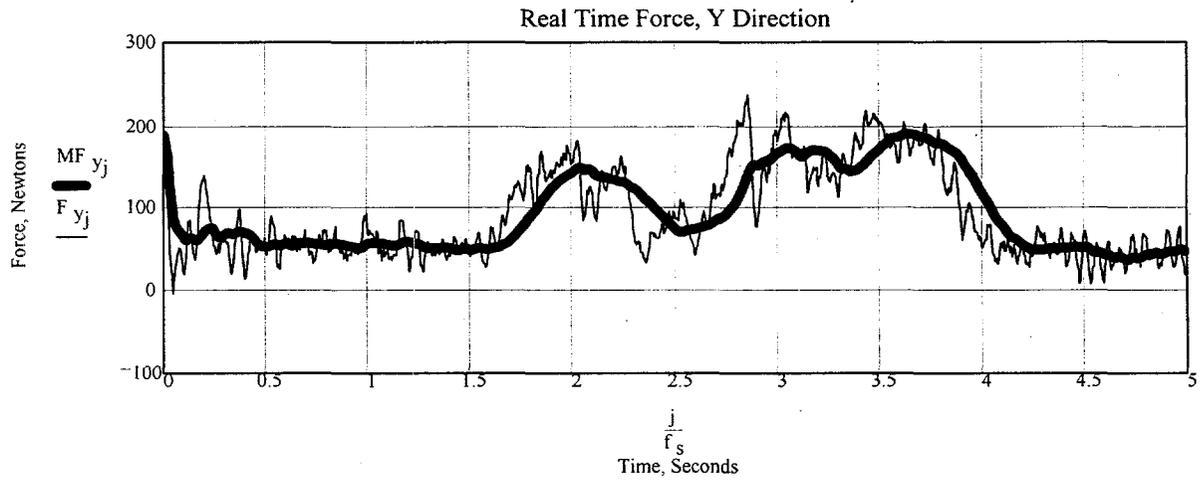
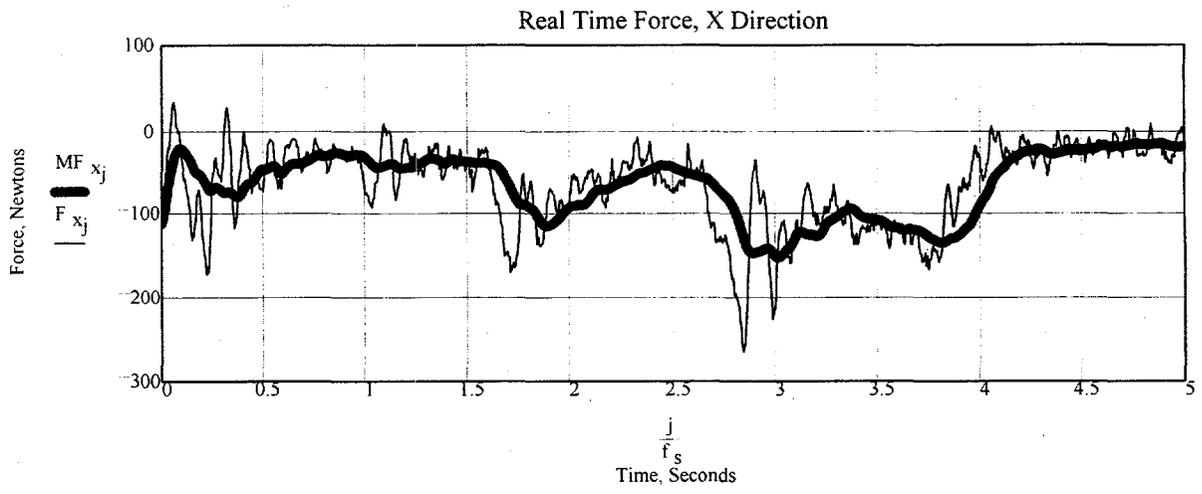
C := 50      Define number of points in moving average
    
```

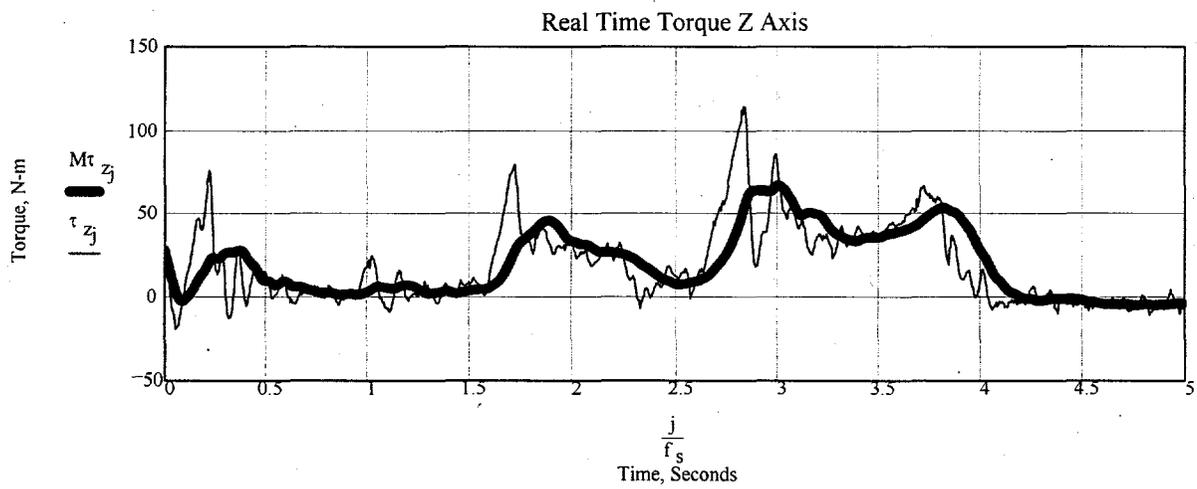
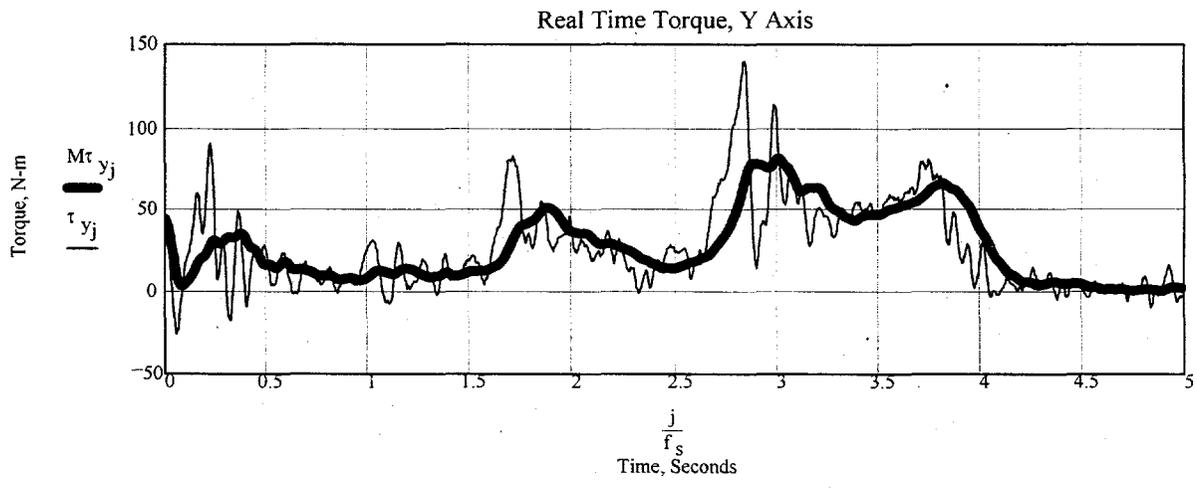
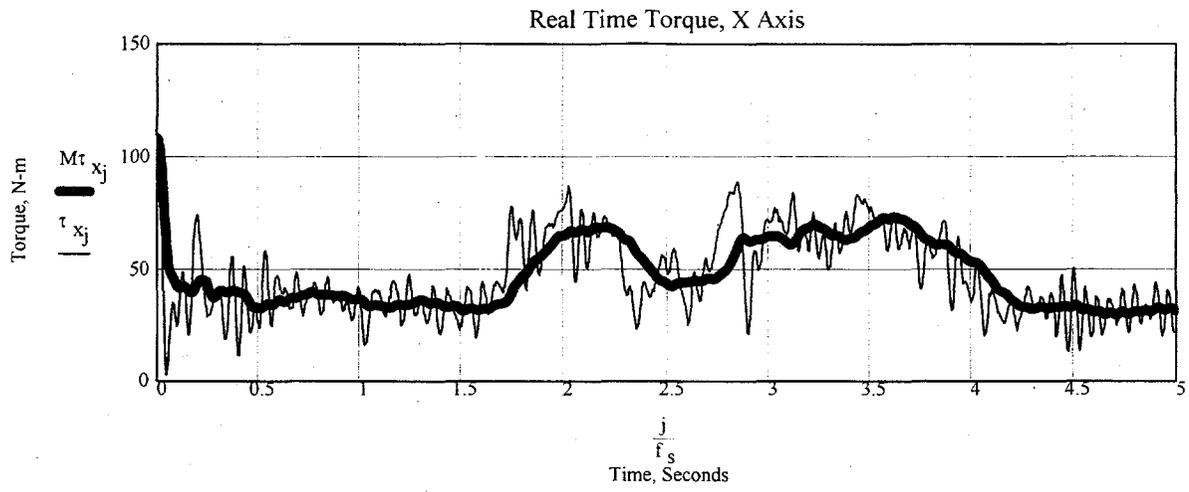
```

MFx := movavg(Fx, C)      MFy := movavg(Fy, C)      MFz := movavg(Fz, C)
    
```

```

Mτx := movavg(τx, C)      Mτy := movavg(τy, C)      Mτz := movavg(τz, C)
    
```





Calculate average, max, and min for each data set. Remove the average for FFT analysis

$$\max(F_x) = 32.82 \quad \min(F_x) = -264.71 \quad \text{mean}(F_x) = -64.95 \quad \text{Newtons}$$

$$\max(F_y) = 236.69 \quad \min(F_y) = -3.83 \quad \text{mean}(F_y) = 92.42 \quad \text{Newtons}$$

$$\max(F_z) = 156.71 \quad \min(F_z) = -77.78 \quad \text{mean}(F_z) = 32.35 \quad \text{Newtons}$$

$$\max(\tau_x) = 108.52 \quad \min(\tau_x) = 2.92 \quad \text{mean}(\tau_x) = 47.02 \quad \text{N-m}$$

$$\max(\tau_y) = 139.92 \quad \min(\tau_y) = -26.41 \quad \text{mean}(\tau_y) = 26.82 \quad \text{N-m}$$

$$\max(\tau_z) = 114.17 \quad \min(\tau_z) = -19.24 \quad \text{mean}(\tau_z) = 19.25 \quad \text{N-m}$$

$$F_{x_mean} := \text{mean}(F_x) \quad F_{y_mean} := \text{mean}(F_y) \quad F_{z_mean} := \text{mean}(F_z)$$

$$\tau_{x_mean} := \text{mean}(\tau_x) \quad \tau_{y_mean} := \text{mean}(\tau_y) \quad \tau_{z_mean} := \text{mean}(\tau_z)$$

$$F_x := F_x - F_{x_mean} \quad F_y := F_y - F_{y_mean} \quad F_z := F_z - F_{z_mean}$$

$$\tau_x := \tau_x - \tau_{x_mean} \quad \tau_y := \tau_y - \tau_{y_mean} \quad \tau_z := \tau_z - \tau_{z_mean}$$

Calculate FFT's

$$\text{pad} := 0..[(\text{count} - N_{\text{new}}) - 1]$$

$$\text{padman}_{\text{pad}} := 0$$

$$Fp_x := \text{stack}(F_x, \text{padman}) \quad Fp_y := \text{stack}(F_y, \text{padman}) \quad Fp_z := \text{stack}(F_z, \text{padman})$$

$$\tau p_x := \text{stack}(\tau_x, \text{padman}) \quad \tau p_y := \text{stack}(\tau_y, \text{padman}) \quad \tau p_z := \text{stack}(\tau_z, \text{padman})$$

$$F_spec_x := \text{fft}(Fp_x) \quad F_spec_y := \text{fft}(Fp_y) \quad F_spec_z := \text{fft}(Fp_z)$$

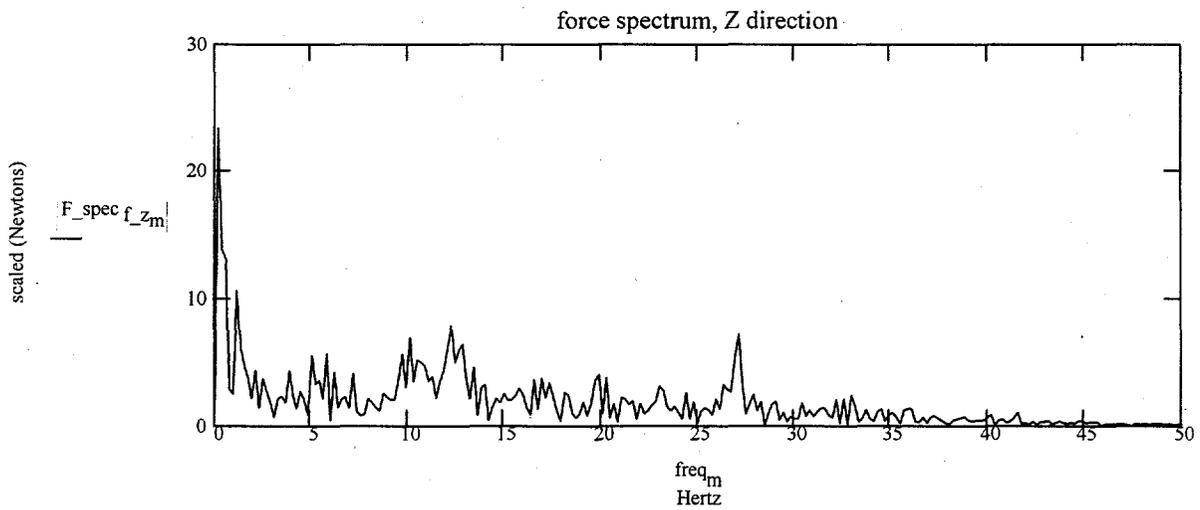
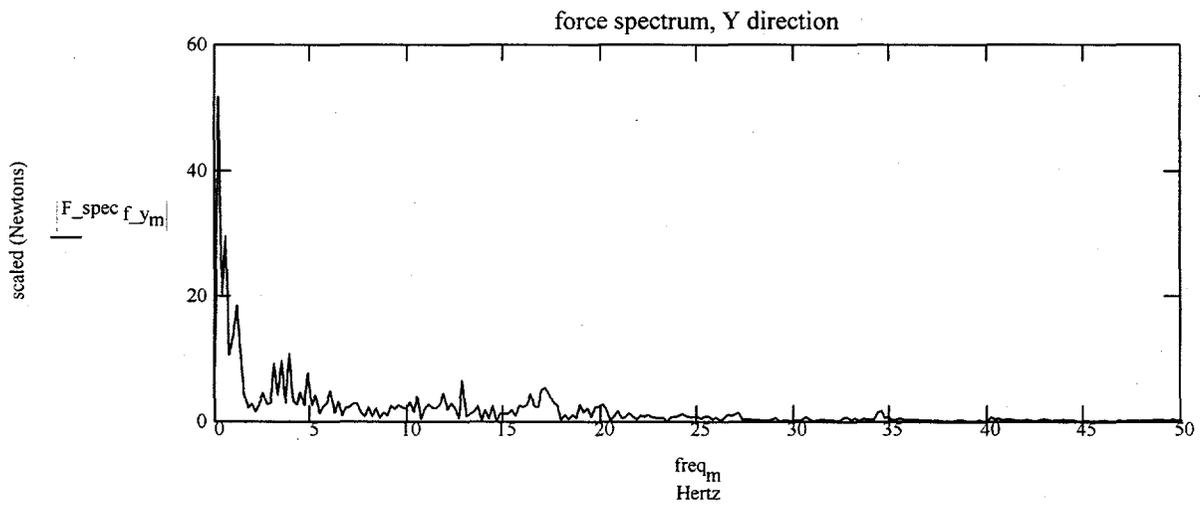
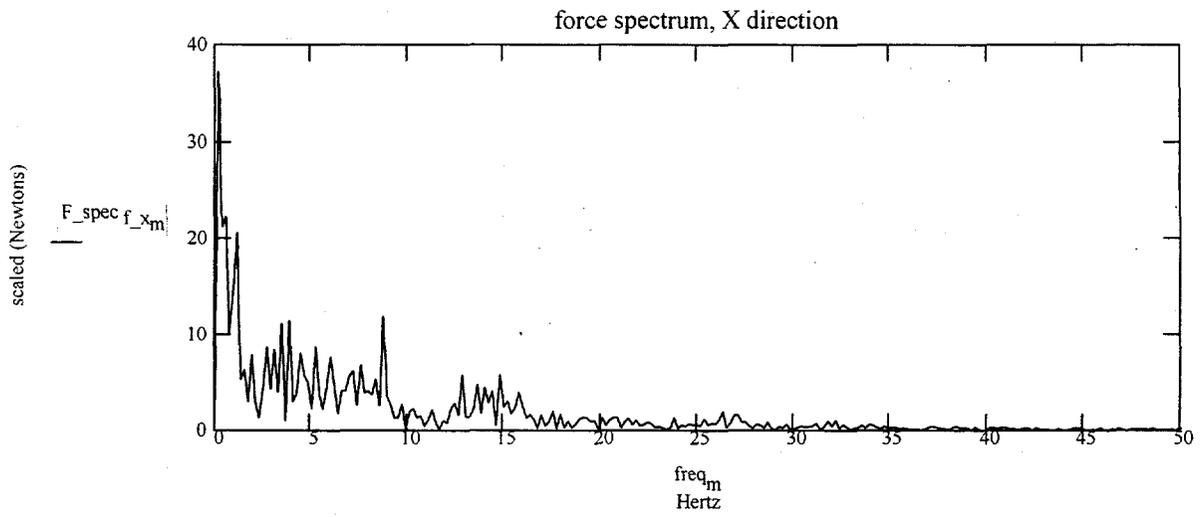
$$\tau_spec_x := \text{fft}(\tau p_x) \quad \tau_spec_y := \text{fft}(\tau p_y) \quad \tau_spec_z := \text{fft}(\tau p_z)$$

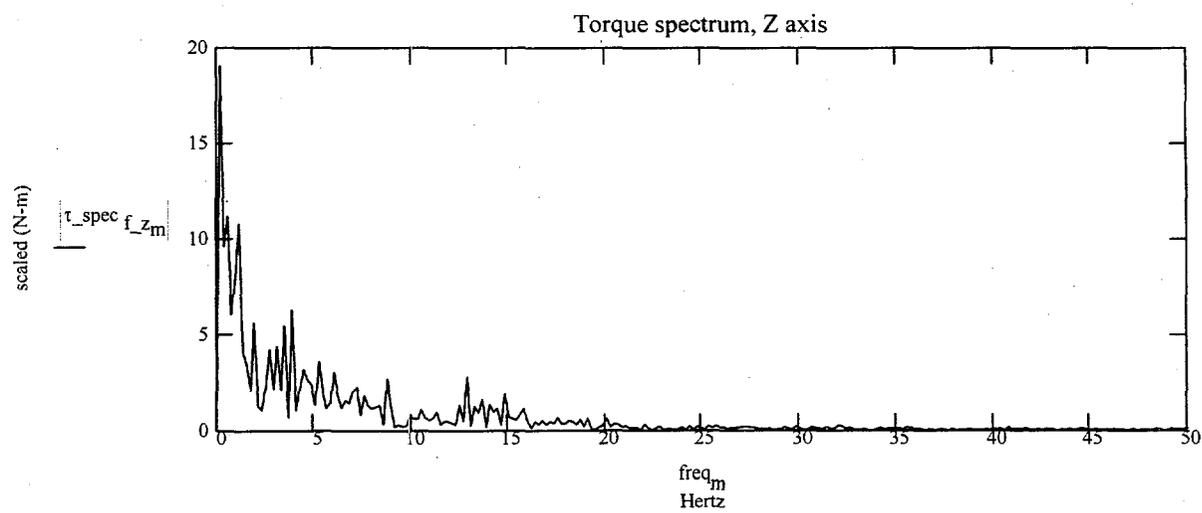
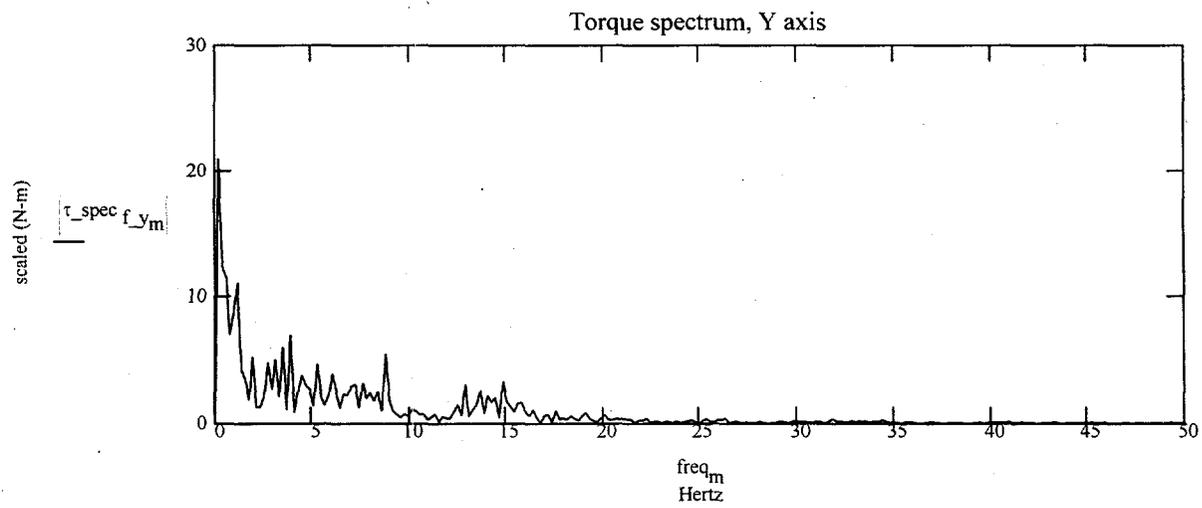
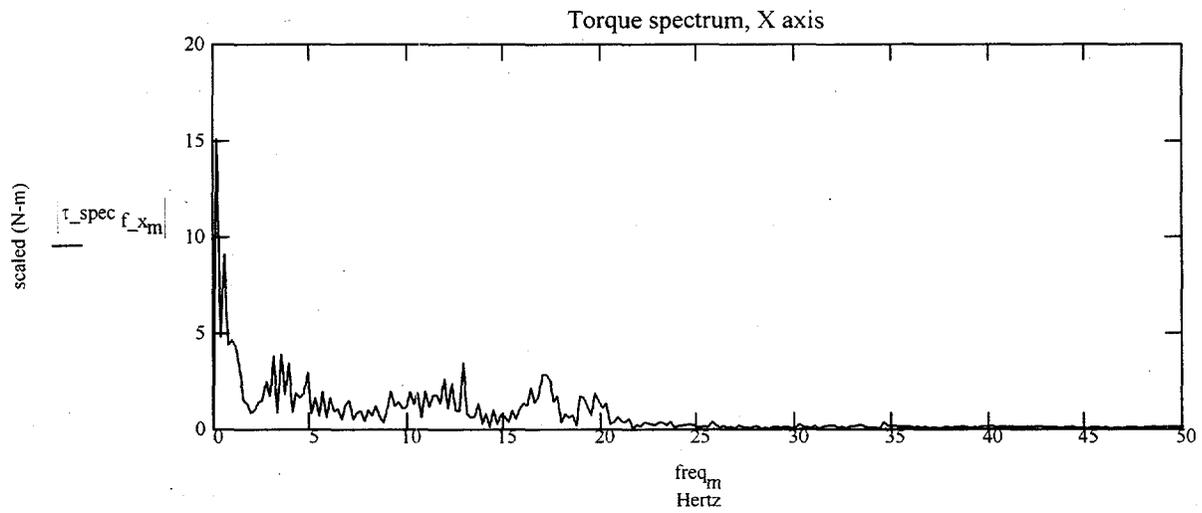
$$K := \text{length}(F_spec_x)$$

$$F_spec_f_x := \frac{F_spec_x}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad F_spec_f_y := \frac{F_spec_y}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad F_spec_f_z := \frac{F_spec_z}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$\tau_spec_f_x := \frac{\tau_spec_x}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad \tau_spec_f_y := \frac{\tau_spec_y}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad \tau_spec_f_z := \frac{\tau_spec_z}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$m := 0..(K - 1) \quad \text{freq}_m := m \cdot f_s \cdot \frac{1}{\text{count}}$$





LWS Frequency Analysis - Saltcake Retrieval

Operating Conditions

End Effector	Light Weight Scarifier	
Sampling Frequency:	200	Hz
Simulant Type	Saltcake #2	
Traverse Speed	12.7	cm/sec
Rotational Speed	762	RPM
Stand-off Distance	0-2.5	cm
Water Jet Pressure	54.8	MPa
Water Jet Flow	26.9	liters/min
Cutting Nozzle Size	1.14	mm

Summary of Results: Reaction forces were less than 275 Newtons. Real-time force variations possibly caused by variation in stand-off distance, which changed the suction force. Frequency response at 13 Hz corresponds to speed of rotation (762 rpm).

Initialize Force and Moment Vectors

```

data := READPRN(1ws29)      m := rows(data)      n := cols(data)      m = 1.8075*104 n = 10
Fxt := data<1> .4.4482      Fyt := data<2> .4.4482      Fzt := data<3> .4.4482      Convert from lbs to Newtons
τxt := data<4> .1.3558      τyt := data<5> .1.3558      τzt := data<6> .1.3558      Convert from ft-lbs to N-m
  
```

Set up data window

```

start := 1000      Start row for window
end := 16075      Data row not included at end
count := 210      Note: Count must be some power of two. Count must be greater than Nnew.
count = 1.024*103
  
```

```

N := rows(Fxt) - end      N = 2*103
  
```

```

i := start..(N-1)      j := 0..N-start-1
  
```

```

fs := 200      Sampling frequency in Hertz
  
```

```

Fxj := Fxtj+start      Fyj := Fytj+start      Fzj := Fztj+start
  
```

```

τxj := τxtj+start      τyj := τytj+start      τzj := τztj+start
  
```

```

Nnew := rows(Fx)      Nnew = 1*103
  
```

```

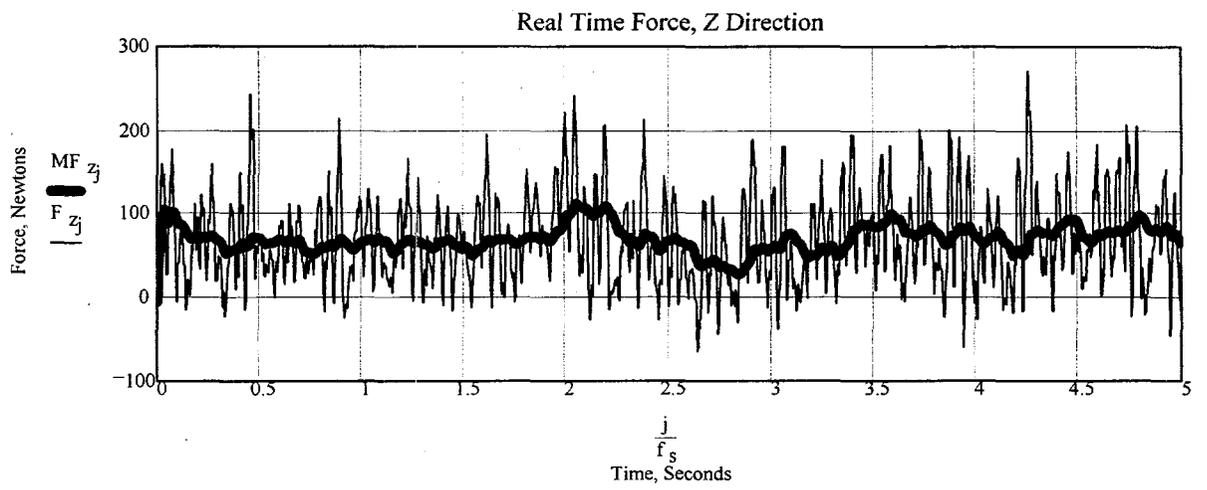
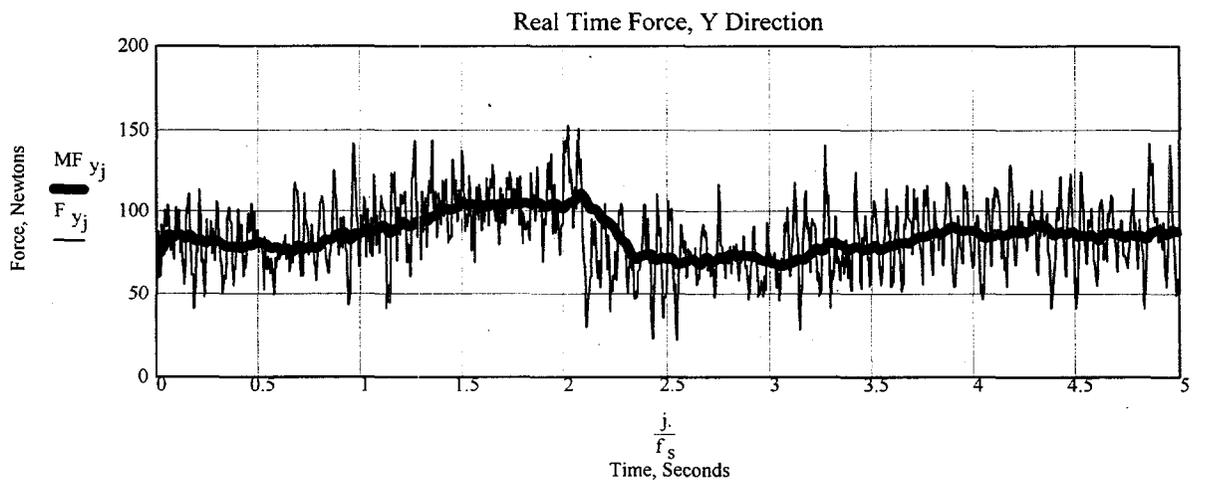
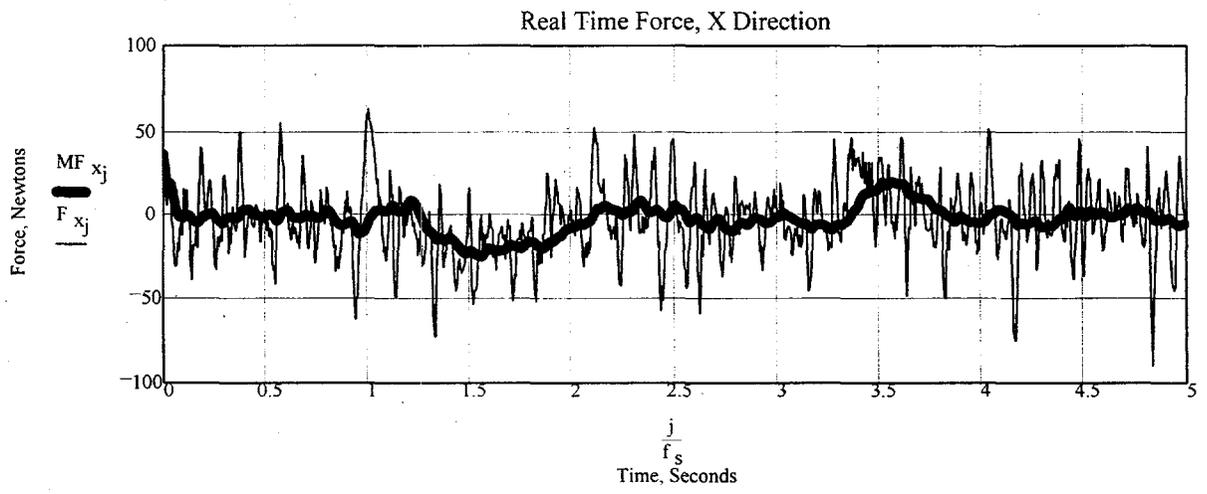
C := 50      Define number of points in moving average
  
```

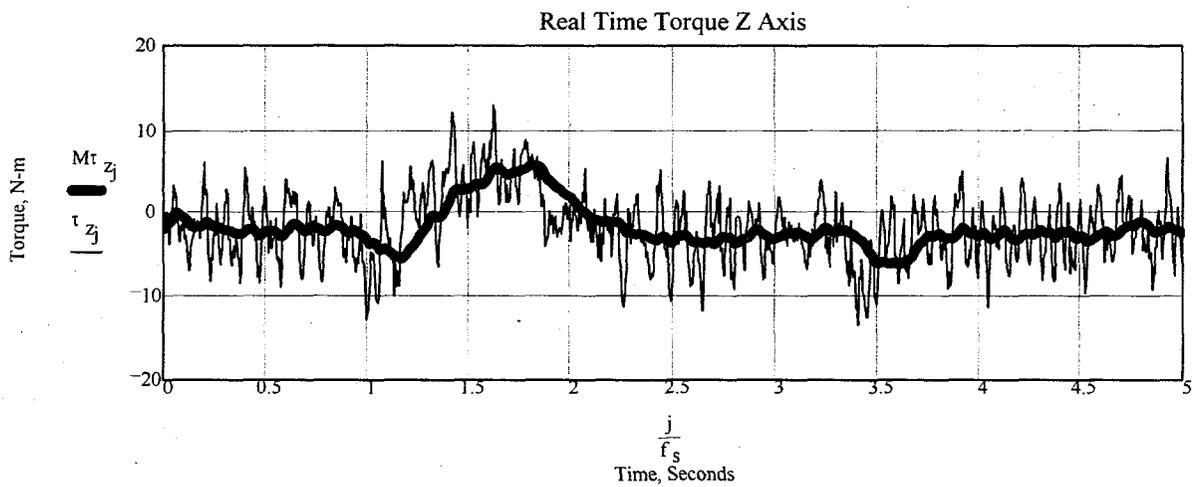
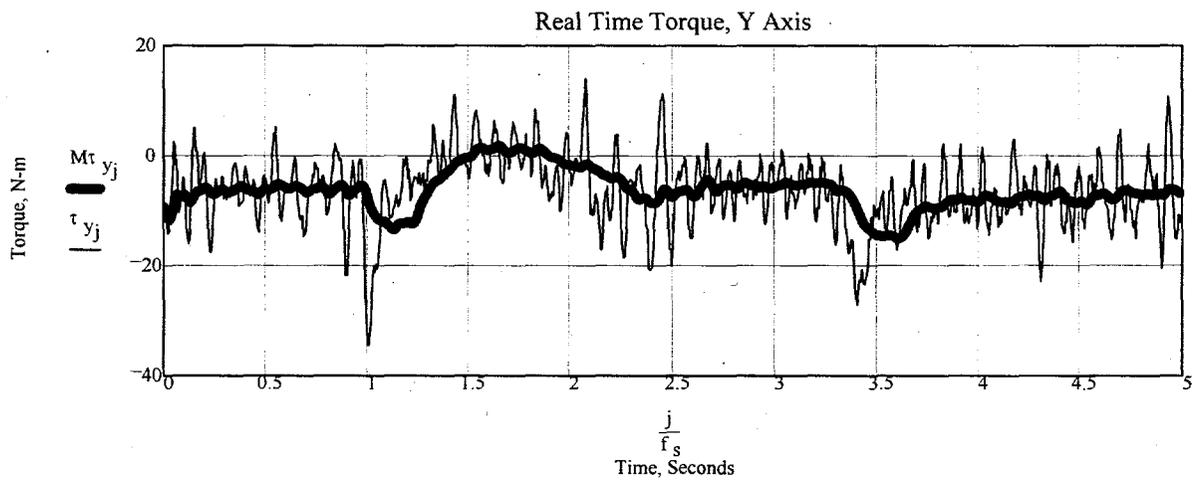
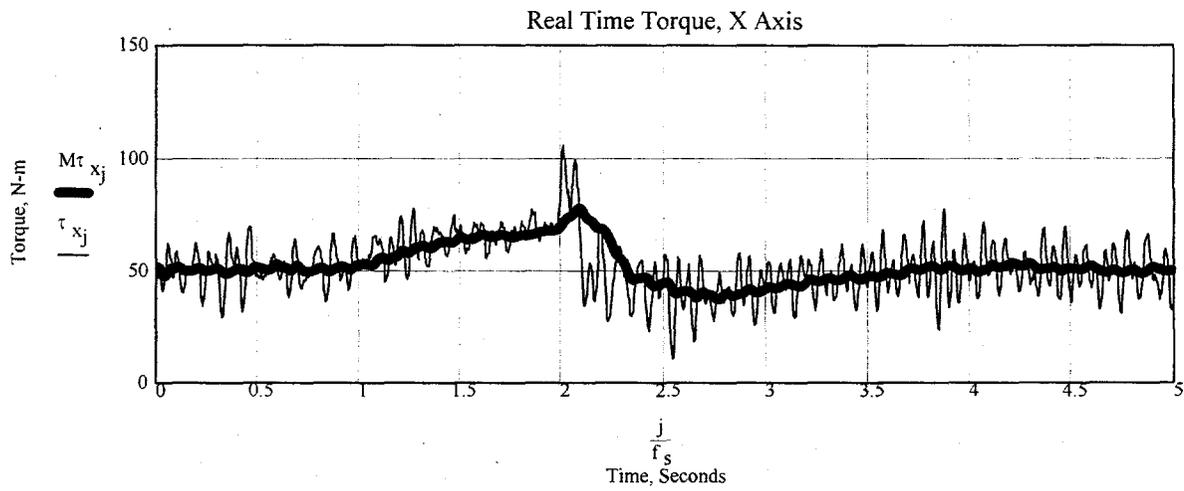
```

MFx := movavg(Fx, C)      MFy := movavg(Fy, C)      MFz := movavg(Fz, C)
  
```

```

Mτx := movavg(τx, C)      Mτy := movavg(τy, C)      Mτz := movavg(τz, C)
  
```





Calculate average, max, and min for each data set. Remove the average for FFT analysis

$\max(F_x) = 62.63$	$\min(F_x) = -89.51$	$\text{mean}(F_x) = -2.89$	Newtons
$\max(F_y) = 151.98$	$\min(F_y) = 22.4$	$\text{mean}(F_y) = 85.27$	Newtons
$\max(F_z) = 270.74$	$\min(F_z) = -64.75$	$\text{mean}(F_z) = 68.85$	Newtons
$\max(\tau_x) = 106.35$	$\min(\tau_x) = 11.03$	$\text{mean}(\tau_x) = 52.6$	N-m
$\max(\tau_y) = 14.1$	$\min(\tau_y) = -34.56$	$\text{mean}(\tau_y) = -6.27$	N-m
$\max(\tau_z) = 12.91$	$\min(\tau_z) = -13.54$	$\text{mean}(\tau_z) = -1.86$	N-m

$$F_{x \text{ mean}} := \text{mean}(F_x) \quad F_{y \text{ mean}} := \text{mean}(F_y) \quad F_{z \text{ mean}} := \text{mean}(F_z)$$

$$\tau_{x \text{ mean}} := \text{mean}(\tau_x) \quad \tau_{y \text{ mean}} := \text{mean}(\tau_y) \quad \tau_{z \text{ mean}} := \text{mean}(\tau_z)$$

$$F_x := F_x - F_{x \text{ mean}} \quad F_y := F_y - F_{y \text{ mean}} \quad F_z := F_z - F_{z \text{ mean}}$$

$$\tau_x := \tau_x - \tau_{x \text{ mean}} \quad \tau_y := \tau_y - \tau_{y \text{ mean}} \quad \tau_z := \tau_z - \tau_{z \text{ mean}}$$

Calculate FFT's

$$\text{pad} := 0..[(\text{count} - N_{\text{new}}) - 1]$$

$$\text{padman}_{\text{pad}} := 0$$

$$Fp_x := \text{stack}(F_x, \text{padman}) \quad Fp_y := \text{stack}(F_y, \text{padman}) \quad Fp_z := \text{stack}(F_z, \text{padman})$$

$$\tau p_x := \text{stack}(\tau_x, \text{padman}) \quad \tau p_y := \text{stack}(\tau_y, \text{padman}) \quad \tau p_z := \text{stack}(\tau_z, \text{padman})$$

$$F_{\text{spec } x} := \text{fft}(Fp_x) \quad F_{\text{spec } y} := \text{fft}(Fp_y) \quad F_{\text{spec } z} := \text{fft}(Fp_z)$$

$$\tau_{\text{spec } x} := \text{fft}(\tau p_x) \quad \tau_{\text{spec } y} := \text{fft}(\tau p_y) \quad \tau_{\text{spec } z} := \text{fft}(\tau p_z)$$

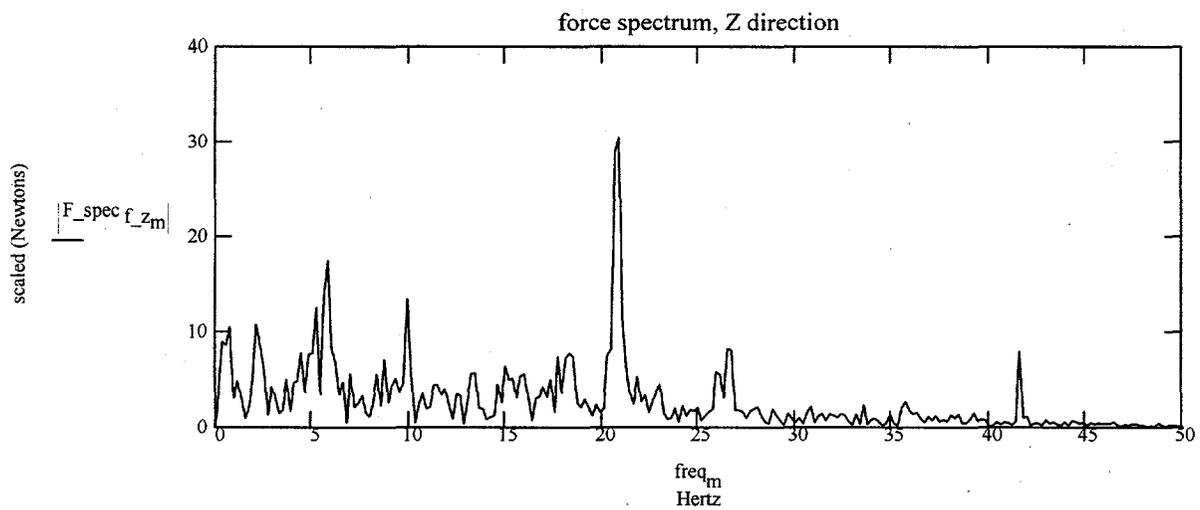
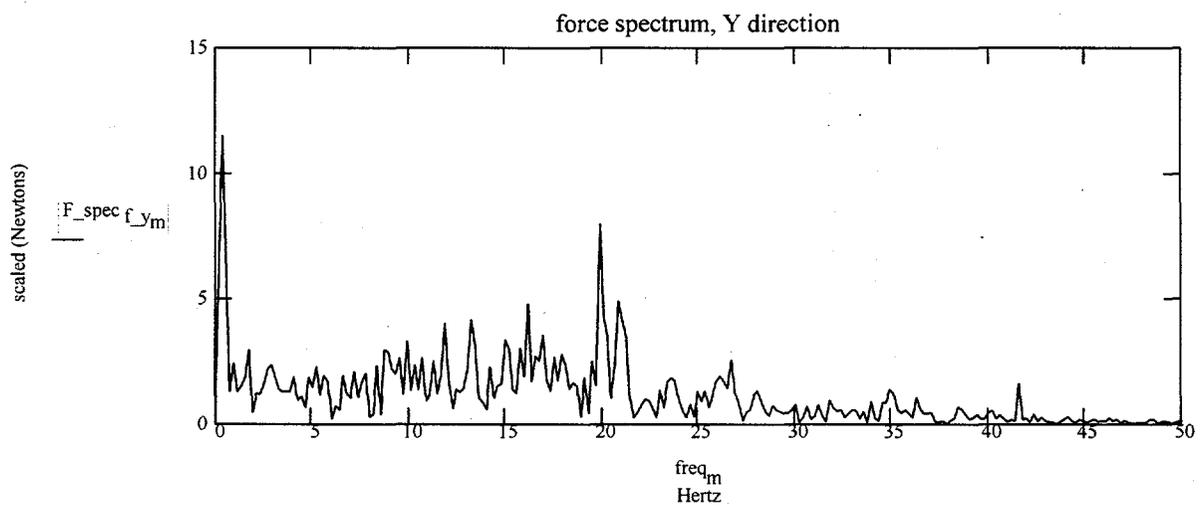
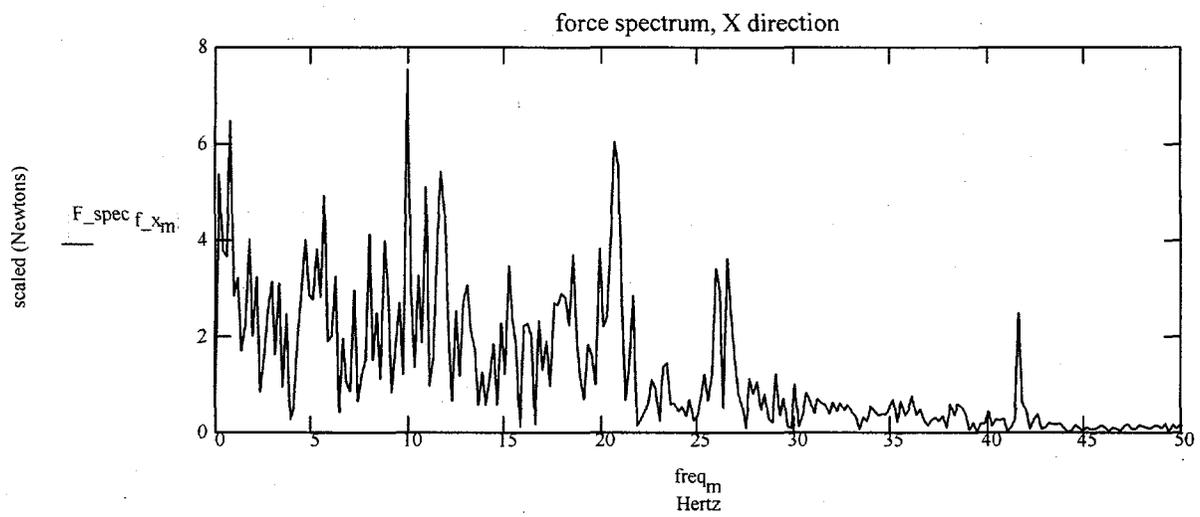
$$K := \text{length}(F_{\text{spec } x})$$

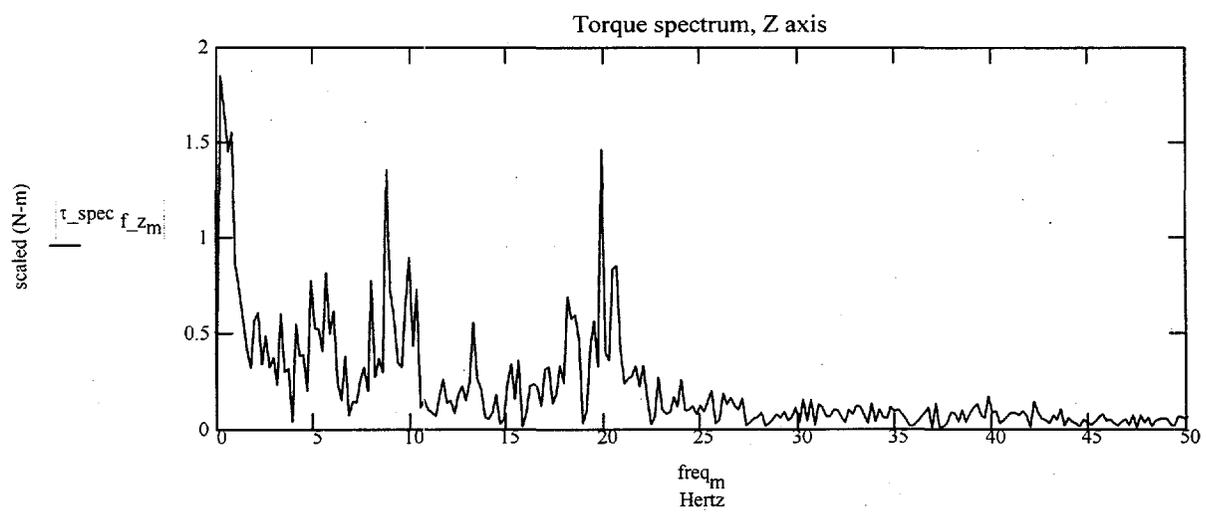
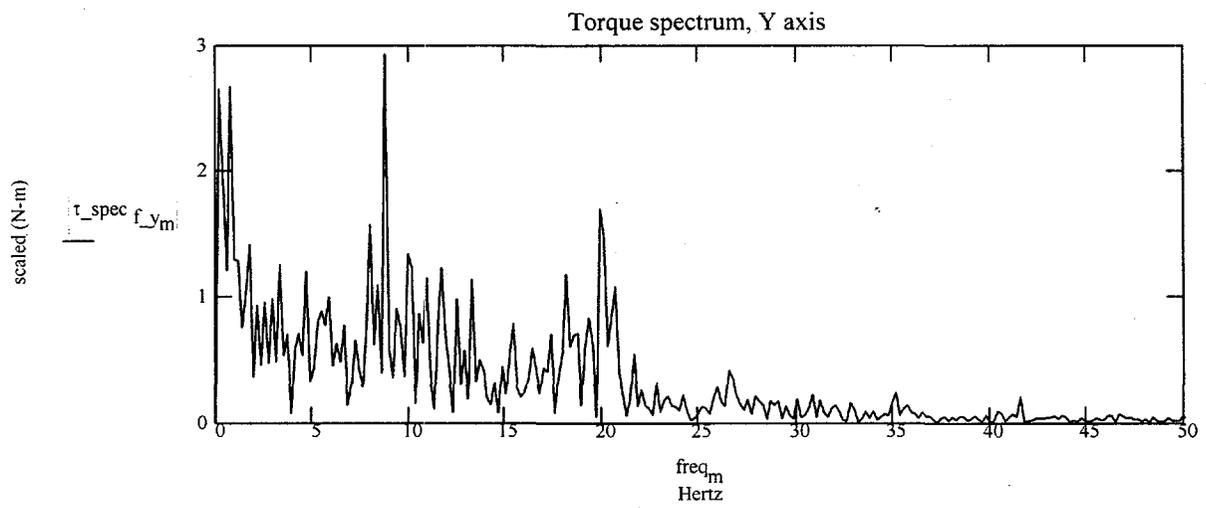
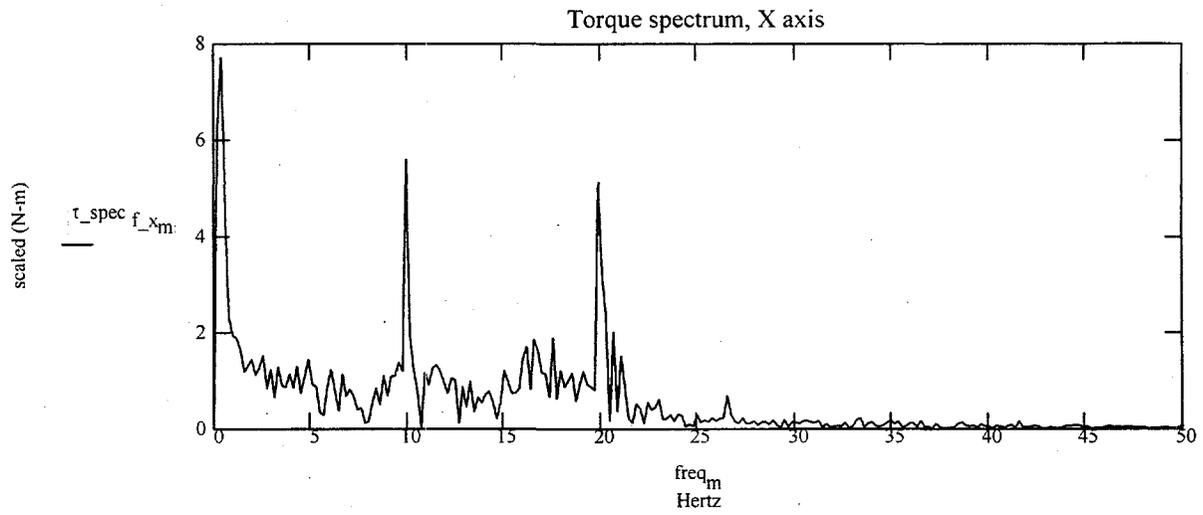
$$F_{\text{spec } f_x} := \frac{F_{\text{spec } x}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad F_{\text{spec } f_y} := \frac{F_{\text{spec } y}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad F_{\text{spec } f_z} := \frac{F_{\text{spec } z}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$\tau_{\text{spec } f_x} := \frac{\tau_{\text{spec } x}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad \tau_{\text{spec } f_y} := \frac{\tau_{\text{spec } y}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)} \quad \tau_{\text{spec } f_z} := \frac{\tau_{\text{spec } z}}{\left(\frac{\sqrt{N_{\text{new}}}}{2}\right)}$$

$$m := 0..(K - 1)$$

$$\text{freq}_m := m \cdot f_s \cdot \frac{1}{\text{count}}$$





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