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Hanford Waste End Effector Phase I Test Report

September 2017

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U.S. DEPARTMENT OF ENERGY
Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

This report describes the Phase I testing program of the Hanford Waste End Effector (HWEE) at the Washington River Protection Solutions Cold Test Facility. Phase I development testing of the HWEE addressed the informational needs defined in RPP-PLAN-61227 (Wooley 2016) for initial assessment of the HWEE to support Hanford single-shell tank A-105 retrieval. Note that the application of the HWEE concept has since been expanded beyond the original focus on one particular tank to potentially address any leaking tanks. The tests were conducted by Pacific Northwest National Laboratory using a robotic positioning system, high-pressure pump, and instrumentation. The tests involved retrieval of wet sludge, hardpan/dried sludge, and hard crust simulants that were prepared as recommended in PNNL-26206 (Gauglitz et al. 2017).

This report will first describe the test equipment, instrumentation, simulant preparation procedures, and testing methodology. Testing results that will be presented include HWEE water usage versus operating pressure, simulant characterization data, dilution ratios, and retrieval rates. Aerosol generation, reaction forces, and other factors that would affect the remote operation of the HWEE will also be presented.

The HWEE successfully retrieved simulants that were specified for the Phase I test campaign as shown in Table ES-1 below. Retrieval rates were calculated using different methods to bound and cross-check the results. Using data from the excavated volume of a single path of undisturbed simulant, kaolin was retrieved at 14.7 gpm, kaolin/plaster was retrieved at 12.2 gpm, and K-Mag was retrieved at 0.1 gpm. This method represents the impact to the tank solids. Using a mass of material retrieved calculation method, kaolin was retrieved at 4.9 gpm and kaolin/plaster was retrieved at 3.0–3.2 gpm. This method, which includes the effect of mining path overlap and proximity of tank bottom and side wall, represents what could be realized depending on the location of solids, tank, and in-tank hardware during retrieval. The retrieval rates for kaolin and kaolin/plaster were reasonable and significantly higher than for the retrieval of K-Mag, a much harder material that required a higher HWEE operating pressure. The water confinement was far better during kaolin and kaolin/plaster retrieval than for K-Mag. Overall, aerosol appeared to be low to moderate during retrieval testing when the standoff distance was minimized.

Table ES-1. Effectiveness Tests Results Summary

		Retrieval Rate (gpm) based on		Dilution Ratio based on	
Simulant	**Test Layer**	**Single path**	**Multi path using Mass removed**	**Single path**	**Multi path using Mass removed**
Kaolin	1st–3rd layers	14.7	4.9	0.92	0.30
Kaolin/plaster	1st–2nd layers	12.2	3.0	0.75	0.18
	1st–4th layers	-	3.1	-	0.19
	1st–5th layers	-	3.2	-	0.20
K-Mag	1st layer	0.1	NA	0.58	NA

Compared to previous results of confined sluicing end effectors provided in Hatchell et al (2016), retrieval of kaolin was higher (14.7 gpm for the HWEE versus 7 gpm previously reported) and retrieval of kaolin/plaster was comparable (12.2 gpm for the HWEE versus 8.9-14.0 gpm). The HWEE was clearly enhanced by the refinements in the screen, skirt, and conveyance inlet, which included the addition of a

fan-jet flush port. The flush port allowed the HWEE's screen to be cleared during retrieval, which greatly improved the efficiency of retrieval operations compared to prior demonstrations where an inefficient back-flush process was used. The enhanced skirt allowed the HWEE to confine the slurry and aerosol over changing topography.

Applying the success criteria of the HWEE Phase I Test effort, in comparison with existing retrieval systems used at Hanford, the Phase I Test was deemed successful.

- Demonstrate an end effector with minimal in-tank water usage that can be used in a leaking tank

  Success for 2/3 simulants. Water used by the HWEE was 4 gpm during retrieval of kaolin and kaolin/plaster and 10 gpm during retrieval of K-Mag (which used much higher pressure waterjets). Water remaining in the simulant tank was less than 1 inch after kaolin and kaolin/plaster retrieval. The water was well contained by the skirt at the point of origin and further confined to the troughs that were cut in the simulant. During K-Mag retrieval, which used much higher pressure waterjets, the water was not confined by the retrieval troughs and very little water was contained by the HWEE skirt.

- Demonstrate potentially higher retrieval effectiveness with lower dilution

  Success. Testing was previously conducted with the MARS-V system using three waste simulants (Shields 2011). Simulant 1M had the highest reported retrieval rate at approximately 4.3 gpm with a dilution ratio of 0.05. Note that Simulant 1M is described as pumpable in the MARS-V test report. The kaolin, which was overall retrieved at a higher 4.9 gpm and with a higher dilution ratio of 0.3 using a conservative mining approach, would not be considered "pumpable" by conventional means.

- Demonstrate an end effector that can be deployed using existing systems

  Success. The size (12.7 inch diameter) and weight (86 lbs) of the HWEE could allow it to be deployed by a lightweight deployment platform, such as the Enhanced Reach Sluicing System, through a small riser.

- Demonstrate visibility in tank is not impacted by aerosol generation from the end effector

  Success. Aerosol generation by the HWEE was low during retrieval of kaolin and kaolin/plaster and moderate during retrieval of K-Mag when the standoff distance was maintained at ¼ inch. This positive result shows the impact of the HWEE skirt design.

Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
CTF	Cold Test Facility
HWEE	Hanford Waste End-Effector
imp	inch per minute
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PRM	pressure reducing manifold
SREE	Sludge Retrieval End Effector
WREE	Waste Retrieval End Effector
WRPS	Washington River Protection Solutions

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1.0 Introduction

This report describes the Phase I testing program of the Hanford Waste End Effector (HWEE) at the Washington River Protection Solutions (WRPS) Cold Test Facility (CTF). Phase I development testing of the HWEE addressed the informational needs defined in RPP-PLAN-61227 (Wooley 2016) for initial assessment of the HWEE to support Hanford single-shell tank A-105 retrieval. Note that the application of the HWEE concept has since been expanded beyond the original focus on one particular tank to potentially address any leaking tanks. The tests were conducted by Pacific Northwest National Laboratory (PNNL) using a robotic positioning system, high-pressure pump, and instrumentation. The tests involved retrieval of wet sludge, hardpan/dried sludge, and hard crust simulants that were prepared as recommended in PNNL-26206 (Gauglitz et al. 2017).

This report will first describe the test equipment, instrumentation, simulant preparation procedures, and testing methodology. Testing results that will be presented include HWEE water usage versus operating pressure, simulant characterization data, dilution ratios, and retrieval rates. Aerosol generation, reaction forces, and other factors that would affect the remote operation of the HWEE will also be presented.

Work was performed under TOC subcontract 36437-220.

1.1 Background

The HWEE is a water-based scarifier originally developed by PNNL for U.S. Department of Energy tank retrieval systems starting back in the 1990s as the confined sluicing end effector and later used with additional development in the waste retrieval of tanks at Oak Ridge National Laboratory (ORNL), specifically, the gunite and associated tanks as described in PNNL-26037 (Hatchell et al. 2016). The HWEE is being assessed for potential use in Hanford waste tank retrieval because it is designed to use less water during waste retrieval compared to other water-based methods (e.g., sluicing) previously used in Hanford tanks. This reduction is primarily because the HWEE uses three closely focused rotating high-pressure jets rather than non-rotating fan jets for dislodging the waste and a high-velocity, shrouded conveyance system to retrieve the water and the waste locally at the point of waste dislodging.

The HWEE is a remote device intended to fragment and dislodge waste and introduce slurried waste into the inlet of a conveyance system. Conceptually, the HWEE is an array of small waterjets rotating around a central conveyance inlet (see Figure 1.1). The design was based in large part on the Sludge Retrieval End Effector (SREE) developed for ORNL. The fundamental goal of the SREE development was to produce a highly reliable, compact, and lightweight end effector that could be decontaminated and maintained inside a glovebox. The HWEE's performance should be somewhat better than the SREE's due to refinements in screen design, skirt design, and conveyance inlet geometry and the addition of the fan-jet flush port. The design of the HWEE is captured in Mullen et al. (1998). The HWEE used for the Phase I testing was fabricated by HiLine Engineering and Fabrication, Inc. based on the procurement specification RPP-SPEC-61356. In addition to the HWEE, HiLine provided an operation and maintenance manual (Melter 2017). The HWEE received from HiLine was modified during testing as follows:

1. HWEE mole was not used during retrieval testing but its water usage was characterized.

2. HWEE screen was patched with a similar screen in a small area but patch holes are slightly larger diamond shape compared with the original hexagonal design.

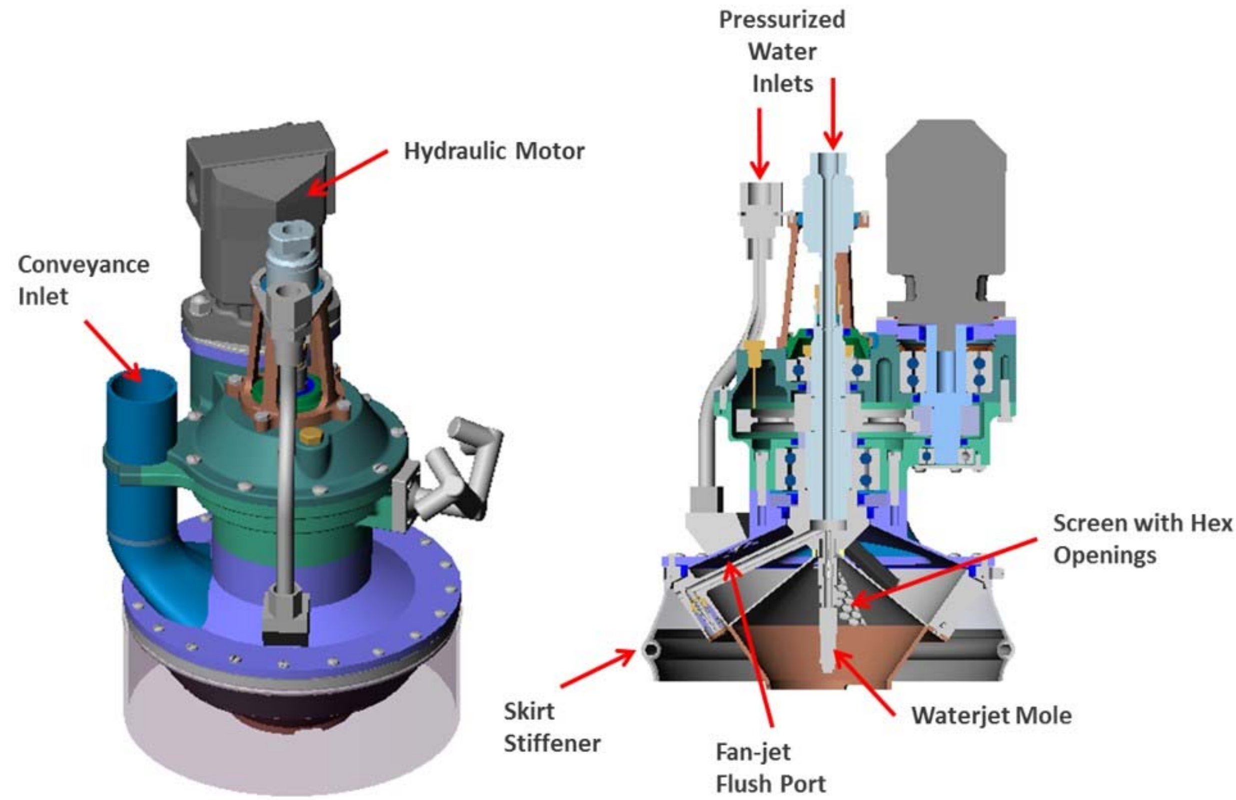

Figure 1.1. Hanford Waste End Effector Concept

1.2 Governing Documents

Governing documents associated with this work are

- Alternate Retrieval Technology Concept Testing Definition (PNNL 2017)
- *Hanford Waste End Effector Prototype Test Plan* (Berglin et al. 2017, PNNL-26549), referred to as the Test Plan in this document
- *Standard Operating Procedures for the Hanford Waste End Effector Test System* (Neill 2017)

The key governing document for test execution and reporting is the final Test Plan that was generated and approved by WRPS to address all statement of work needs. Prior to testing, a standard operating procedure was generated and approved by WRPS and submitted as part of the WRPS HWEE CTF work package.

1.3 Test Objectives

Table 1.1 summarizes the objectives of the tests in terms of data requirements, type of data collected, and desired accuracy. The desired accuracy was based on qualitative judgment on accuracy required to determine if the end effector performs adequately or requires design modifications.

Table 1.1. HWEE Phase I Data Requirements

Data Requirement	Data Type	Target Accuracy Objective
Retrieval		
Determine slurry output and dilution ratio for different test materials including: Kaolin (Sludge) Kaolin/Plaster (Hardpan) K-Mag (Saltcake)	Test data Video record	±10%
Visually observe slurry product after decant and note presence of large fragments.	Photo record	Qualitative
Measure HWEE tool reaction forces and frequency content during normal operation.	Test data Video record	±5%
Aerosol Generation		
Visually monitor aerosol generation during retrieval tests.	Video record	Qualitative
Screen Plugging		
Determine estimated frequency of screen and shroud plugging during retrieval tests. Evaluate remote flushing techniques to eliminate screen plugging.	Video record	Qualitative
Simulant Production		
Measure density and strength of test simulants to ensure consistency.	Test data	Measurement device Dependent*

*Note: Simulant strength measurements will use a viscometer or penetrometer as applicable to the simulant type. Simulant density measurements will use a gas pycnometer.

2.0 Test System

2.1 Overview

PNNL erected a mobile testing platform at the CTF off Horn Rapids Road in Richland, Washington, as described in Test Plan section 4 (Test Approach). WRPS supplied the HWEE fabricated by HiLine Engineering based on past design information and CTF services (water, air, electrical), structure (tent anchor blocks, operations trailer, disposal basin), and support (operators, forklift, man lift). PNNL purchased, supplied, and erected all other equipment and instrumentation as described in the following sections.

An overview of the HWEE test system is shown in Figures 2.1 through 2.4. Test system erection at CTF started in June 2017 and was completed in early August 2017. Testing started in early August and completed on August 21, 2017. The following sections provide a description of the test equipment and instrumentation used.

Figure 2.1. HWEE Test System Inside Tent

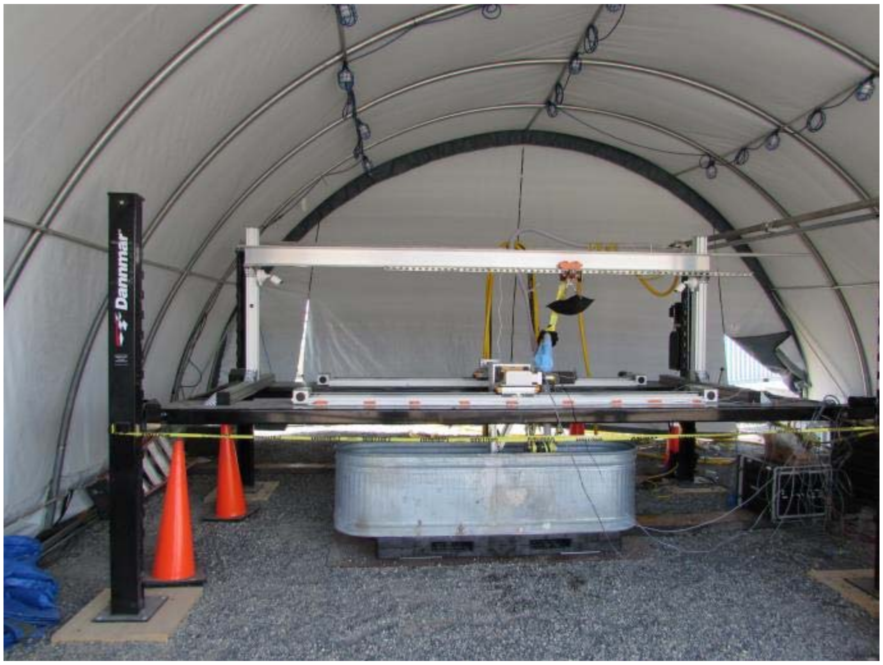

Figure 2.2. HWEE Test System Inside Tent (Retrieval Tank to Right Not Shown)

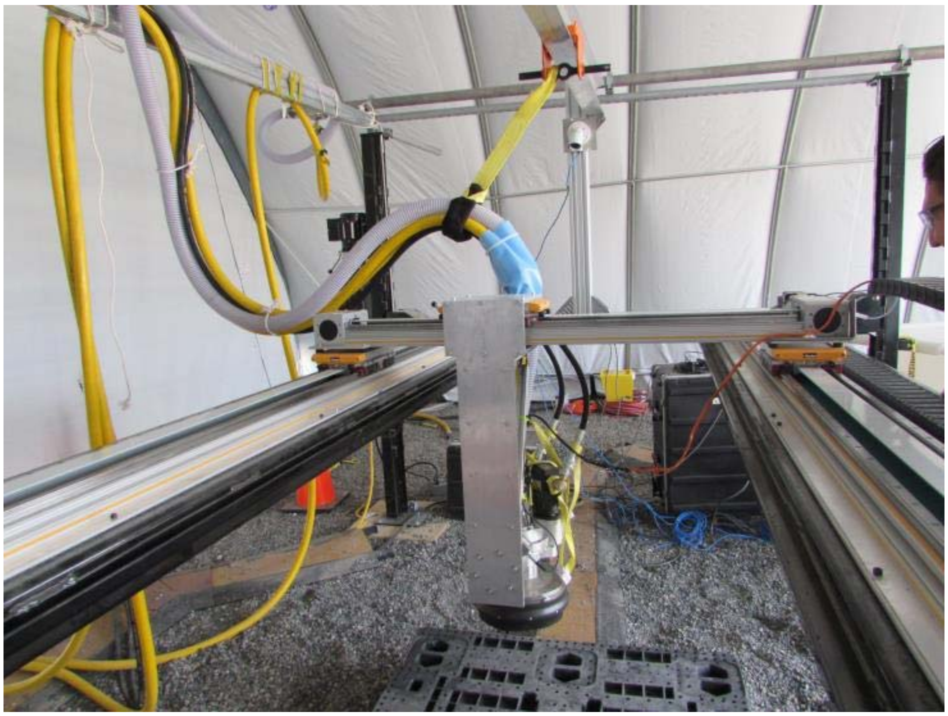

Figure 2.3. HWEE Test System – HWEE Attachment and Hose Management System

Figure 2.4. HWEE Test System – HWEE Connections

Test equipment and instrumentation used for HWEE testing are initially described in the Test Plan; see sections 4.2.1, Equipment, and 4.2.2, Instrumentation. All test equipment and instrumentation were protected by a tent enclosure with the exception of the NLB Corporation rental high-pressure pump, hydraulic power unit, and diaphragm pump that were located outside because of exhaust and noise considerations. All other equipment including the HWEE components (HWEE, jet pump, hose line management system, conveyance hose) attached to the gantry, simulant and retrieval tanks, high-pressure water control components (foot pedal, pressure reducing manifold) and instrumentation where located in the tent enclosure.

2.2 Equipment

The following equipment systems were provided as part of this testing effort.

2.2.1 HWEE

The HWEE supplied by WRPS via HiLine is described in the Test Plan section 3.1. During testing the HWEE had three 0.038-inch diameter nozzles installed that were rotated by a hydraulic motor up to 300 rpm. The two high-pressure water hoses to the HWEE rotary jets and mole and two hydraulic hoses to the HWEE rotary motor attached by quick connect fittings vertically on top of the HWEE. The conveyance hose attached over the HWEE conveyance port using an adapter fitting with set screw for securing. The HWEE connected to the gantry using an attachment bracket that sandwiched the force/torque sensor to the gantry down structure. The HWEE configuration used during testing is shown in Figure 2.5 and Figure 2.6.

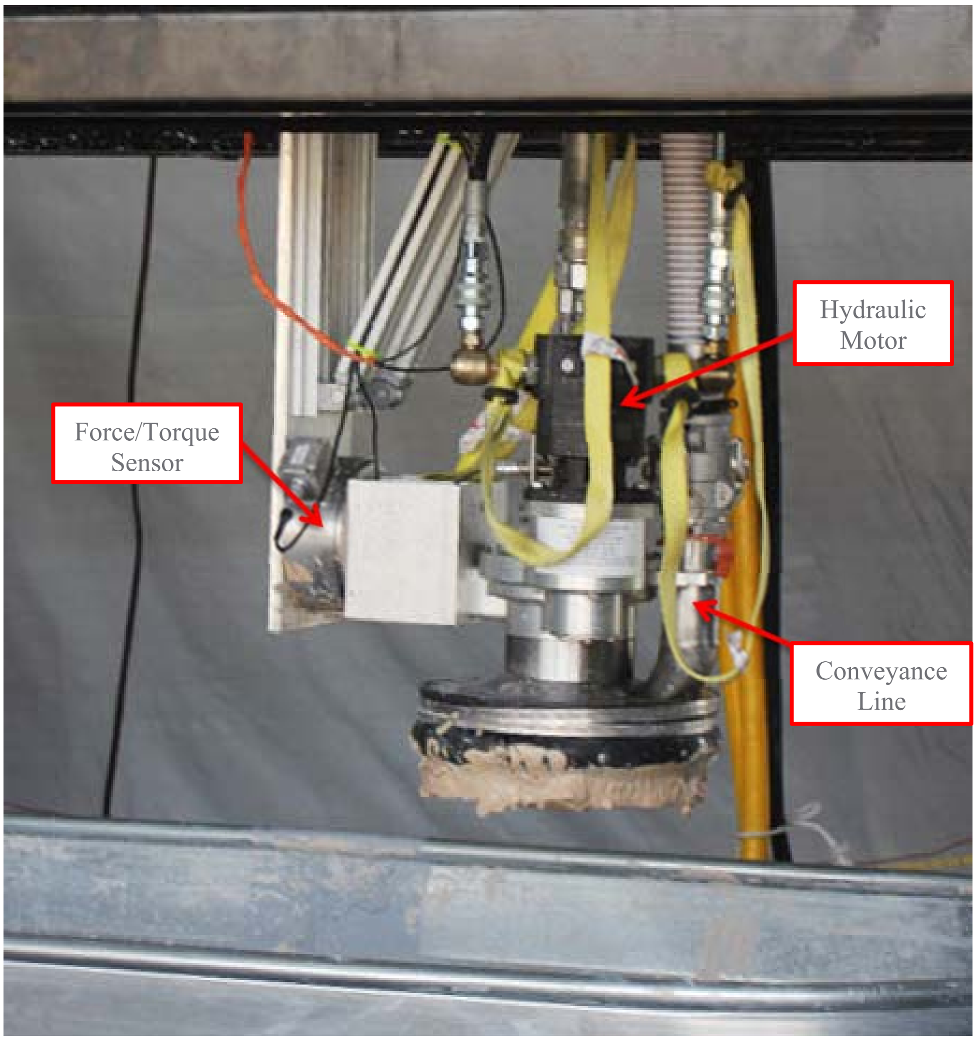

Figure 2.5. HWEE Testing Configuration

Challenges encountered during the test campaign are as follows. The original HWEE attachment bracket with round profile was bent during initial setup due to stresses caused by weight in combination with scanner motion and was replaced with a channel profile bracket prior to retrieval tests, although the team determined that simulant erosion testing could proceed without adverse impact while awaiting bracket replacement. During component flush testing at high pressure (10,000 psi), the HWEE screen weld broke and damaged the screen; this was repaired prior to retrieval tests. Prior to retrieval testing, the HWEE flushing mole associated with the HWEE rotary jets was found to be ineffective at screen cleaning due to mole spray pattern and continuous water usage and was plugged. At the end of K-Mag retrieval, the HWEE rotation stopped after extended low speed operation that generated heated oil. After cooldown, HWEE rotation operated normally. WRPS plans to do a "post-test" inspection/rebuild of the HWEE.

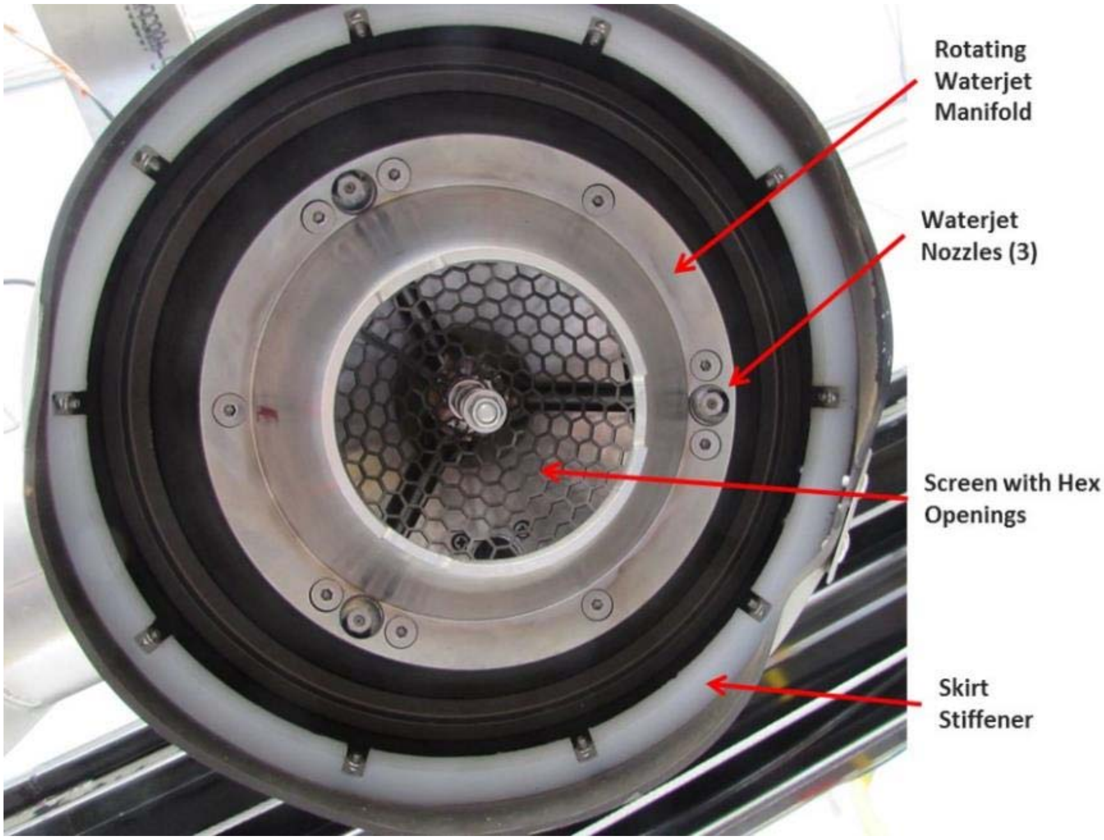

Figure 2.6. Bottom View of the HWEE

2.2.2 High-Pressure Water System for HWEE and Jet Pump Operation

The high-pressure water system used for HWEE and jet pump operations supplied water pressure up to 10,000 psi and 43 gpm. The high-pressure pump, shown in Figure 2.7 was rented from NLB Corporation and consisted of the company's 225 Series pump unit with 300 hp diesel motor and 10K psi plungers installed. As part of the rental, NLB also supplied the 100 feet of hose to the NLB-supplied foot pedal for controlling on/off operations.

Figure 2.7. NLB Corporation 225 Series Pump

Other equipment purchased from NLB was used including:

- 50 feet of hose to the pressure reducing manifold (PRM)
- 50 feet of hose to each of the HWEE components:
  - HWEE rotary jets and mole
  - HWEE flush
  - HWEE jet pump via the hose management system on the gantry

The piping and instrumentation design schematic (see Figure 2.8) includes details of the high-pressure water system routing.

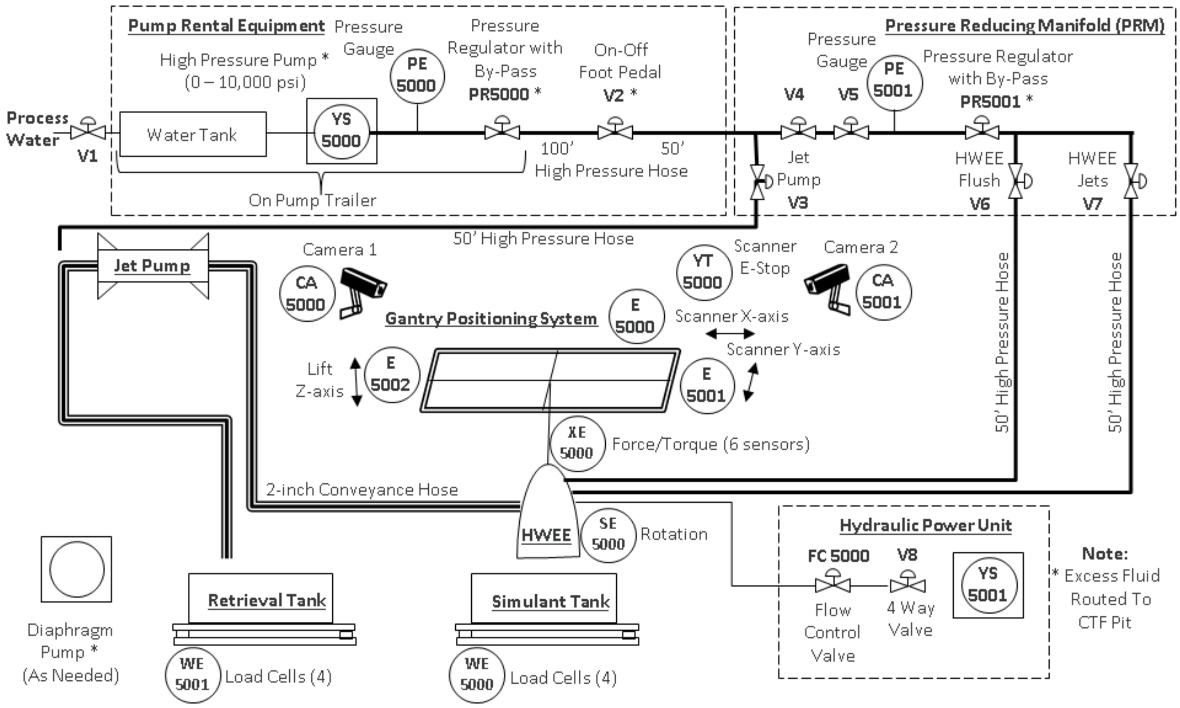

Figure 2.8. HWEE Test System Schematic

The PRM (see Figure 2.9) allowed reduced pressure operation of the HWEE rotary jets/mole, HWEE flush, and the HWEE jet pump that operated at pump supplied pressure. Using the PRM, all three HWEE component operations can be run together, in combinations, or individually. Pressure adjustment needle valves in the PRM limited maximum pressure to the HWEE rotary jet/mole and HWEE flush to around 6,600 to 7,000 psi with the associated pressure regulator fully engaged. The manual needle valves required many turns to open and close, which proved to be some detriment to quick operations desired for flushing. During kaolin/plaster retrieval operations, 10 to 20 seconds was required to open and close the PRM needle valve flush line manually and this was reduced to 2 to 4 seconds on the kaolin retrieval operations using an electric drill for the valve activation sequence. Because of the PRM pressure limitations, component water usage testing bypassed the PRM so that the full pressure supplied by the pump (10,000 psi less minimal line losses) could be used.

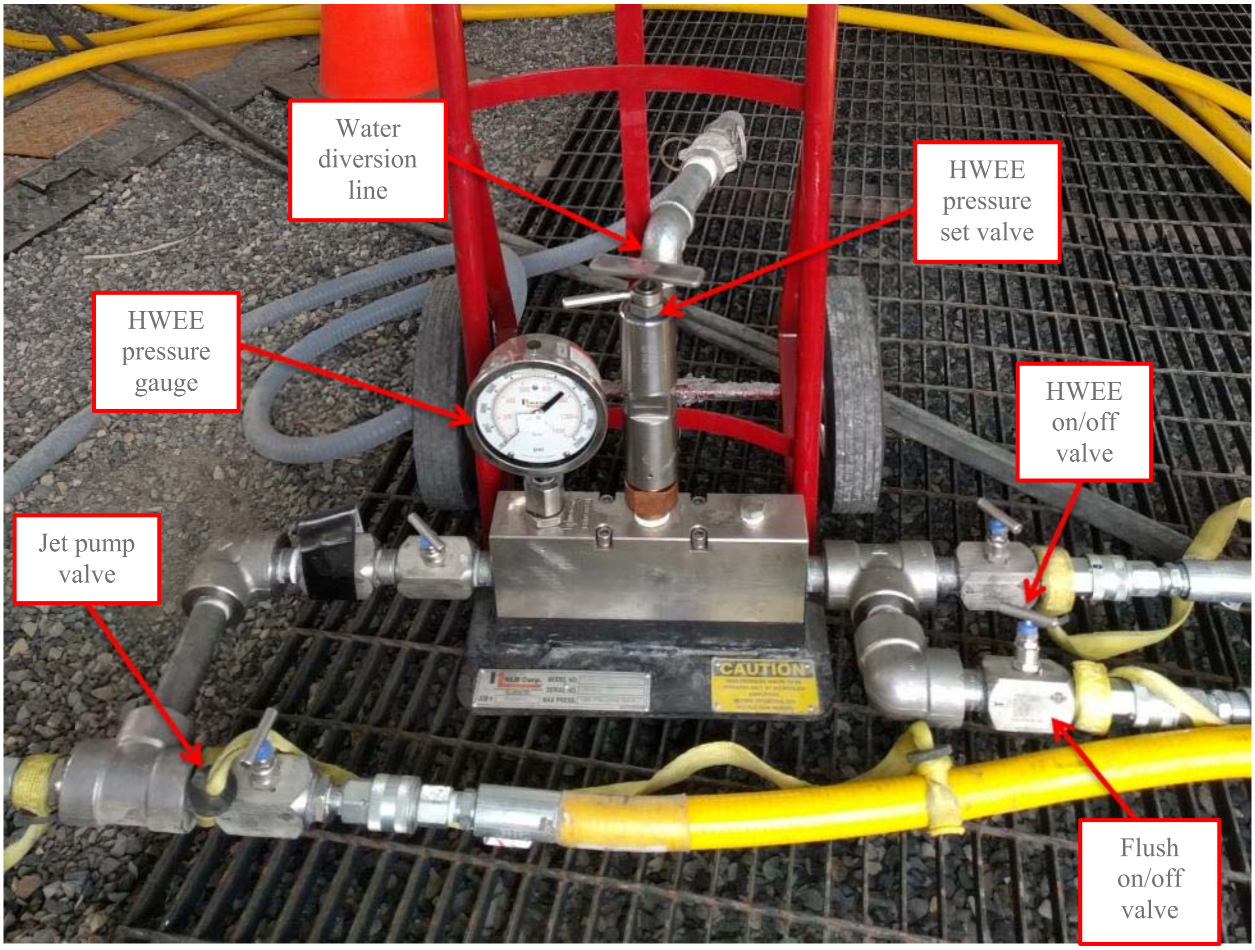

Figure 2.9. Pressure Reducing Manifold Details

The high-pressure water system controlled pressure by diverting (i.e., by-passing) water out of the system. Industrial practice would typically dump this diverted water on the ground but, due to a limitation on water release to the ground, this water was diverted to the CTF basin via hose from the various diversion devices that included the main pump, foot pedal, and PRM pressure regulator.

2.2.3 Hydraulic Power for HWEE Jet Rotation

A small hydraulic power unit from Foster Manufacturing Corporations (see Figures 2.10 and 2.11) operated the HWEE hydraulic motor that spun the HWEE rotary jets. This was a custom supplied unit designated Model 13-1-3 GC with 13 hp motor with electric start, flow control valve, flow meter, to-way three-position manual control valve, and fan-cooled heat exchanger. This unit supplied up to 3 gpm at 3,000 psi to achieve 300 rpm rotation of the HWEE hydraulic motor. Hydraulic hoses connected the pump unit to the HWEE hydraulic motor via quick connect fitting and was routed via the hose management system on the gantry. Vegetable based oil was used for hydraulic operations.

Figure 2.10. Hydraulic Power for HWEE Jet Rotation Control - Pump

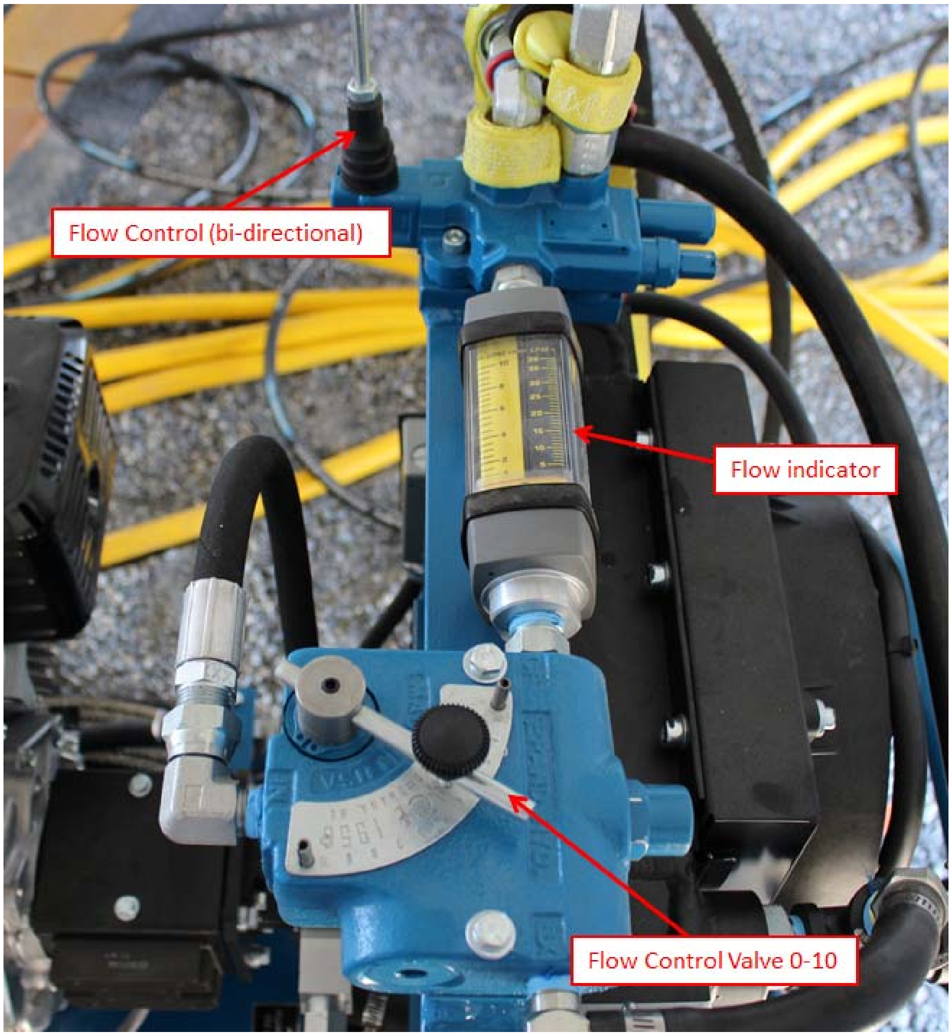

Figure 2.11. Hydraulic Power for HWEE Jet Rotation Control Details

During K-Mag retrieval, the HWEE rotary jet rotation was slowed down to 75–100 rpm. To achieve this operation, the hydraulic power unit does not fully circulate hydraulic fluid through the heat exchanger and temperatures can rise during extended operation. This happened during extended K-Mag retrieval operations and HWEE rotation stopped. After several hours of shutdown/cooldown the HWEE operated normally; however, some small amount of oil leakage was detected and subsequently cleaned up.

2.2.4 Gantry Motion Control System

The gantry system (see Figure 2.12) provided three translational degrees of movement for the HWEE using a scanner for X-/Y-axis motions and a manual lift for Z-axis motions.

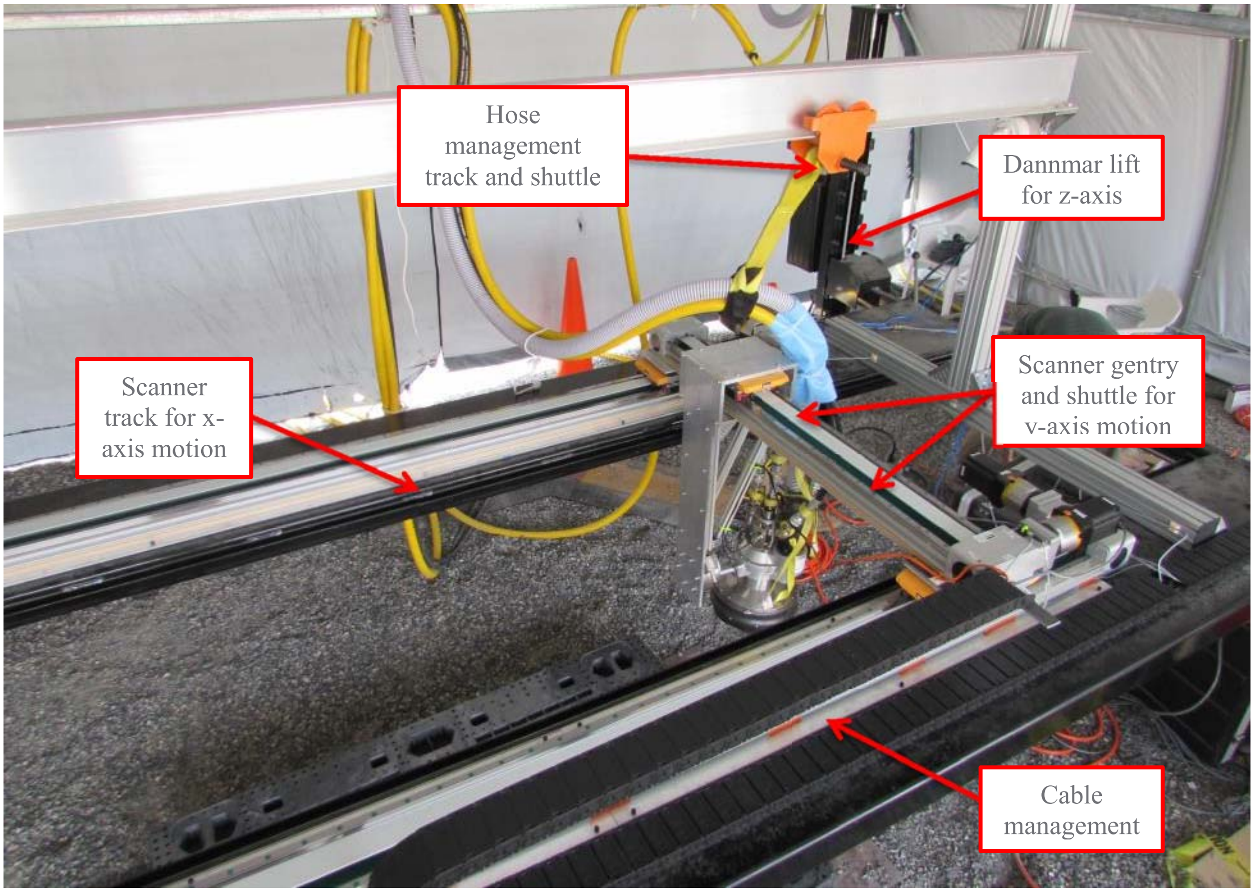

Figure 2.12. Gantry Motion Control System

For rectilinear motion, a scanner system was assembled using a custom Parker Hannifin Corporation electric stepper motor system. X-axis motion was provided by two Parker belt-driven linear actuators operating in parallel that provided about 8 feet of travel. Y-axis motion was provided by a single belt-driven linear actuator that provided about 3 feet of travel. The HWEE was mounted to the Y-axis carriage. X- and Y-axis motion was independently controlled and could be either manually operated or programmed (e.g., serpentine path) at speeds up to 300 inches per minute (ipm). The scanner system was mounted to the top side of the lift tracks. Cable management of scanner and instrument cables was provided by a cable track system mounted to the lift and connected to the X-axis carriage.

For Z-axis motion, a vehicle lift from the Dannmar Equipment Corporation was acquired that provided a heavy duty base for mounting the X-Y scanner with HWEE. The lift was operated manually and the height range of the tracks was from ground level to about 7 feet height. The Dannmar lift was a model D-7/X with a maximum lift capacity of 7,000 lbs and used a small electric hydraulic motor to actuate a cylinder/cable system to move the lift up and down.

The HWEE is attached to the scanner Y-axis track system using a drop bracket that extended down between the tracks of the Dannmar lift. This resulted in the bottom metal portion of the HWEE extending approximately 32 inches below the top of the lift tracks. The HWEE hoses were bundled and routed through the hose management system to allow the hoses to move “freely” as the HWEE was in motion.

The hose management system consisted of a beam/trolley system that attached 4 feet above the Dannmar lift tracks. The hoses where bundled and attached to the trolley using a nylon strap with swing length of around 24 feet. X-motion was the long direction and was assisted by the trolley rolling motion in the same direction. Y-motion was shorter and was assisted by the swinging motion of the trolley strap side-to-side. Z-motion was assisted by having the beam portion of the trolley directly connected to the lift Z-axis motion and a secondary static bar mounted higher to allow the hoses from the trolley sling to extend upward and over with some limited sliding capability.

2.2.5 Simulant System

The simulant system consisted of a simulant tank (See Figure 2.13) mounted on a pallet and a matching pallet supported by load cells under the gantry. The simulant tanks were galvanized stock tanks sized around 8 feet long, 3 feet wide, and 3 feet high with a capacity of approximately 300 gallon. Prior to simulant addition, a wooden rectangle-shaped partition was put in the bottom of the simulant tank according to the height for the simulant to be added; 8 inches for kaolin and kaolin/plaster and 4 inches for K-Mag. The wooden frame was approximately 5 feet long and 3 feet wide. Plastic on the order of 6–10 mil was used to line the simulant frame and cover the simulant after installation. The simulant crew made up the simulants and packed them into the simulant tank frame at PNNL. Simulant tank and/or material were delivered to CTF as needed for testing operations.

Figure 2.13. Simulant Tank System

The simulant tank was inserted on top of the simulant load cell pallet with a forklift. Prior to starting simulant testing and retrieval operations, any simulant coverings were removed and X-/Y-axis scanner motion and lift Z-axis motion was checked to determine mining path and limitations (e.g., tank side walls, simulant wooden frame).

Prior to simulant retrieval operations, the open ends of the tank without simulant were used to set water pressure on the various HWEE components to meet test conditions. Since this water was not associated with retrieval operations, a diaphragm pump was used to pump out the “setup” water. When completed, the HWEE was moved into position over the simulant to its starting position to begin retrieval. Prior to the start of any retrieval operation the simulant tank weight was noted or “tared.”

During simulant retrieval operations, the water from the HWEE rotary jet, HWEE flush, and dislodged simulant were exposed to the HWEE screen and conveyance port where they may be drawn up via the jet pump and transported.

During pauses of simulant retrieval operations, the retrieval progress could be viewed and photographed. The width and depth of the simulant troughs were measured with a caliper or tape measure. In some cases, a diaphragm pump was used to remove water to aid in the visual and physical measurements.

After simulant retrieval operations were completed, a final visual and measurement record was made as applicable. Simulant were reformatted in the simulant tank for aerosol testing. Finally, simulant was removed from the simulant tank and disposed in the simulant receipt pit basin located at the CTF. The simulant tank and associated pallet was removed from simulant load cell pallet and moved/stored as appropriate.

2.2.6 Retrieval System

The retrieval system started at the HWEE suction port and ended at the retrieval tank. The HWEE jet pump provided the motivation force to draw and transport water and simulant into the HWEE suction port and pump it into the retrieval tank. A 2-inch conveyance hose connected the HWEE suction port to the HWEE jet pump as shown in Figure 2.14. From the jet pump, metal pipe and fittings were used to transport and then dissipate transport energy prior to depositing contents in the rectangle poly retrieval tank having internal dimensions of approximately 72-3/4 inches long, 36 inches wide, and 35 inches high.

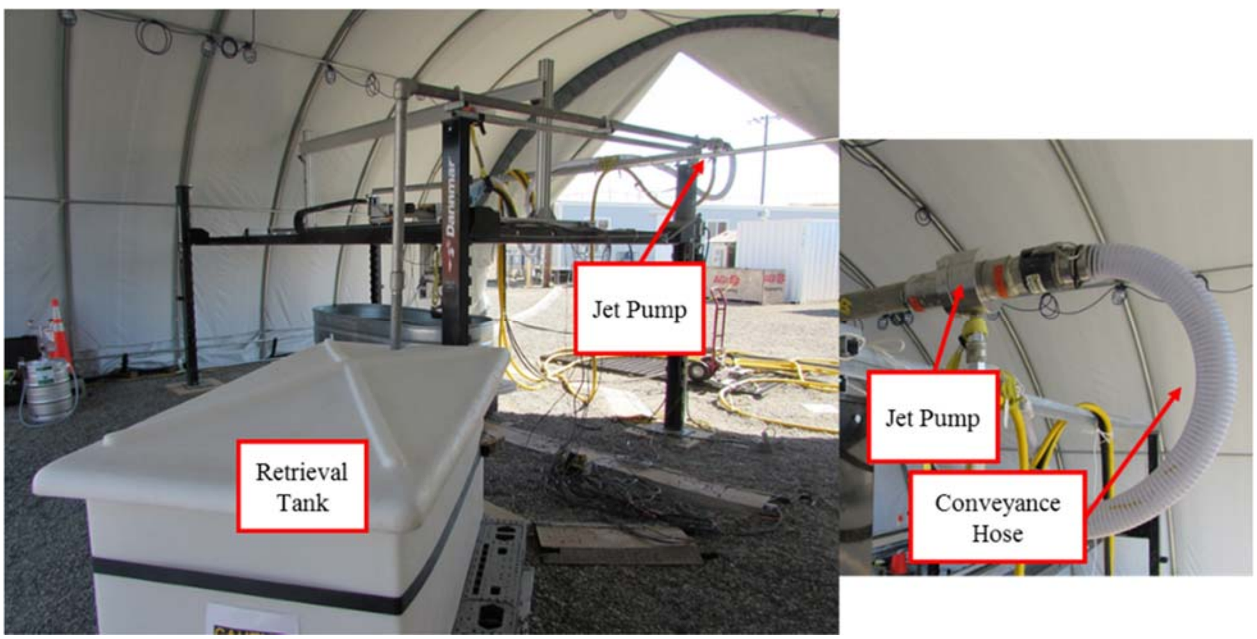

Figure 2.14. Overview of Retrieval System (left) and Jet Pump (right)

The HWEE jet pump was an AquaDyne model 61102958 Dyna-vac with 2-inch NPT end fittings and with six 0.031 inch diameter nozzles. Operating pressure during retrieval operations was typically 9,500 to 10,000 psi as measured at the main pressure pump and then going through 200 feet of high pressure hose, a foot pedal, and one needle valve on the PRM to the jet pump pressure inlet fitting. The foot pedal was used to interrupt flow from the high-pressure pump to the HWEE and jet pump to conserve water. Whenever the HWEE jet pump was operating, its water flow was deposited into the retrieval tank. During retrieval operations, jet pump water flow was likely occurring during pressure setup operations, just prior to retrieval operations start, during all retrieval operations, and often for a period after retrieval that included dewatering operations. The jet pump lift of simulant material was approximately 77 inches when HWEE was positioned ¼ inch above the simulant surface at the start of retrieval testing. The conveyance hose between the HWEE to jet pump was approximately 246 inches of 2-inch conveyance hose and 9 inches of 2-inch pipe. Conveyance line downstream of jet pump was all 2-inch pipe consisting of approximately 136 inches of horizontal pipe, 66 inches of vertical drop, and then into the horizontal dispersion pipe apparatus (see Figure 5.11) in the retrieval tank."

Prior to a simulant retrieval operation, the retrieval tank was cleaned, emptied, and its weight "tared." During retrieval operations, fluid extracted from simulant system operations and water from the HWEE jet pump were deposited in the retrieval tank. Due to the strong jet of water from the HWEE jet pump through the downstream piping to the retrieval tank, a transport energy dispersion pipe end was constructed consisting of two cross-pipe branches (for a total of four outlets) and end damper cap with 2-inch pipe. Capacity of retrieval tank was limited by the height of the dispersion pipe above the bottom of the tank (approximately 24 inches) because submersion/near submersion of the dispersion outlets caused water from the retrieval tank to splash out.

The retrieval tank was drained at various steps in the testing process and included the following: when retrieval tank reached capacity (i.e., dispersion outlets), when testing was completed, when a logical step during retrieval had been reached, or when testing was stopped. The retrieval tank was drained using a diaphragm pump into the CTF basin. Prior to draining, the tank was weighed and occasionally the tank level measured from the outside using a measuring tape at two opposing locations to estimate tank volume contents. The process for draining the retrieval tank during a retrieval test was to first dewater the liquid on top using the diaphragm pump, next material left at the bottom of the tank was inspected for any large simulant pieces or unexpected objects, and finally the tank was cleaned and drained. Visual records were recorded of the retrieval tank inspection operations as deemed appropriate.

2.2.7 Tent Enclosure

A tent enclosure from Rhino Shelter (see Figure 2.15) was used at CTF to house and protect HWEE equipment and provide a weather deterrent. Tent size was 30 feet wide, 30 feet deep, and 15 feet high in the center and was oriented at CTF with the vertical ends in a north/south direction. The tent was a circle/ellipse shaped structure supported by metal framing with flat vertical ends and anchored using a series of eco-blocks along the sides with straps to the bottom of the frame structure. A zippered door system was oriented on the south end, while the north end was left open. The tent door rope restraint failed due to ultraviolet damage and was replaced. The open end was used for forklift operations to setup HWEE equipment and move simulant tanks in and out as required for testing.

Figure 2.15. Tent Enclosure

2.3 Instrumentation

A measurement and test equipment list was provided in Appendix A of the Test Plan. The data were acquired by a data acquisition system running Daisylab. All the data were acquired at 500 Hz and stored in a CSV file. The data acquisition clock and camera times were synchronized so events captured by the cameras could be correlated with test data. The instrumentation is briefly described below. All appropriate instrumentation was verified as being in calibration (as per the Test Plan).

- **Data acquisition system**. The sensors were connected to a data acquisition system (DaqBook/2001 manufactured by Measurement Computing), which was connected to a laptop running Windows 7.
- **Waterjet pressure transducers**. A visual pressure gauge was included in the high-pressure pump. The gauge was downstream of the pressure reducing valve, so that the gauge can be used to set the discharge pressure. A second visual pressure gauge was included on the pressure reducing manifold that can be used to set lower discharge pressures to the HWEE than the jet pump.
- **Force-torque sensor**. To measure dynamic forces due to suction, inertia, and waterjet reaction, a sensor that measures forces and torques along three axes was attached to the HWEE interface bracket. The sensor selected was model Omega160 IP65, manufactured by ATI Industrial Automation. The force-torque sensor is intended for robotic applications and harsh wet environments. 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.
- **Speed sensor**. An optical tachometer was installed on the HWEE to measure manifold rotational speed (MCS-655M manufactured by Electromatic Eq. Company). A reflector was epoxied to the HWEE manifold to provide a return signal for the speed sensor. There was some concern that the speed sensor would be affected by simulant and water splatter, but the sensor worked flawlessly throughout testing.
- **Tank load cells**. Load cells were installed under both the simulant and receipt tanks to measure the weight of water/simulant transferred during retrieval simulations. The load cell chosen, model SPWE-

SR-2.5K manufactured by Load Cell Central, and is designed for operation in rugged environments where side loads may occur. The load cells worked well throughout testing, and were not affected by incidental impact loads from the fork lift.

- **Position (X-, Y-, Z-axis)**. Position of the HWEE in three-dimensional space was monitored relative to a home position (X-/Y-axis horizontal plane) set by the location of limit switches. From the home position, all movements were relative. A linear potentiometer (model SP1-25 manufactured by Measurement Specialties) was used to measure the height of the lift relative to a starting point. A visual scale was also used during manual lift adjustment. Limit switches were installed on the X and Y actuators to avoid collisions between the HWEE and the tank walls.
- **Calipers**. Simulant retrieval features (e.g., trough depth) were measured with a set of digital calipers.
- **Simulant Strength**. A pocket penetrometer, Model S-170 manufactured by Durham, was used to measure the two kaolin-based simulants strengths prior to testing.

3.0 Test Methods

Test methods are detailed in section 5.0 of the Test Plan. Changes to the Test Plan made during testing have been incorporated into a rereleased Test Plan that reflects the actual test methods used. The following table describes the tests that were completed.

Table 3.1. HWEE Phase I Tests

Test Phase	Test Focus	Test Parameter	Key Data Expected
Instrumentation Verification and Check-out Tests	Controls and Instrumentation Calibration	• Performance check sensors with known weights, pressures, etc. • Verify controls operation and flush capability	• Performance check of sensors in the installed condition
Start-up Retrieval Tests	Water Usage, Simulant Response, and Simulant Retrieval	• Tests with kaolin, kaolin-plaster, and K-Mag • Waterjet and flush jet flow versus operating pressure • Flat topography	• Verify basic retrieval operating parameters (traverse speed, distance between adjacent passes) • Identify plugging and screen cleaning frequency • Measure simulant erosion and retrieval cutting profiles • Measure water usage • Aerosol generation
Effectiveness Retrieval Tests	Simulant Retrieval	• Tests with kaolin, kaolin-plaster, and K-Mag • Flat topography	• Verify basic operating parameters • Identify plugging problems • Water usage • Slurry density • Slurry output rate • Aerosol generation

4.0 Simulants

Simulants have previously been designed for retrieval testing to represent certain characteristics of hard saltcake and sludges expected in Hanford waste tanks (Powell 1996). Gauglitz et al. (2017) reviewed these prior simulant materials for use in the current application, and three of the prior simulants were selected to generally span the expected range of shear and/or compressive strength for Hanford waste hardpan/dried sludge. As noted in Gauglitz et al. (2017), strength is being used as an alternate physical property because information on the erosion behavior, a key waste property for confined sluicing, of the simulants and waste is generally not known. Although no new simulants were developed for Phase I, the simulants that were chosen are expected to bound the typical wastes in Hanford tanks.

To meet the objectives of Phase I testing, the three simulants were prepared as specified in the prior work. The Phase I simulant materials were thus selected to match the prior products. However, preparation and characterization of bench-scale simulant samples for yield stress in shear (shear strength) demonstrated strength differences, so the recipes were adjusted accordingly. The HWEE Phase I simulant recipes and characterizations are summarized in section 4.1. Preparation descriptions are also provided. In section 4.2, data useful to describe erosion rate characteristics for each of the three simulants is discussed.

4.1 Simulant Preparation and Characterization

The simulants used in Phase I testing were specified by Gauglitz et al. (2017).

- Kaolin Simulant: ~3,500 Pa, kaolin/water, with a shear strength value of 3,500 Pa, was selected because it was used in the most recent testing of confined sluicing with the Waste Retrieval End Effector WREE (Hatchell et al. 2016).

- Kaolin-Plaster Simulant: ~150,000 Pa, kaolin/plaster of Paris/water, with a shear strength value of 150,000 Pa, was selected because this was the strength used for this simulant used in the previous WREE testing (Hatchell et al. 2016).

- K-Mag Simulant (saltcake): ~15,000,000 Pa K-Mag/water is a hard saltcake simulant that is expected to be bounding for Hanford waste, and this value of compressive strength is representative of the K-Mag recipes used in high-pressure jet erosion studies reported by Powell et al. (1997).

The as-prepared simulants are summarized in Table 4.1. Using the previously prepared recipes as specified for Phase I testing, all simulant characterization was to be considered confirmatory in nature. However, preparation and characterization of bench-scale simulant samples of the kaolin and kaolin/plaster for yield stress in shear (shear strength) using the original recipes (see Gauglitz et al. 2017) demonstrated substantial strength differences from the specified targets, so the recipes were adjusted to those listed in Table 4.1. The adjusted Phase I HWEE kaolin and kaolin/plaster simulants had measured shear strengths that were within 7% of the approximate targets specified in Gauglitz et al. (2017).

Table 4.1. Phase I HWEE Simulants

Simulant	Solids	Phase I Recipe[8]	Density[4] (g/mL)	Strength (Pa)
Kaolin (Sludge)	EPK Pulverized Kaolin Clay[1]	64 wt% kaolin clay 36 wt% Richland city water	1.649	3.7 kPa[5]
Kaolin/Plaster (Hardpan)	EPK Pulverized Kaolin Clay[1] DAP Plaster Wall Patch, Plaster of Paris[2]	19 wt% kaolin clay 52.5 wt% plaster 28.5% Richland city water	1.928	160 kPa[6]
K-Mag (Saltcake)	Dynamate[3]	80 wt% Dynamate 20 wt% Richland city water	2.383	12 MPa[7]

1 Feldspar Corporation (Edgar, Florida)
2 DAP (Baltimore, Maryland). UPC# 10304
3 Prince Agri Products, Inc. (Quincy, Illinois). Feed-grade potassium magnesium sulfate, Item Number: 09-1285.
4 Measurement Device: Micromeritics AccuPyc II 1340 pycnometer with slurry head. Procedure: Burns (2017)
5 Measurement Device: Haake VT550 Viscometer. Procedure: Daniel (2007)
6 Measurement Device: Geotest E-280 pocket penetrometer. Procedure: Performance check of specific device followed Onishi et al. (2011); true unconfined compressive strength (UCS) [kg/cm^2] = 1.247 * measured UCS [kg/cm^2]. Conversion to shear strength; shear strength = 42.8 * true UCS [kg/cm^2] (Onishi et al. 2011).
7 Measurement Device: MTS Bionix 400. Procedure: manufacturer operating manual for compressive strength
8 Weights of simulants solids were made for as-received materials.

For the K-Mag simulant, visual observation of the Dynamate particulate suggested that the current material consisted of smaller particulate than previously used. The different compressive strength for the as-prepared material, 12 MPa vs. the approximately 15 MPa target, prepared as specified in the original recipe, is postulated to be attributable to this material difference. No attempt was made to adjust the recipe given the apparent product difference and the significantly bounding nature of this simulant; for a given material, a higher strength can most typically be associated with a more challenging material to erode (e.g., Gauglitz et al. 2017).

Using the appropriately defined PNNL standard operating procedures for each material, the following preparation methodologies were followed:

- Kaolin – The "thick" nature of this simulant required careful preparation. Multiple batches of approximately 11.1 gallons each were concurrently prepared in 30 gallon sealable drums. The kaolin was first added to the drums, and the appropriate water mass was then added by pouring down the side of the container. Mixing was accomplished by periodically rolling the drums during the nominally 3 week preparation period. The simulant was loaded from the drums into the simulant tank using appropriate hand tools.

- Kaolin/plaster – Multiple batches of approximately 15 gallons each were sequentially prepared in a 15 gallon drum mixer. The small batches were necessitated by the "thick" nature of the simulant material. The kaolin and plaster solids were homogenously premixed at the appropriate ratios and added to the mixer followed by water. The batches were sequentially mixed to uniform consistency and loaded from the mixer into the test vessel using appropriate hand tools. A set period of 4 days was allowed prior to testing.

- K-Mag. – The "fluid" nature of the prepared material prior to hardening allowed hand-mixing preparation. Multiple batches of approximately 2.6 gallons each were sequentially prepared in 5-gallon buckets and then loaded into the test vessel using appropriate hand tools. Each batch was allowed to set for 45 minutes to 1 hour for hardening prior to the next layer being added. Gravity settling of the material prior to hardening caused a supernatant liquid layer to develop which was pumped off. From lab conditions of nominally 22°C, the material heated to approximately 40°C during hardening. Limited material expansion of the hardened material was observed in lab-scale preparation tests, so concrete expansion joints were used on the test vessel walls. The prepared simulant was cured a minimum of 3 days prior to testing. Since a set period of 4 days was used for the simulant batch used in effectiveness testing, a sample was prepared to facilitate compressive strength characterization testing.

4.2 Separate Effects Testing

Gauglitz et al. (2017) specified the critical shear stress (the applied shear stress for which greater values result in the onset of erosion at a certain rate) as a key processing property, following the American Society for Testing and Materials (ASTM) Method C1750-11 that provides general considerations for the development, verification, validation, and documentation of high-level radioactive waste tank simulants. A material's critical shear stress for surface erosion provides a lower bound for the applied shear stress required to initiate erosion at a minimum rate. Higher applied stress values are required for a range of erosion rates, and critical shear stress values can be defined for each rate. However, there was no information on the erosion rate of the simulants (Gauglitz et al. 2017) and extremely limited waste information (e.g., Meacham et al. 2012) for this key waste property.

As noted in Gauglitz et al. (2017), strength (shear and compressive as specified in the original work, section 4.1) is being used as an alternate physical property. The use of shear strength relative to the shear strength of a simulant with a different composition can be misleading with respect to the erosion rate at a given applied stress; for example, a simulant with a higher shear strength can erode at a faster rate than a different simulant with a lower shear strength when the same stress is applied. Therefore, data useful to describe erosion rate characteristics for each of the three simulants were collected during Phase I HWEE startup testing.

ASTM D5852-00 provides a standard method of expressing erosion resistance. In general, the method relies on providing an applied stress via a fluid jet to a sediment surface for finite test periods and measuring the resultant scour depth. A modification of this technique was applied in Meacham et al. (2012) using erosion depth or erosion distance at increasing applied stresses to estimate a critical stress for erosion of waste and simulants. Using a similar approach, for information only data were taken using the HWEE for each of the three simulants.

The HWEE was operated at a fixed simulant location that was previously undisturbed with no rotation at a set operating pressure and duration. The three jets of the HWEE thus bored three holes into the simulant surface that were characterized for depth. Subsequent tests at new locations were at different set operating pressures and durations. The resultant data set provides a representative erosion depth as a function of operating pressure and time for each simulant. For a given operating pressure and time, a simulant with a shallower depth of bored hole was more resistant to erosion from the HWEE jets, similar hole depth indicated similar resistance to erosion, etc.

For these tests, the three simulant materials were co-located in a single test vessel and were uniform in depth. The HWEE was set to a constant standoff distance (nominally 0.25 inches, ±0.25 inches) above the flat region of the undisturbed simulant surfaces. The exact standoff distance is immaterial to these test results; of significance is that the HWEE elevation was held constant over each of the simulants. The separate effects test results are summarized in Table 4.2 (provided for information only).

Table 4.2. Separate Effects Tests Results Summary

Simulant	HWEE Operating Pressure (psi)	Nominal HWEE Operating Time (s)	Average Jet Penetration Depth (in.)[1]
Kaolin	1,000	10	Complete Simulant Depth[1]
	1,000	2	
	1,000	0.7	
Kaolin/plaster	1,000	10	
	1,000	2	
	1,000	0.5	
K-Mag	1,000	0.71	1.81
	1,000	2.2	1.93
	1,000	10	2.45
	5,000	2	1.88
	5,000	9.5	4.44

[1] Simulant depth with jet angle for these tests was nominally 5.3 in. Simulant depths may slightly vary, and HWEE body was at slight angle to waste surface.

It is significant to note that:

- The kaolin and kaolin/plaster simulants, at significantly different shear strength of 3.6 kPa and 160 kPa respectively (Table 4.1), were eroded to the same depth over the range of HWEE operations tested. These results imply that the erosion behavior of the kaolin and kaolin/plaster simulants is similar for the tested HWEE operational parameters.
- The K-Mag simulant, at a much larger compressive strength of 12 MPa (Table 4.1), was eroded to a substantially shallower depth than the kaolin and kaolin/plaster at the same HWEE operating pressures and times. These results imply that the K-Mag is more resistant to erosion than the kaolin and kaolin/plaster simulants. The strength of the K-Mag simulant versus measured shear strength reported for Hanford waste is discussed below.
- The jet erosion depth into K-Mag simulant is shown to increase with operating pressure and time as expected.

If the compressive strength of the K-Mag is related to the shear strength by the typical factor of 0.5, the K-Mag shear strength is 6 MPa.[1] This result for shear strength is a factor of approximately 328 larger

[1] Although this relation for compressive strength and shear strength has been supported by practice as well as by experimentation and numerical results, it is not universally accepted. See Appendix B of Gauglitz et al. (2009).

than the highest shear vane measured shear strength reported for Hanford waste sediment (see entry for AY-101 in Table I.2 of Wells et al. 2011), and 240 times larger than the maximum shear vane measured shear strength reported for Hanford waste crust (see entry for SY-101 in Figure 11.3 of Poloski et al. 2007). Again emphasizing that the strength is being used as an alternate physical property for erosion, the impingement of the HWEE jet into the K-Mag may be indicative that the HWEE would be capable of eroding most Hanford wastes.

5.0 HWEE Demonstrations

5.1 HWEE Components Testing

This section provides the results of testing that was conducted to establish baseline water usage of the HWEE, mole, flush line, and jet pump. This section also provides the results of tests to determine the water retrieval rate of the jet pump versus operating pressure.

5.1.1 Water Usage

This water usage testing was done to fulfill data requirements in the Test Plan (section 6.1.1, Water Usage of HWEE) for the HWEE and associated components listed in the following subsections. Water usage is derived using a catch-and-weigh system to collect and weigh the water the device(s) used during steady-state conditions for a collection time; typically at least 1 minute. The calculation for water usage is:

Water Weight Collected (steady state) / Collection Time = Water Usage Rate

Data was collected over a range of operating pressures, typically from 1,000 to 10,000 psi in 1,000 psi increments and repeated twice using slightly larger increments. To achieve the highest pressures, the PRM was not used and the HWEE component hoses were connected directly to the high-pressure foot pedal. This testing configuration had pressure measured at the main high-pressure pump and then had water flowing through 150 feet of high-pressure hose (0.50-inch inner diameter) and one foot pedal prior to reaching the HWEE component being tested.

Prior to data collection, the weight of the tank is typically tared (e.g., zeroed) and then as the device runs the weight in the tank increases. Various tanks were used to collect water during water usage testing.

Initial HWEE water usage testing in a small open tank (done on 8/8/2017) allowed water to spray and splash out of the tank resulting in water loss that could not be accounted for. All subsequent water usage testing associated with the HWEE directly (HWEE, mole, and flush) had the HWEE tarped to direct all water spray and splashing back into the water collection tank so that it could be included in the water usage calculation. The HWEE standoff distance from the water collection tank bottom was on the order of 22 inches to the HWEE metal bottom. Standoff distance was required to allow water collection to be accumulated in the water collection tank without submerging the water jet, however, this is not the typical operating mode and much closer standoff distances (i.e., ¼ inch) reduces or eliminates water spray and splash considerably. The HWEE manifold was not rotating during the water usage tests.

For some of this testing, the HWEE was slightly skewed from perpendicular due to the HWEE connection arm being bent (see section 2.2.1) and rubber shroud may not have been attached. Because only water usage data was being collected, these items had no effect on the results of data being collected.

The water usage composite summary data are shown in Figure 5.1 and Table 5.1.

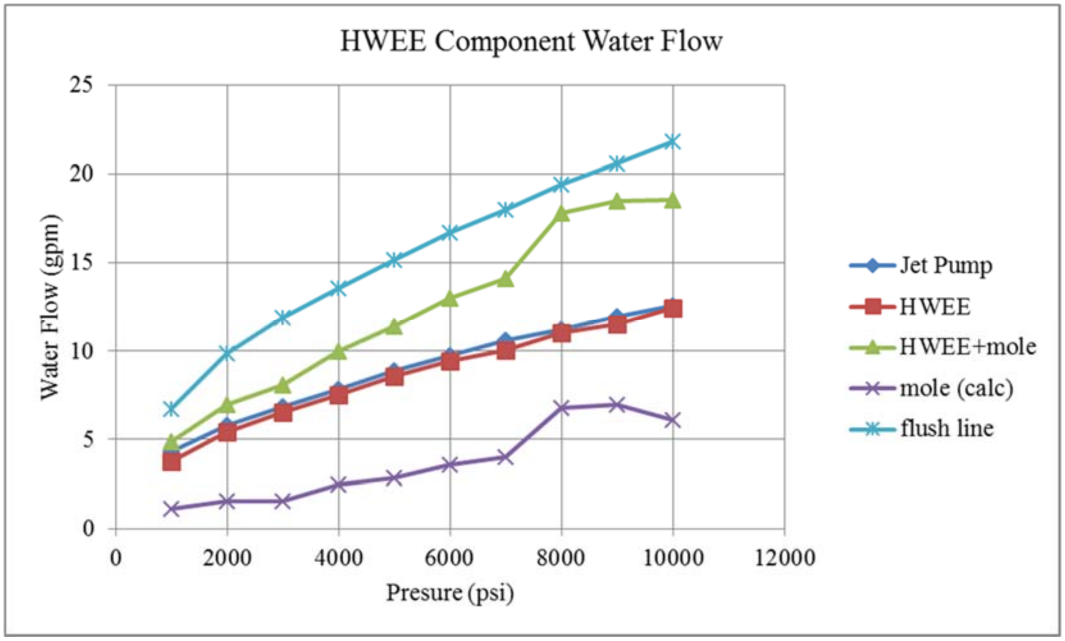

Figure 5.1. Water Usage Composite Summary Graph

Table 5.1. Water Usage Composite Summary Data

Pressure (psi)	**Water Usage (gpm)**				
	Jet Pump	HWEE	HWEE+mole	mole (calc)	Flush Line
1000	4.33	3.74	4.86	1.12	6.72
2000	5.81	5.42	6.98	1.56	9.84
3000	6.84	6.52	8.09	1.57	11.89
4000	7.85	7.54	9.99	2.45	13.58
5000	8.88	8.56	11.38	2.82	15.18
6000	9.72	9.44	13.01	3.57	16.68
7000	10.63	10.06	14.09	4.03	18.03
8000	11.23	11.01	17.8	6.79	19.42
9000	11.97	11.52	18.52	7	20.6
10000	12.59	12.45	18.57	6.12	21.83

5.1.1.1 HWEE

Water usage of only the HWEE rotating jets is shown in Figure 5.2 and Table 5.2 with initial run and two repeat runs at larger intervals all taken on 8/18/2017. For this testing the HWEE mole had been permanently plugged and jets were not rotating. This data will be also be used to determine HWEE mole only water usage.

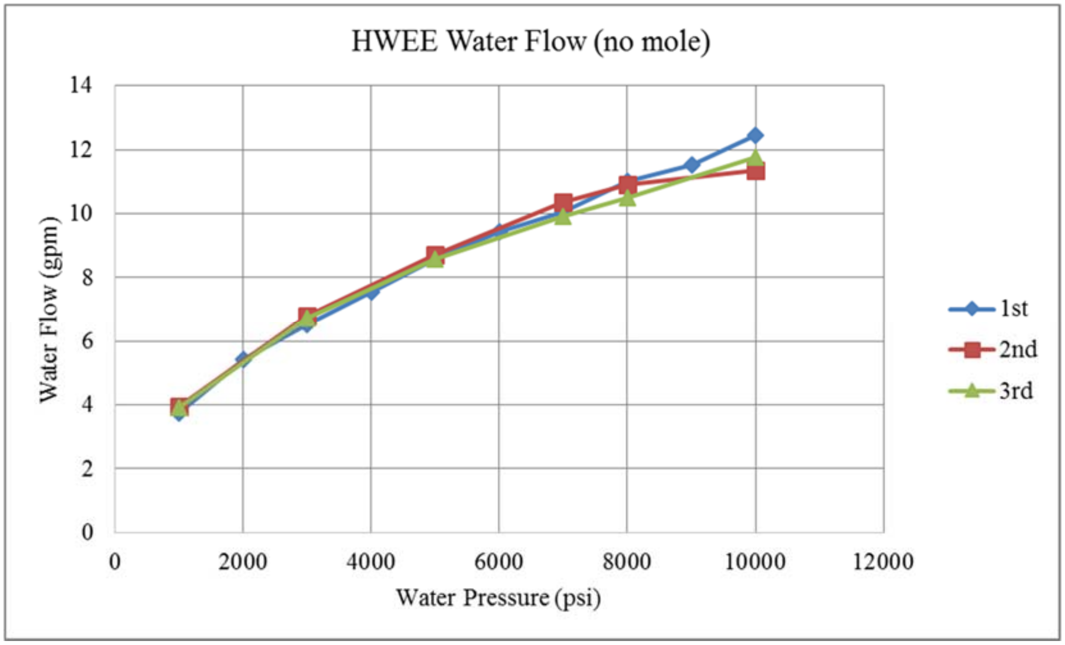

Figure 5.2. Water Usage HWEE with Repeat Runs Graph

Table 5.2. Water Usage HWEE with Repeat Runs Data

Pressure (psi)	**Water Usage (gpm)**				
	1st	2nd	3rd	Average	Std. Dev.
1000	3.74	3.95	3.92	3.87	0.11
2000	5.42				
3000	6.52	6.78	6.73	6.68	0.14
4000	7.54				
5000	8.56	8.7	8.57	8.61	0.08
6000	9.44				
7000	10.06	10.36	9.91	10.11	0.23
8000	11.01	10.92	10.51	10.81	0.27
9000	11.52				
10000	12.45	11.34	11.76	11.85	0.56

5.1.1.2 HWEE Flush

Water usage of only the HWEE flush originating inside the HWEE screen is shown in Figure 5.3 and Table 5.3 with initial run data taken on 8/11/2017 and two repeat runs at larger intervals taken on 8/12/2017.

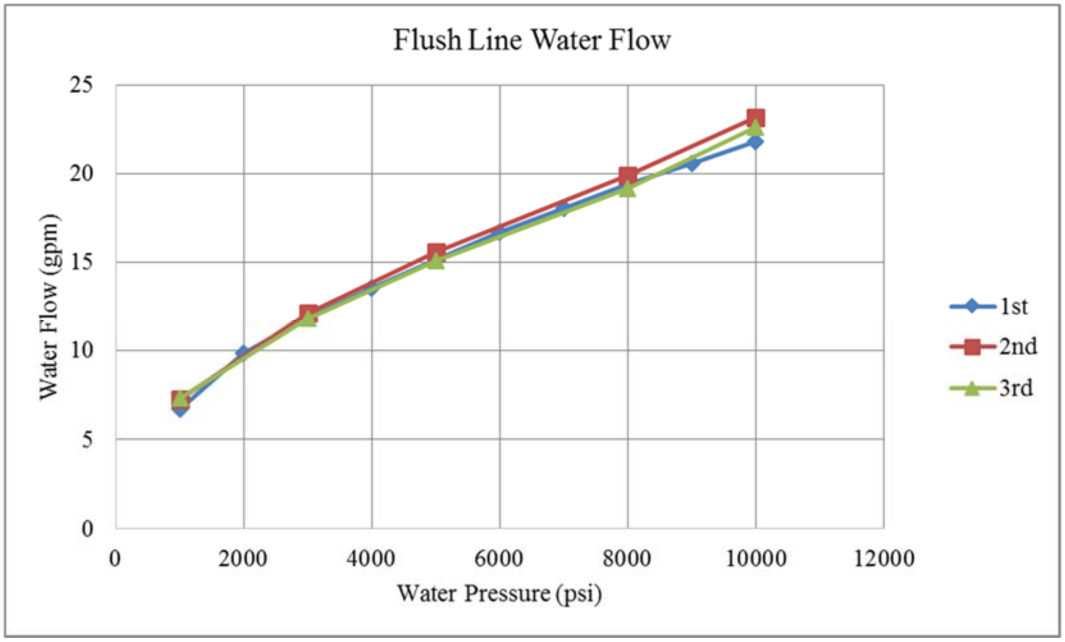

Figure 5.3. Water Usage HWEE Flush with Repeat Runs Graph

Table 5.3. Water Usage HWEE Flush with Repeat Runs Data

Pressure (psi)	**Water Usage (gpm)**				
	1st	2nd	3rd	Average	Std. Dev.
1000	6.72	7.26	7.32	7.10	0.33
2000	9.84				
3000	11.89	12.15	11.84	11.96	0.17
4000	13.58				
5000	15.18	15.57	15.12	15.29	0.24
6000	16.68				
7000	18.03				
8000	19.42	19.89	19.19	19.50	0.36
9000	20.6				
10000	21.83	23.17	22.6	22.53	0.67

5.1.1.3 HWEE Mole

Water usage of only the HWEE mole originating outside the HWEE screen is determined from two data sets in the following calculation:

Water Usage (HWEE and mole together) – Water Usage (HWEE with mole plugged) = HWEE Mole water usage

The first data set is the HWEE and mole operating together with initial run data taken on 8/11/2017 and two repeat runs at larger intervals on 8/12/2017 with results shown in Figure 5.4 andTable 5.4.

The second data set is the HWEE only (mole plugged) described in section 5.1.1.1.

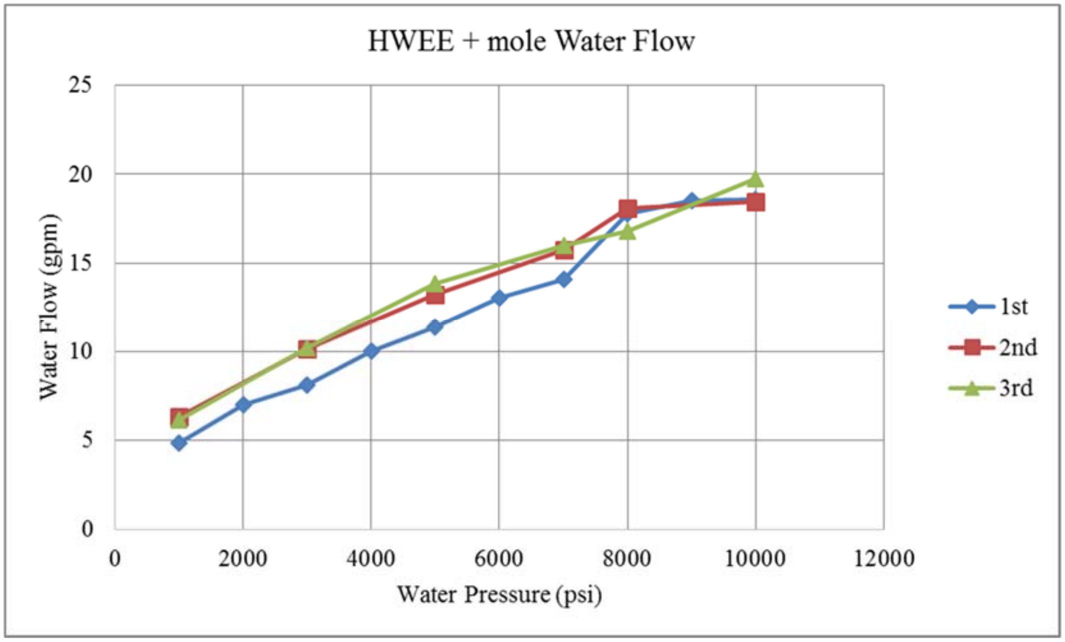

Figure 5.4. Water Usage HWEE + Mole with Repeat Runs Graph

Table 5.4. Water Usage HWEE + Mole with Repeat Runs Data

Pressure (psi)	**Water Usage (gpm)**				
	1st	2nd	3rd	Average	Std. Dev.
1000	4.86	6.33	6.12	5.77	0.80
2000	6.98				
3000	8.09	10.12	10.18	9.46	1.19
4000	9.99				
5000	11.38	13.19	13.83	12.80	1.27
6000	13.01				
7000	14.09	15.75	16.01	15.28	1.04
8000	17.8	18.06	16.79	17.55	0.67
9000	18.52				
10000	18.57	18.44	19.76	18.92	0.73

The calculated HWEE mole only data is shown in Figure 5.5 and Table 5.5.

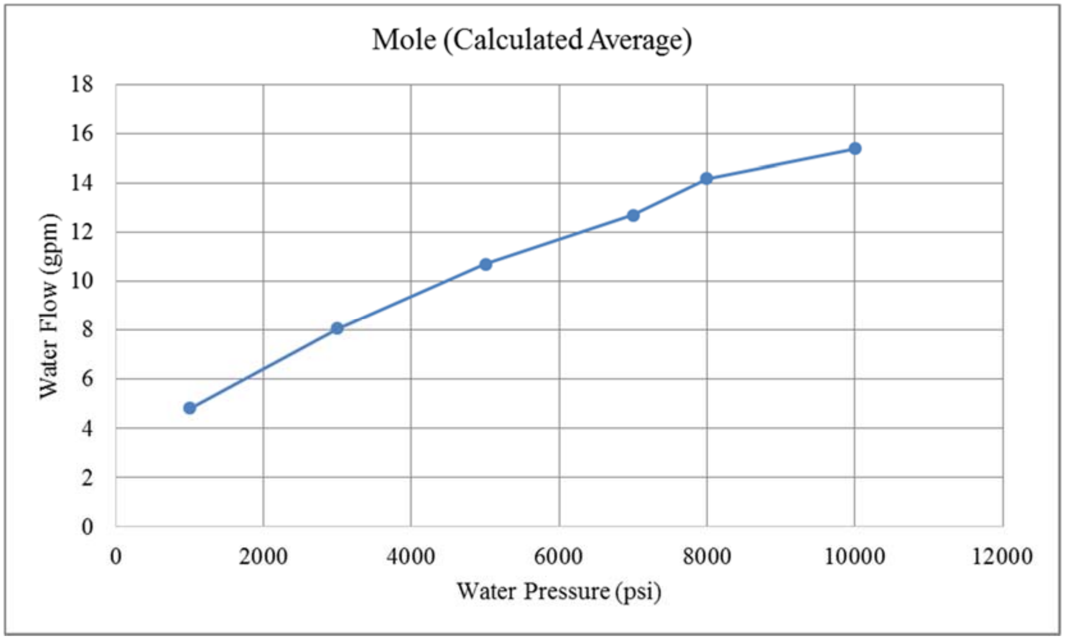

Figure 5.5. Water Usage HWEE Mole (Calculated) Graph

Table 5.5. Water Usage HWEE Mole (Calculated) Data

Pressure (psi)	**Water Usage (gpm)**		
	HWEE (Average)	HWEE+Mole (Average)	Mole (Calculated Average)
1000	3.87	5.77	4.82
2000			
3000	6.68	9.46	8.07
4000			
5000	8.61	12.80	10.71
6000			
7000	10.11	15.28	12.70
8000	10.81	17.55	14.18
9000			
10000	11.85	18.92	15.39

5.1.1.4 HWEE Jet Pump

Water usage of only the HWEE jet pump is shown in Figure 5.6 and Table 5.6 with initial run data taken on 8/11/2017 and two repeat runs at larger intervals taken on 8/12/2017. Water collection for the HWEE jet pump was in the retrieval tank.

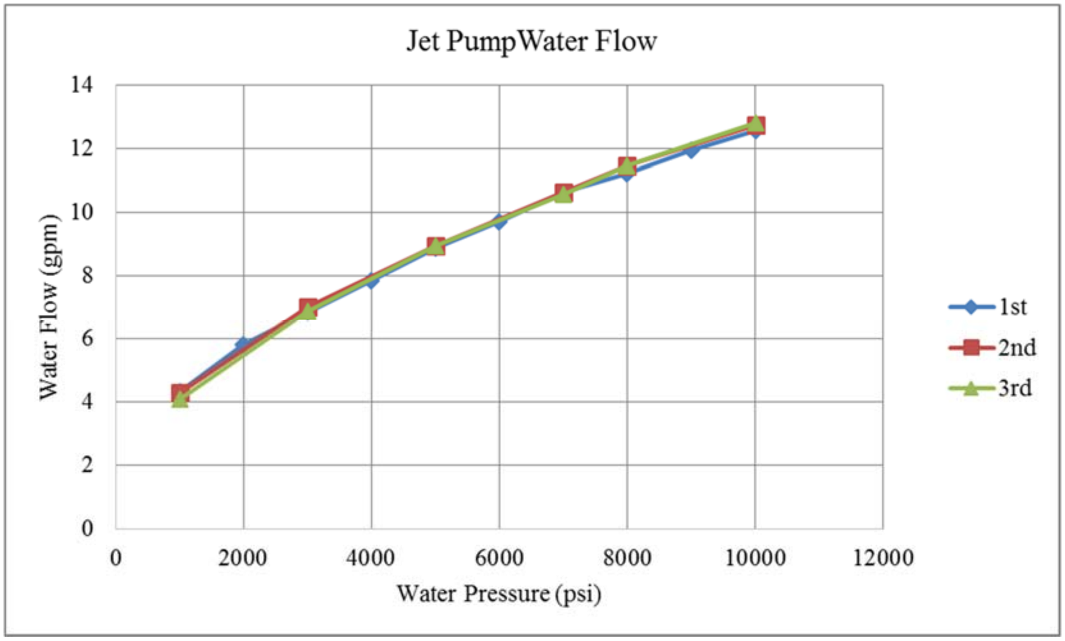

Figure 5.6. Water Usage HWEE Jet Pump with Repeat Runs Graph

Table 5.6. Water Usage HWEE Jet Pump with Repeat Runs Data

Pressure (psi)	**Water Usage (gpm)**				
	1st	2nd	3rd	Average	St. Dev.
1000	4.33	4.28	4.09	4.23	0.13
2000	5.81				
3000	6.84	7.03	6.88	6.92	0.10
4000	7.85				
5000	8.88	8.94	8.94	8.92	0.03
6000	9.72				
7000	10.63	10.63	10.59	10.62	0.02
8000	11.23	11.48	11.47	11.39	0.14
9000	11.97				
10000	12.59	12.73	12.82	12.71	0.12

5.1.2 Water Retrieval

Water retrieval by the HWEE jet pump was collected to determine performance to pump water when fully submerged and if HWEE flush spray was being contained at low pressures. These water collection data are associated with Test Plan section 2.1 D.1 (Determine water usage/water remaining) and 2.1 D.4 (Determine frequency of back flushing or cleaning and associated water usage).

Water retrieval is derived using a catch-and-weigh system to collect and weigh water the device(s) during steady-state conditions for a collection time; typically at least 1 minute. The calculation for water retrieval is:

(Water Weight Collected (steady state) / Collection Time) – HWEE Jet Pump Water Usage = Water Retrieval Rate

Data was collected over a range of operating pressures, typically from 1,000 to 10,000 psi in 1,000 psi increments and repeated twice using slight larger increments. To achieve the highest pressures, the PRM was not used and the HWEE component hoses were connected directly to the high-pressure foot pedal. This testing configuration had the 10,000 psi operating pressure measured at the main high-pressure pump and then had water flowing through 150 feet of high-pressure hose and one foot pedal prior to reaching the HWEE component being tested.

Prior to data collection, the weight of the retrieval tank is typically tared (e.g., zeroed) and then as the device runs the weight in the tank increases.

5.1.2.1 HWEE Flooded Suction with HWEE Jet Pump

Water retrieval of the HWEE jet pump with the HWEE suction flooded is shown in Figure 5.7 and Table 5.7 with initial data and two repeat runs at larger intervals taken on 8/24/2017. Water collection for the HWEE jet pump was in the retrieval tank and HWEE jet pump was operating at 10,000 psi. Water retrieval rate is calculated using the equation in section 5.1.2 determined by total water collected (HWEE suction port water collected plus HWEE jet pump water) less HWEE jet pump water used.

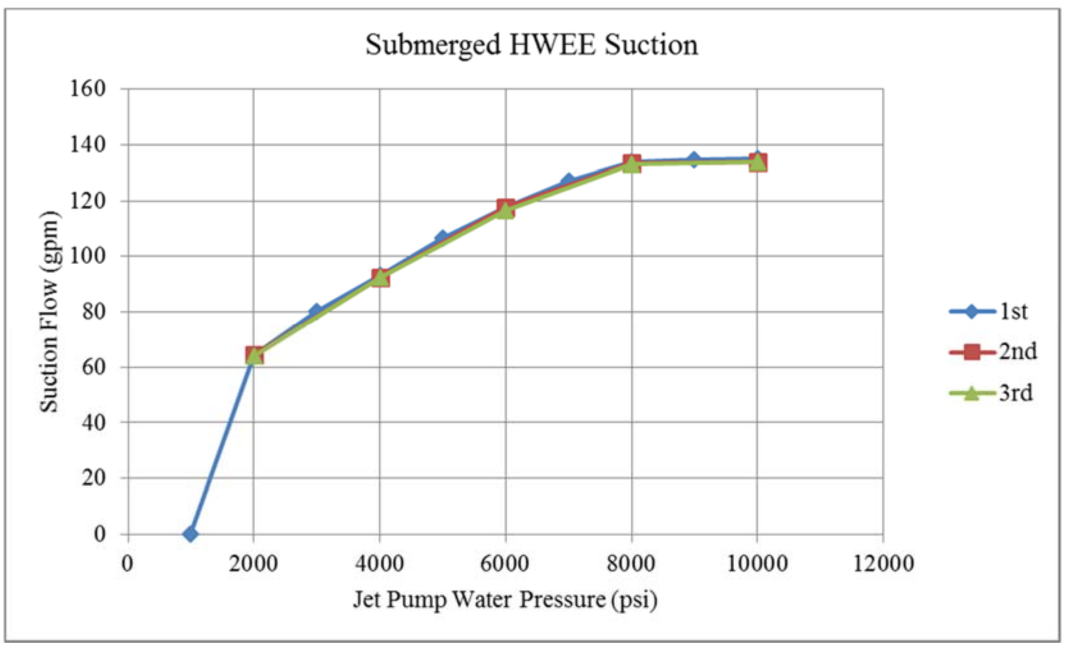

Figure 5.7. Water Retrieval HWEE Flooded Suction with Jet Pump with Repeat Runs Graph

Table 5.7. Water Retrieval using the HWEE Flooded Suction with Jet Pump with Repeat Runs Data

Pressure (psi)	Water Retrieval (gpm)				
	1st	2nd	3rd	Average	St. Dev.
1000	0.05				
2000	64.3	64.3	63.9	64.17	0.23
3000	80.3				
4000	93.2	92.4	92.6	92.73	0.42
5000	106.6				
6000	117.7	117.7	116.6	117.33	0.64
7000	127				
8000	134	133.5	132.9	133.47	0.55
9000	134.5				
10000	135.1	134	133.8	134.30	0.70

Water retrieval of the HWEE jet pump for this test was evaluated by submerging the HWEE fully into a water pool (i.e., HWEE flooded suction) and determining water retrieval rates at various HWEE jet pump pressures from 1,000 to 10,000 psi. Higher pressure runs with high retrieval rates required the HWEE to be actively moved down (i.e., lift moved down in Z-axis) to keep HWEE suction flooded.

Some earlier data were taken and not used because of unaccountable water. Data taken on 8/8/17 at 8,000 psi had water splashing out of the retrieval tank due to lack of the jet pump energy dispersion system that was later rectified. Data on 8/17/2017 had some bad data on the initial run between 3,000 and 10,000 psi because a submersible pump used to transfer water from retrieval tank previous run was found to be siphoning water when left connected. Additional repeat runs at larger intervals on 8/17/2017 with siphon stopped (hose disconnected) confirmed that initial run data were suspect because of siphon issue. Test runs on 8/24/2017 produced the best data (reported here) and the submersible pump hose was disconnected before all test runs.

5.1.2.2 Flush Spray Capture by HWEE Jet Pump

During testing it was speculated that the HWEE jet pump may be capturing all or a portion of the internal flush spray, especially at low flush pressures in the range of 500 to 1,000 psi. If this phenomenon was occurring it may be a way to flush the HWEE screen with minimal or no water addition into the simulant tank. Some very preliminary testing was done on 8/28/2017 with the HWEE located at the top of the capture tank (several feet off the tank bottom). Testing was completed for the flush operating at 500 psi with cone jets rotating with water off (i.e., no jet cone spray) but stopped early during the 1,000 psi run when it appeared the flush fitting may be leaking. Quick inspection of the flush fittings did not see any obvious leak or untightened fitting on HWEE but this may need to be checked during any WRPS post-test inspection of the HWEE.

Test results are inconclusive, but visual observation of flush water capture by the HWEE suction port was not promising as there was noticeable flush spray exiting the bottom of the HWEE and being collected in the capture tank. It is speculated that the jet pump may have a better chance of capturing the internal flush spray when the HWEE is in close proximity to the surface in its more typical operating condition. With the HWEE skirt close to the surface, the jet pump may be able to provide more suction influence on the flush spray; however, there was no testing done to evaluate this theory.

5.2 Retrieval Demonstrations

The retrieval demonstrations were performed as outlined in Test Plan section 5.2, HWEE Retrieval Tests, to determine the HWEE performance at retrieving a wide range of simulant types that could be expected in a Hanford tank farm waste tank retrieval that included kaolin (sludge), kaolin/plaster (hardpan), and K-Mag (saltcake). Phase I retrieval testing is intended to start determining the retrieval characteristics of the currently designed HWEE concept with its new features (see section 1.1 and Test Plan section 3.0) regarding, waste retrieval rate, waste dilution ration, water usage/water remaining, screen flush/cleaning frequency, and aerosol generation. Retrieval testing results from the WREE were used as a baseline (see Test Plan section 2.2, Prior Testing Results) for setting the initial HWEE retrieval parameters for kaolin (sludge) and kaolin/plaster (hardpan) simulants. No previous retrieval operation of a HWEE-type device in K-Mag (saltcake) had been done so these operating parameters had to be developed as part of this testing effort.

The retrieval demonstrations were done in two progressive testing steps (see Figure 5.8) as follows:

1. Retrieval Startup Testing (from Test Plan section 5.2.2, Retrieval Startup Test Procedure) – This retrieval testing consisted of all three testing simulants together in a simulant bed separated into individual strips for each simulant that would allow HWEE testing over a single path for about 6 feet in length. For kaolin (sludge) and kaolin/plaster (hardpan) this testing was a verification that the HWEE operating parameters outlined in the Test Plan were adequate and adjust as necessary for the follow-on retrieval tests of a single simulant in a larger volume test bed (see next step). For K-Mag (saltcake) the intent was similar but instead the operating parameters had to be developed since there was no previous data to verify against.

2. Retrieval Testing (from Test Plan section 5.2.3, Retrieval Test Procedure) – This retrieval testing consisted of each simulant material is a much larger simulant bed that allowed extending horizontal mining path (i.e., serpentine path of at least six legs verses a single path) and deeper mining due to more simulant depth (8 inches verses 4 inches), except for K-Mag that was at 4-inch depth.

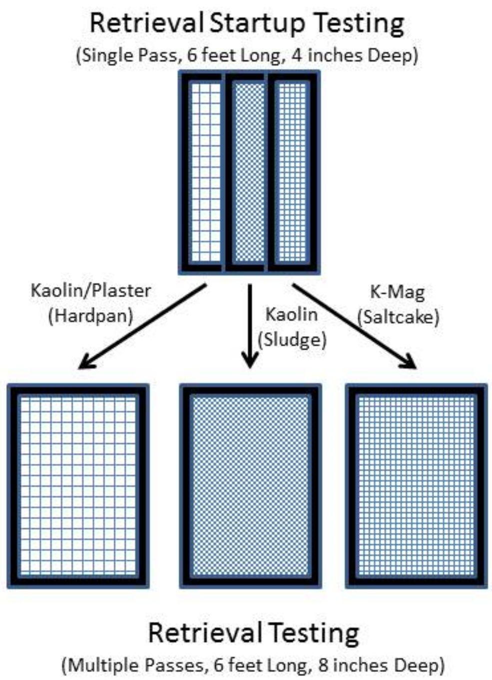

Figure 5.8. Retrieval Demonstration Tests

5.2.1 Retrieval Startup Testing

Retrieval startup testing verified proper operation of the test equipment and provided HWEE performance parameters in the three simulants. The key goals were fulfilled in this testing as the HWEE retrieval operating parameters (nozzle size, water pressure, and traverse speed) were determined to adequately cut into the different simulant material (target depth of 1 inch). During this testing HWEE screen inlet plugging was not observed, although some buildup of kaolin and kaolin-plaster was noted on the screen at the end each traverse. Based on this, the screen was conservatively flushed after every traverse. This testing did not optimize any retrieval parameters but only determined viable HWEE retrieval parameters to be used in the following larger single simulant retrieval tests (see section 5.2.2, Retrieval Effectiveness Testing).

Retrieval startup testing was started and completed on 8/16/2017. Test results are summarized in Figure 5.9.and Table 5.8 and Table 5.9. The equipment initial target parameters defined for these simulant and operating procedures is found in the Test Plan section 5.2.2.

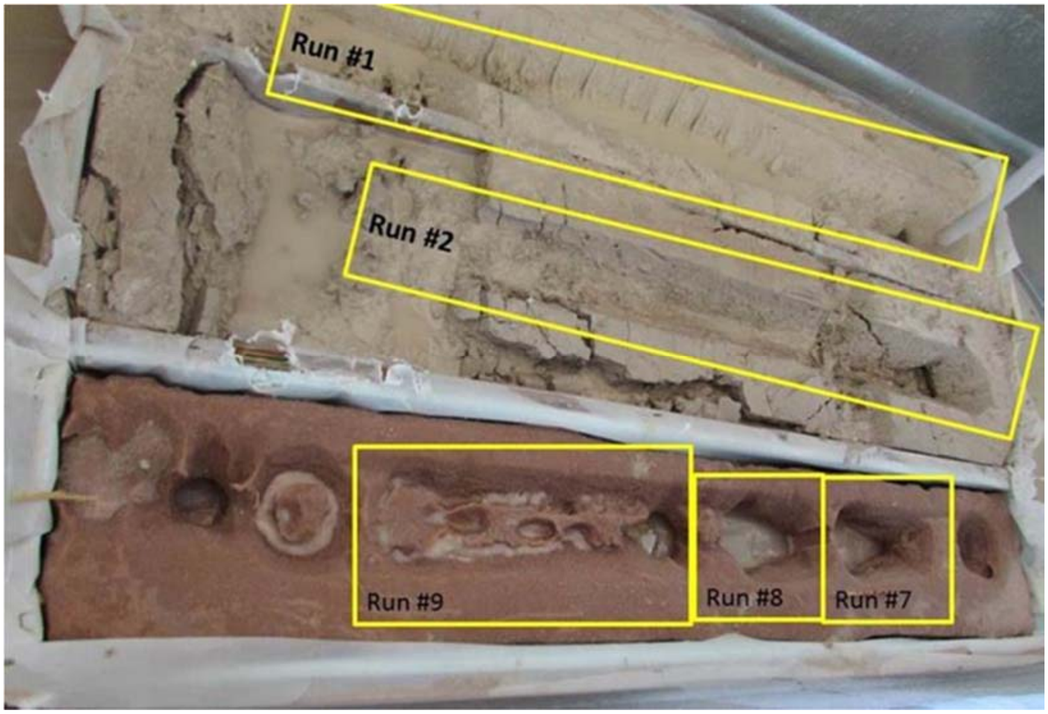

Figure 5.9. Retrieval Startup Test Simulant Results (Kaolin/Plaster, Kaolin, K-Mag top to bottom)

Table 5.8. Retrieval Startup Test Summary

Run	**Simulant**	**Traverse Details**	**Traverse Speed** (ipm)	**Pressure HWEE/Pump** (psi)	**RPM** (nom)	**Comments**
1	Kaolin/Plaster (hardpan)	Single pass 1/4 inch above with return pass 1 inch lower	300	1000 / 9500	300	Clean groove produced
2	Kaolin (sludge)	Single pass 1/4 inch above with return pass 1 inch lower	300	1,000 / 9500	300	Groove produced but not as clean as kaolin/plaster
3	K-Mag (saltcake)	Single Short Run	150	3000 / 9500	300	Limited surface penetration
4			75	6600 / 10000	300	
5			75	6700 / 10000	75	
6			75	~9500* / 10000	75	
7		Single Short Run (Over previous runs with limited penetration)	1	~9500* / 10000	75	Full penetration through simulant to wood base below
8			1	6600 / 10000	100	
9			8	6600 / 10000	100	Penetration deep but high ridges were 3/4 inch below surface

Note: * Estimated HWEE pressure. HWEE connected directly to from foot pedal like component testing to achieve maximum pressure. HWEE jet pump not operating for this testing. Water buildup in retrieval area was minimal so should have minimal effect on retrieval.

Table 5.9. Retrieval Startup Measurement Summary

<table>
<tr><th rowspan="2">Run</th><th rowspan="2">Simulant</th><th colspan="4">Measurements of Mining Penetration Into Simulant</th></tr>
<tr><th>Longitutdial / Traverse Location in Field</th><th>Top Width (inches)</th><th>Undisturb Depth (inch)</th><th>Comments</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Kaolin/Plaster (hardpan)</td><td>Center / Center</td><td>5.39</td><td>4.24</td><td>Depth of 1.48 inch to top of liquid in trench</td></tr>
<tr><td>18 inches from West / Center</td><td>5.43</td><td>3.5</td><td></td></tr>
<tr><td>18 inches from West / Center</td><td>5.4</td><td>2.7</td><td></td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">Kaolin (sludge)</td><td>Center / Center</td><td>5.4</td><td>4.25</td><td></td></tr>
<tr><td>18 inches from West / Center</td><td>5.25</td><td>4.25</td><td></td></tr>
<tr><td>18 inches from West / Center</td><td>5.25</td><td>4.25</td><td></td></tr>
<tr><td colspan="6">K-Mag Notes:</td></tr>
<tr><td>3</td><td rowspan="7">K-Mag (saltcake)</td><td colspan="4">Penetration at start of run: Circle 2.75 inch wide and 0.29 inches deep due to longer dwell time before movement. Penetration much less after run continued.</td></tr>
<tr><td>4</td><td colspan="4">Measured ~ 0.05 inch depth of 3.75 inch wide</td></tr>
<tr><td>5</td><td colspan="4" rowspan="4">No measurements taken. Visual observation only.</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td><td colspan="4">Measured depth 0.9 inch at center and 1.46 inch deep at edges.</td></tr>
</table>

Kaolin and kaolin/plaster retrieval startup testing (runs 1 and 2 respectively in Table 5.8) confirmed that the defined operating parameters in the Test Plan were adequate after an initial pass with HWEE spaced ¼ inch above the simulant and then a return pass were sufficient to allow the HWEE to be lowered from the initial pass height to 0.75 inch below the original simulant surface.

K-Mag retrieval startup testing required an iterative process to determine adequate parameters for retrieval testing as shown by the number of tests completed. Retrieval runs at the higher transverse speeds (75 to 300 inches per minute) show little to no surface penetration (runs 3–6). In the middle of this testing (runs 6 and 7), the HWEE was disconnected from the PRM and tied directly to the main pump to generate about 3,000 psi more pressure (increase from 6600 psi to around 9500 psi) as done in HWEE components testing (see section 5.1) but surface penetration on run 6 was similar to the previous run 5. At this point it was decided to slow the transverse speed way down to spend more time on target to get penetration into the K-Mag surface and 1 ipm was arbitrarily picked as a starting point. Operating at this slow speed at maximum pressure (run 7) resulted in a complete cone-shaped penetration of the K-Mag to the wooden base and therefore this parameter was too conservative for the targeted 1-inch penetration target. The HWEE was reconfigured back to normal operating mode using the PRM with HWEE jet pump operating and the previous test was rerun (run 8) but with the HWEE now limited to 6600 psi maximum pressure; penetration results were comparable to run 7 and again the operating parameters were too conservative. Since transverse speeds of 75 imp was not enough and 1 ipm was too much, it was decided to increase the transverse speed to 8 ipm which would be approximately 10% of the lowest high range tested resulting in run 9. Good penetration into the K-Mag was achieved at 8 ipm; however, post-test measurements showed ridging effects with minimum depth of 0.9 inches, which was less than the targeted 1-inch minimum depth. K-Mag testing was stopped after run 9 because insufficient simulant remained in the test bed to do more testing.

In summary, this testing confirmed the kaolin and kaolin/plaster operating parameters for retrieval. K-Mag testing revealed that run 9 operating parameters at 8 ipm were close to meeting the 1-inch target depth so it was decided that 6 ipm should be a sufficient but likely somewhat conservative starting parameter for the following retrieval testing. Since K-Mag is hard and impacts to the HWEE could be damaging, it was decided by all, including the client to error on the slightly conservative side regarding mining depth with K-Mag. The equipment operating parameters confirmed by startup retrieval testing for the different simulants are listed in section 5.2.2, Retrieval Effectiveness Testing.

5.2.2 Retrieval Effectiveness Testing

Retrieval effectiveness testing defined the performance and operating characteristics of the HWEE to retrieve waste simulants kaolin (sludge), kaolin/sludge (hardpan) and K-Mag (saltcake) in a limited mining operation on small volumes with a flat topographical surface. The operating parameters for this testing (provided in Table 5.10) were obtained from earlier retrieval startup testing (see section 5.2.1). The testing goal to demonstrate the effectiveness of the HWEE to retrieval these waste simulants is reported in section 5.3, Retrieval Effectiveness Results; however, these reported results likely do not fully demonstrate the HWEE's full effectiveness capability because the Phase I test setup and scope of work was designed to show viability of retrieval and not optimization. Some of the HWEE associated features that should be optimized to further benefit HWEE retrieval effectiveness include: (1) design features (e.g., nozzle type, size, shape); (2) operating parameters (e.g., transverse speed, standoff distance, and jet rotation); and (3) mining strategy (e.g., mining path, tilting HWEE tilt to reach tank edges, alternating the direction of the mining path). This testing effort obtained valuable information for using and optimizing the HWEE to more effectively retrieve the simulants as part of this testing effort as well as for configuring, tuning, and using the HWEE to retrieve different simulants or different retrieval operation scenarios in the future.

Table 5.10. Retrieval Startup Testing Equipment Operating Parameters

Kaolin (Sludge)	Rotation Speed Traverse Speed Waterjet pressure HWEE vertical stepping	300 RPM 300 inches/minute 1000 psi 1 inch
Kaolin/Plaster (Hardpan)	Rotation Speed Traverse Speed Waterjet pressure HWEE vertical stepping	300 RPM 300 inches/minute 3000 psi 1 inch
K-Mag (Saltcake	Rotation Speed Traverse Speed Waterjet pressure HWEE vertical stepping	75-100 RPM 6 inches/minute 6,600 to 7,000 psi 1 inch

For this retrieval testing there were some operational mining restraints resulting from the test setup operational envelope that includes the following:

- Avoiding contact of the HWEE with hard surfaces such as the simulant mold side frame as well as the bottom and sides of the simulant tank.
- Avoiding contact of the HWEE with simulant edges and features left by previous mining operation as layers of mining occurred. Because the Phase I test setup limited the HWEE orientation to only the vertical axis (no tilt), the cone-shaped mining path created left-sloped edges and required the HWEE to step inward to avoid the edges and deeper mining occurred or offset mining path to take out simulant ridges left between the previous mining operation; this was especially necessary for the harder waste forms like the K-Mag and less so for softer waste forms like the kaolin.
- The Phase I test setup had limited automatic X-Y path movement during this retrieval testing. The testing schedule limited the programming of the gantry scanner system to only a serpentine path that started along the X-axis, jogged over in Y-axis, returned in the opposite direction in X-axis parallel to the start path and then jogged over in Y-axis to the next start position. These X and Y axis motions were programmed together to form a serpentine path as required for each layer and included modification of start and stop distances for both axis. Because of this limitation, simulant ridges left between the X-axis paths had to be removed by moving the HWEE over these ridges and then mining the limited simulant left in the same directional path resulting in inefficient mining as related to retrieval rate and dilution ration. The capability to vary the mining path from layer to layer as well as HWEE head tilt would be expected to increase mining efficiency but this was out of scope for this testing effort.

The actual retrieval methods and results are described in the following subsections for the three waste simulants tested: kaolin (sludge) section 5.2.2.1; kaolin/sludge (hardpan) section 5.2.2.2; and K-Mag (saltcake) section 5.2.2.3. The general testing procedure for retrieval effectiveness testing is found in the Test Plan (see section 5.2.3, Retrieval Test Procedure).

A summary of the actual effectiveness retrieval testing parameters used and mining details/results is shown in Table 5.11. More comprehensive mining details are listed in Appendix A.

Table 5.11. Mining Parameters and Results for HWEE Retrieval Tests

Simulant	**Traverse Speed** (ipm)	**Pressure HWEE/Pump** (psi)	**RPM** (nom)	**Mining Details**	**Mining Results**
Kaolin (sludge)	300	1000 / 9500	300	Similar for both kaolin and kaolin/plaster Total of 7 layers mined, 1 inch depth each layer. Mining path area stepped in as HWEE moved down; starting at 7 passes per layer and ending at 4 passes. Pass location adjusted to mine ridges as needed.	Similar for both kaolin and kaolin/plaster Bored deep on early passes and penetrating to bottom before half mined. Where ridges developed between serpentine path, path adjusted over ridges where they were knocked down substantially. Kaolin more soup like during mining than kaolin/plaster.
Kaolin/ Plaster (hardpan)	300	1,000 / 9500	300		
K-Mag (saltcake)	Overall			Total of 3 layers. Start 7 and end 6 passes per layer.	See details below.

Simulant	Traverse Speed (ipm)	Pressure HWEE/Pump (psi)	RPM (nom)	Mining Details	Mining Results
	6	6600 / 10000	80	Layer 1	Initial pass bored v-groove to bottom with some higher ridges left.
	300	1000 / 10000	300	Layer 2	Clean up pass to remove ridges.
	24	6600 / 10000	90	Layer 3	Final pass removed remaining ridges and tore into bottom wood frame structure.

General mining setup and procedure used during retrieval testing are defined in the steps below. Minor variations that occurred during testing will be discussed in the appropriate simulant specific sub-sections.

1. Make up simulant and place in wood forms at the bottom of the metal simulant container. Move the simulant container under the gantry system for access by the HWEE. Prior to mining the simulant, ensure it is sufficiently cured and characterized.
2. Initial HWEE operation parameters were defined from retrieval startup testing. Ensure all testing parameters are defined and set including the horizontal and vertical positions required for the HWEE automated serpentine path movement. Set horizontal motion to avoid obstructions (e.g., simulant form walls) and vertical motion to obtain a starting height ¼-inch above the simulant surface. Dry run the HWEE serpentine path above simulant to verify clear path for mining.
3. Move HWEE over end of simulant tank outside the simulant frame to set water pressures at the main pump and PRM as required. Pressure is controlled by a remote pump foot pedal for on/off to HWEE pressure components and PRM. Water deposited in simulant tank is removed continuous by an auxiliary diaphragm pump as this is not retrieval tracked water.
4. Move HWEE to starting position in horizontal plane and adjust lift down to the previous defined vertical distance for ¼-inch standoff distance of the HWEE metal bottom to simulant surface. Ensure data acquisition system in operating.
5. When mining operations are ready to start, turn on pressure using the foot pedal and quickly proceed to next step.
6. Start programmed mining path. During mining, activate flush at the appropriate defined locations. When mining path is complete for a layer, de-activated foot pedal to reduce pressure. Prior to pressure deactivation, water to HWEE may be turned off to allow HWEE jet pump remove any localized fluids.
7. HOLD POINTS AS REQUIRED: At the end of each mining layer run, stop and take measurements as appropriate. Holds throughout the testing run may be added to observe testing or other issues that may arise during testing such as the retrieval tank is full and needs to be emptied.

8. Lift HWEE vertically and return to horizontal start position. Activate pressure and move HWEE vertically downward to the next mining layer (typically 1-inch).
9. Repeat steps 5 and 6 until mining operation is completed.

More detail of the above steps can be found in the Test Plan section 5.2.3, Retrieval Test Procedure.

During retrieval, the HWEE rotary water jets in close contact with the simulant are continuously running and interacting with the simulant to break it up locally. The HWEE jet pump ideally is providing sufficient suction at the internal HWEE conveyance port to remove both broken up simulant and water (including flush water) up though the HWEE screen and transport them to the retrieval tank. As the retrieved simulant passes through the HWEE jet pump, the high pressure water from the jet pump may additionally break up the simulant as they are all transported to the simulant tank. To prevent or clear the HWEE screen from simulant clogs, the high pressure spray jet from the HWEE flush systems are used; generally at a set location in the mining path for this testing as deemed appropriate. Flushing operations for this testing only used the HWEE spray flush (see section 5.3.4 for more information related to flushing and screen cleaning related to this testing).

The mining techniques were developed and modified as retrieval demonstrations progressed. Because there was limited simulant volume to work with, parameters picked and mining strategy used was generally conservative. To maximum simulant volume, the full horizontal plane of the simulant bed but used for mining. As downward mining progressed layer by layer, the horizontal mining envelope had to be reduced to avoid the HWEE from contacting the sides of the simulant form (made of wood) as well as the slanted profile made by the HWEE rotary jets that cut the simulant in a slope under the HWEE and for the harder simulants would eventually physically contact the HWEE outer profile as it moved down. Because the HWEE was fixed in a vertical plane, the HWEE could not be pivoted to mine away the sides so therefore inward steps were required as mining depth progressed. This resulted in end profile of the fully retrieved simulants leaving a bathtub shaped trough with simulant on the sides and the wood form bottom exposed.

Also during retrieval mining process, the cone shaped profile of the HWEE jet tended to leave ridges between the horizontal serpentine paths and hence limited the overall horizontal plan retrieval depth to the ridge peaks; especially for the harder simulants. The retrieval mining strategy was adjusted to allow each subsequent layer to center over the simulant ridges left and take those down. This was an obvious inefficient mining technique but did allow for maximum use of the simulant material provided for testing.

Prior to the start of retrieval testing, the simulant was characterized by various techniques depending on the simulant. A typical example is the kaolin and kaolin/plaster simulant where penetrometer readings were made and a sample material was removed for density determination (see Figure 5.10)

Figure 5.10. Retrieval Simulant Field Characterization (Kaolin/Plaster shown)

During retrieval testing, the retrieval tank was collecting retrieved waste and water. When retrieval was completed or the retrieval tank needed to be emptied the collected slurry was observed for any large chucks or abnormalities. Throughout retrieval testing, no large chunks or globs of simulant were noted; but in the case of K-Mag testing, the mining operation penetrated the simulant and into the plastic liner and wood from beneath that were found during retrieval tank observations. Typical retrieval tank slurry had a very liquid top portion with simulant fine particles settled on the bottom and the layering can be seen through the opaque plastic tank that was often measured in to opposing locations to get a general volume of simulant fluid material received (see Figure 5.11)

Figure 5.11. Retrieval Simulant Field Characterization (Kaolin/Plaster shown)

At retrieval stops or at the end of retrieval, the mining profile of the simulate was analyzed. The main method used was to measure waste profiles at various points and concentrating on both low and high points as well as the horizontal path provide left during the mining trail. High and low measurements were and referenced back to the original waste surface. Width profiles were also measured where applicable. The measurements taken were not exact as the simulant had uneven surfaces, the deeply mined portions were often filled with a soft slurry mix or granular simulant material. During depth measurements under some of these conditions, the simulant mining interface surface had to be determined by feel and not by sight. Some of the different measurement techniques are shown in Figure 5.12.

Figure 5.12. Retrieval Testing Simulant Mining Profile Measurements

The discussions in this section are general and used to provide the bases for the following subsections that discuss specific retrieval effectiveness testing for each simulant kaolin (sludge), kaolin/plaster (hardpan), and K-Mag (saltcake).

5.2.2.1 Kaolin (Sludge)

Retrieval of kaolin was effective as performed at the target parameters initially set as summarized in Table 5.11. Result of kaolin retrieval effectiveness testing can be found in section 5.3 and specifically the retrieval rates and slurry dilution rates in section 5.3.1, aerosol generation in section 5.3.2, HWEE reaction forces/torques in section 5.3.3, and flush in section 5.3.4. Specific details related to kaolin retrieval process are further discussed in this section.

Kaolin retrieval testing was started and completed on 8/23/2017. A client demonstration of kaolin retrieval was included during the start of this testing consisting of the successful mining of the first three layers of kaolin in rapid succession with no stops during or between layers for any measured mining assessment as agreed with the client. After the client demonstration, the remaining kaolin was mined and retrieved in layers in the typical manner as other HWEE simulant retrieval testing; however, at the start of this continued retrieval the kaolin had been mostly mined (i.e., broken up to the bottom) and a kaolin/water slurry was all that remained to be mined. The kaolin mining progression is shown in Figure 5.13 and Figure 5.14 and mining details are summarized in

Table 5.12 and Table 5.13, with supporting details in Appendix A.

Figure 5.13. Mining of Kaolin During Retrieval Effectiveness Testing (First and Mid Layers)

Figure 5.14. Mining of Kaolin During Retrieval Effectiveness Testing (Final Layer)

Table 5.12. Mining Operation Summary of Kaolin Effectiveness Retrieval

Mining Details By Layer		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Drop height from previous layer	inches	Start	1	1	1	1	1	1
Position from original simulant surface	inches	0.25	-0.75	-1.75	-2.75	-3.75	-4.75	-5.75
Passes per Layer		6	6	5	5	5	4	4
X-Axis Traverse	inches	~ 44	~ 44	~ 44	~ 44	~ 44	~ 44	~ 44
Y-Axis Offset Between Serpentine Paths on Layer	inches	3.75	3.75	3.75	3.75	3.75	3.75	3.75
X-Axis Offset Inward from Original Serpentine Path			None	None	None	None	None	None
Y-Axis Offset Inward from Original Serpentine Path			None	None	~ 1	1.75	1.75	1.75
Flushing per Layer		End of each pass.						
Flush Time	seconds	2 to 3						
Flush Pressure	psi	500	500	500	500	500	500	500

Table 5.13. Mining Measurement Summary of Kaolin Effectiveness Retrieval

Layer of Measurement	**HWEE Depth (inches)**	**Mining Notes** * HWEE metal bottom depth to original simulant surface. Kaolin simulant depth 8 inches.
1	+ 0.25	Simulant Tank: Start mining at Layer 1 and continuously mine through Layer 3. No measurements on Layers 1 and 2. Retrieval Tank: Continuously filling through Layer 3.
3	-1.75	Simulant Tank: Mined through 3 layers without measurement resulting in a large mined indention in simulant bed. Mined to the bottom of simulant (~ - 8 inches) but light slurry level at - 2.25 inches. Retrieval Tank: Milky liquid with fine particles settled on bottom. No large particles or clumps observed.
4	-2.75	Simulant Tank: Suction only run over simulant bed to removed slurry in Layer 3. Slurry level at -3.34 inches. Retrieval Tank: Milky liquid with fine particles settled on bottom. No large particles or clumps observed.
7	-5.75	Simulant Tank: Completion of mining. Slurry level at -7.22 inches. About 0.75 inches of liquid in tank with some clumps left. Retrieval Tank: Filled 10-1/4 inches on average from opposing corner measurements (11 and 9-1/2 inches). Milky liquid with fine particles settled on bottom. No large particles or clumps observed.

5.2.2.2 Kaolin/Plaster (Hardpan)

Retrieval of kaolin was effective as performed at the target parameters initially set as summarized in Table 5.11. Result of kaolin/plaster retrieval effectiveness testing can be found in section 5.3 and specifically the retrieval rates and slurry dilution rates in section 5.3.1, aerosol generation in section 5.3.2, HWEE reaction forces/torques in section 5.3.3, and flush in section 5.3.4. Specific details related to kaolin/plaster retrieval process are further discussed in this section. Kaolin/plaster retrieval testing was started and completed on 8/18/2017. This was the first simulant attempted for retrieval effectiveness testing. Mining occurred progressively in layers and was adjusted as necessary to keep HWEE within confines of the simulant side forms and away from any hard mining surfaces left during the downward progression. The kaolin mining progression is shown in Figure 5.15 and Figure 5.16 and mining detail summarized in Table 5.14 with supporting details in Appendix A.

Figure 5.15. Mining of Kaolin/Plaster During Retrieval Effectiveness Testing (First and Mid Layers; bottom photo shows prominent ridges after the first pass)

Figure 5.16. Mining of Kaolin/Plaster During Retrieval Effectiveness Testing (Final Layer)

Table 5.14. Mining Operation Summary of Kaolin/Plaster Effectiveness Retrieval

Mining Details By Layer		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Drop height from previous layer	inches	Start	1	1	1	1	1	1
Position from original simulant surface	inches	0.25	-0.75	-1.75	-2.75	-3.75	-4.75	-5.75
Passes per Layer		6	6	5	5	5	4	4
X-Axis Traverse	inches	~ 44	~ 44	~ 44	~ 44	~ 44	~ 44	~ 44
Y-Axis Offset Between Serpentine Paths on Layer	inches	4.3	4.3	4.3	4.3	4.3	4.3	4.3
X-Axis Offset Inward from Original Serpentine Path			None	None	None	None	None	None
Y-Axis Offset Inward from Original Serpentine Path			None	None	~ 1	1.75	1.75	1.75
Flushing per Layer		End of return pass.						
Flush Time	seconds	18 to 24						
Flush Pressure	psi	500	500	500	500	500	500	500

Table 5.15. Mining Measurement Summary of Kaolin/Plaster Effectiveness Retrieval

Layer of Measurement	HWEE Depth * (inches)	Mining Notes: * HWEE metal bottom depth to original simulant surface. Kaolin/Plaster simulant depth 8 inches.
1	+ 0.25	Simulant Tank: First layer mining. Retrieval Tank: Milky liquid with a distinguishable layer of fine particles settled on bottom. No large particles or clumps observed.
2	-0.75	Simulant Tank: Mining left trough with ridges between passes. Measurements of depths recorded at two locations: 1) Trough 5.33 inches and Ridge 1.37 inches and 2) Trough 5 inches and Ridge 2.5 inches. Retrieval Tank: Filled 13-3/8 inches on average from opposing corner measurements (14 and 12-5/8 inches) with noticeable interface layer 3-1/4 inches on average from opposing corner measurements (4 and 2-3/8 inches). Milky liquid with a distinguishable layer of fine particles settled on bottom. No large particles or clumps observed.
3	-1.75	Simulant Tank: No measurement taken. Retrieval Tank: Milky liquid with a distinguishable layer of fine particles settled on bottom. No large particles or clumps observed.
4	-2.75	Simulant Tank: Mining left trough with ridges between passes. Measurements of depths recorded at one locations: 1) Trough 6.99 inches and Ridge 3.46 inches. Retrieval Tank: Milky liquid with a distinguishable layer of fine particles settled on bottom. No large particles or clumps observed.
5	-3.75	Simulant Tank: Mining left trough with ridges between passes. Measurements of depths recorded at one locations: 1) Trough 8 inches and Ridge 5.74 inches. Retrieval Tank: Filled 13-1/4 inches on average from opposing corner measurements (17 and 5-1/2 inches) with noticeable interface layer 6 inches on average from opposing corner measurements (9 and 7 inches). Milky liquid with a distinguishable layer of fine particles settled on bottom. No large particles or clumps observed.
7	-5.75	Simulant Tank: Completion of mining. Mining left trough with ridges between passes. Measurements of depths recorded at one locations: 1) Trough 8 inches (to wood base) and Ridge 6.09 inches. Retrieval Tank: Filled 10-1/2 inches on average from opposing corner measurements (11 and 10 inches) with noticeable interface layer 3-1/2 inches on average from opposing corner measurements (4 and 3 inches). Milky liquid with a distinguishable layer of fine particles settled on bottom. No large particles or clumps observed.

5.2.2.3 K-Mag (Saltcake)

Retrieval of K-Mag was effective as performed at the target parameters initially set as summarized in Table 5.11. Result of K-Mag retrieval effectiveness testing can be found in section 5.3 and specifically the retrieval rates and slurry dilution rates in section 5.3.1, aerosol generation in section 5.3.2, HWEE reaction forces/torques in section 5.3.3, and flush in section 5.3.4. Specific details related to K-Mag retrieval process are further discussed in this section.

K-Mag retrieval testing was started and completed on 8/25/2017. This was the last simulant attempted for retrieval effectiveness testing the there was no prior retrieval history for this material. Mining occurred progressively in layers and was adjusted as necessary to keep HWEE within confines of the simulant side forms and away from any hard mining surfaces left during the downward progression. Retrieval of K-

Mag was effective as performed at the target parameters initially set as summarized in Table 5.11. K-Mag mining is shown in Figure 5.17 and Figure 5.18 with end results shown in Figure 5.19. Mining details related to this retrieval are summarized in Table 5.16 and Table 5.17 with supporting details in Appendix A.

Figure 5.17. Mining of K-Mag During Retrieval Effectiveness Testing (Start)

Figure 5.18. Mining of K-Mag During Retrieval Effectiveness Testing (Start)

Figure 5.19. Mining of K-Mag During Retrieval Effectiveness Testing (Final)

Table 5.16. Mining Detail Summary of K-Mag Effectiveness Retrieval

Mining Details By Layer		1	2	3
Drop height from previous layer	inches	Start	1.25	1
Position from original simulant surface	inches	0.25	-1	-2
Passes per Layer		7	7	6
X-Axis Traverse	inches	43	~ 43 (est)	~ 43 (est)
Y-Axis Offset Between Serpentine Paths on Layer	inches	3	3	3
X-Axis Offset Inward from Original Serpentine Path	inches		None	1.5
Y-Axis Offset Inward from Original Serpentine Path	inches		None	1.5
Flushing per Layer		None	3rd and 7th pass	End of each X path
Flush Time	seconds	None	2 to 3	2 to 3
Flush Pressure	psi	None	500	500

Table 5.17. Mining Summary of K-Mag Simulant Removal for Effectiveness Retrieval

Layer of Measurement	**HWEE Depth * (inches)**	**Mining Notes** * HWEE metal bottom depth to original simulant surface. K-Mag simulant depth 4 inches.
1	+ 0.25	Simulant Tank: First layer mining. Mining left trough with ridges between passes. Measurements of depths recorded at three high point locations: Ridges at 1.03, 1.8, and Mound 1.22 inches and Troughs to bottom (4 inches). Retrieval Tank: Filled multiple times over layer, paused and dumped slurry in tank at end of each pass. Pass 1: No measurement. Pass 2: 14-3/4 inches on average from opposing corner measurements (15-1/2 and 14 inches). Pass 3: 14 inches on average from opposing corner measurements (15 and 13 inches). Pass 4: 14-1/4 inches on average from opposing corner measurements (15 and 13-1/2 inches). Pass 5: 14-1/8 inches on average from opposing corner measurements (15 and 13-1/4 inches). Pass 6: 14-1/4 inches on average from opposing corner measurements (14-3/4 and 12-3/4 inches). Pass 7: 13-3/8 inches on average from opposing corner measurements (14 and 12-3/4 inches). Milky liquid with a layer of fine particles settled on bottom. No large particles or clumps observed.
2	-1	Simulant Tank: Mining to remove ridges. Measurements of depths recorded at three high point locations: Ridges at 1.03, 1.8, and Mound 1.22 inches and Troughs to bottom (4 inches). Retrieval Tank: Filled multiple times over layer, paused and dumped slurry in tank at end of each pass. No measurement. Milky liquid with a layer of fine particles settled on bottom. Particles of wood and plastic from simulant form observed.

Layer of Measurement	HWEE Depth * (inches)	**Mining Notes** * HWEE metal bottom depth to original simulant surface. K-Mag simulant depth 4 inches.
3	-2	Simulant Tank: Completion of mining. Mining trough left is through the simulant to wood form (4 inches) and no ridges left. Retrieval Tank: Filled multiple times over layer, paused and dumped slurry in tank at end of each pass. Pass 1, 2, 3, 4, 5: No measurement. Pass 6 (final pass): 18-3/8 inches on average from opposing corner measurements (19-1/4 and 17-1/2 inches). Milky liquid with a layer of fine particles settled on bottom. Particles of wood and plastic from simulant form observed.

5.3 Retrieval Effectiveness Results

Retrieval effectiveness of the HWEE for Phase I testing is described using the metrics of retrieval and slurry dilution rates, aerosol generation, HWEE reaction forces and torque, and flushing.

5.3.1 Retrieval Rates and Dilution Ratios

Retrieval rates and slurry dilution ratios are calculated for the Phase I HWEE effectiveness tests. Three general approaches are employed. First, following past practice (e.g., Hatchell et al. 2016), retrieval rates (RR, volume per time) are derived from the mining path area (A, length squared) and the mining path speed (MPS, length per time) by

$$\mathrm{RR} = \mathrm{A} \times \mathrm{MPS} \tag{5.1}$$

Equation (5.1) is applicable for test operations where the HWEE is mining undisturbed, uniform, and horizontal simulant.

The mining path area is simply approximated as an isosceles triangle formed by the rotating angled jets. From Figure 5.20, the depth at which the jets converge with a 0.25 inch standoff distance from the simulant surface is approximately 3.2 inches. The measured depths-of-cut reported in Section 5.2 are typically greater than this value for the kaolin and kaolin/plaster at the retrieval test conditions. This comparison therefore dictates cut depths below the jet convergence, indicating the deflected jets continued to erode simulant, which renders the isosceles triangle are assumption subject to uncertainty. However, as provided in Figure 5.20, the cut-width with the 0.25 inch standoff distance from the simulant surface is approximately 4.4 inches, whereas the measured widths provided in Section 5.2 are larger for the kaolin and kaolin/plaster. Therefore, in conjunction with the observed sloped side cuts of the operations (e.g., Figure 5.20), the isosceles triangle assumption is deemed as a reasonable and simple approximation of the cut area for all three simulants.

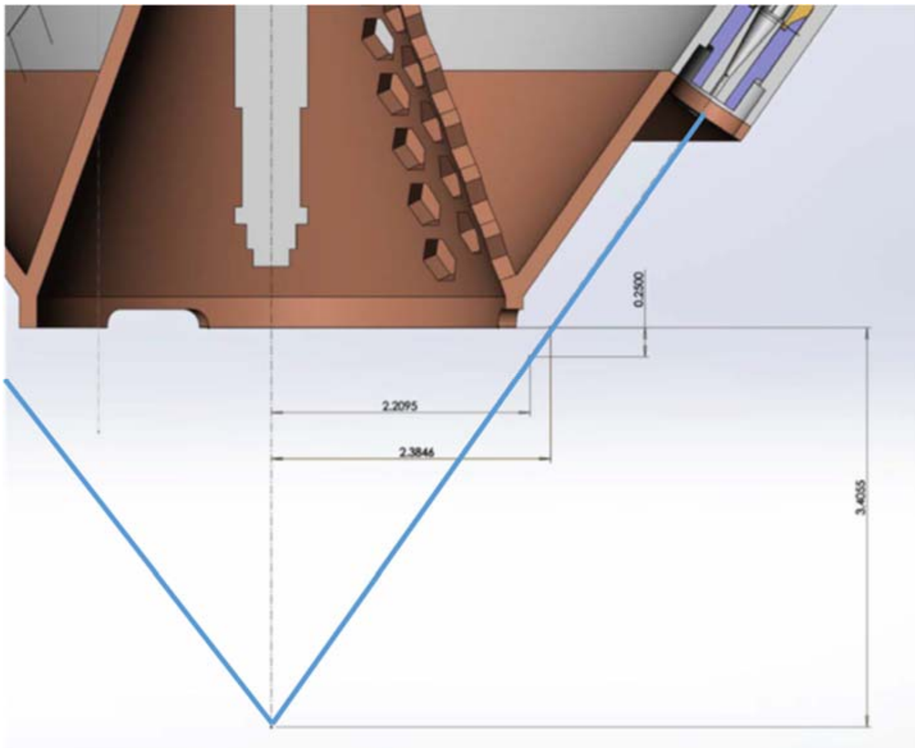

Figure 5.20. HWEE Jet Trajectory

The second approach used to estimate the retrieval rate (RR_m, volume per time) uses the mass of material retrieved into the retrieval tank (M, mass), water usage rates (W, volume per time, see section 5.1.1), simulant and water density (ρ_S and ρ respectively, mass per volume) and test operation time (T, time). As described in Section 2.2.5, there were hemispherical ends to the simulant tank without simulant that were not reached by the HWEE. Observation of test video shows water accumulation in these areas during retrieval testing as well as limited water remaining in the simulant area. Thus, for the retrieval rate calculation, the mass in the retrieval tank is increased by the term M_w (mass), the water remaining in the simulant tank, as

$$RR_m = \frac{(M + M_w) - (W \times T \times \rho)}{\rho_S \times T} \tag{5.2}$$

For this analysis, M_w is assumed to be equal to the the water mass that would be in the simulant volume removed from the test vessel, see Equation (5.3). This accounts for the HWEE water that was assumed to be retrieved instantaneously by the HWEE suction, when in fact a portion of the water was left behind in the simulant tank. Equation (5.2) also accounts for the “overlap” of mining paths. Mining path overlap occurs when the horizontal and/or vertical translation of the HWEE is such that subsequent paths have the jets “cutting” into starting-condition simulant volume that was already removed by prior operation. A generous overlap was used in the Phase I tests to provide a margin against collisions between the HWEE and simulant ridges, but the overlap reduced the multipass retrieval rate. Thus, $RR \geq RR_m$.

A third retrieval rate calculation approach was used to provide a check against the second approach. The numerator of Equation (5.2) divided by the simulant density describes the simulant volume transferred to the retrieval tank. The simulant volume removed from the test vessel (V, volume) can also be estimated from the excavation measurements reported in Appendix A. The third retrieval rate estimate is provided by this method (RR_v, volume per time) as

$$RR_v = \frac{V}{T} \tag{5.3}$$

Equation (5.3) also accounts for the "overlap" of mining paths, but, given the complicated topography of the simulant remaining in the test vessel (e.g., Figure 5.14), this estimated retrieval rate is likely the least accurate method.

Slurry dilution ratios are determined by dividing RR, RR_m, and RR_v by W. The calculated retrieval rates and slurry dilution ratios are presented in Table 5.18 by simulant type and test layer. Calculation input parameters are taken from Sections 5.1 and 5.2. As expected, RR is greater than RR_m and RR_v. The multipass and mulilayer test retrieval rates, determined via RR_m and RR_v, were constrained by avoidance of having the HWEE impact ridges and edges of the simulant and test vessel, and the limited simulant depth. The retrieval rate limiting effects of the proximity of the bottom of test vessel and vessel edges would not be as significant in a large-scale deployment. Thus, it is expected the bulk retrieval in a large-scale system would be closer to RR than to RR_m and RR_v. The much lower retrieval rates of the K-Mag are significantly impacted by the fifty times reduction in translation rate and higher jet pressure, Section 5.2, necessitated by the challenging nature of this simulant (see Section 4).

Table 5.18. Effectiveness Tests Results Summary

Simulant	Test Layer	Retrieval Rate (gpm)			Dilution Ratio		
		RR[1]	**RR_m**	**RR_v**	**RR[1]**	**RR_m**	**RR_v**
Kaolin	1st–3rd layers	14.7	4.9	5.0	0.92	0.30	0.31
Kaolin/plaster	1st–2nd layers	12.2[2]	3.0	4.3	0.75[2]	0.18	0.27
	1st–4th layers	-	3.1	3.6	-	0.19	0.22
	1st–5th layers	-	3.2	3.2	-	0.20	0.20
K-Mag	1st layer	0.1	NA[3]	0.2	0.58	NA[3]	0.01

[1] From single-path dimensions during start up testing; Test Phase column not applicable.

[2] Average result. Dimensions in single path had variation, resulting in RR range 14.8 to 9.5 gpm (~36% variation), and associated dilution ratio of 0.93 to 0.59.

[3] Result not available. Complications occurred during testing due to loss of suction and jet rotation resulting in unknown water mass added to receipt vessel from jet pump.

A summary of test results for the WREE, a prior iteration of the HWEE, is provided in Hatchell et al. (2016). These prior retrieval tests focused on measuring retrieval performance during sludge (kaolin) and hardpan (kaolin/plaster) retrieval. Sludge retrieval had a reported rate of approximately 7 gpm. Hardpan retrieval rates ranged from 8.9-14.0 gpm. For these retrieval rates, the excavated volume was assumed to be rectangular, as opposed to the RR assumption in the current of triangular. The reported RR results in Table 5.18 would be increased by a factor of two for a direct comparison. Thus the HWEE maintained a higher retrieval rate for kaolin and kaolin plaster than was measured with the WREE.

For C-105 retrieval efforts using the MARS-V system, a total of ~270,000 gallons of water was used to remove ~58,400 gallons of waste during a slurry transfer duration of 1,494 hours (Scholkowfsky 2016). The resulting dilution ratio is approximately 0.22. As demonstrated by the HWEE testing, the dilution ratio depends not only on the operating parameters of the device, but also on the waste or simulant properties including surface topography and strength. Given the unknown configurations of the C-105 waste, direct comparison of the dilution ratios between the MARS-V system application in C-105 is invalid.

However, testing was conducted with the MARS-V system using three waste simulants (Shields 2011). Simulant 1M had the largest reported retrieval rate at approximately 257 gph (4.3 gpm) and that simulant is described in CEES-09-195-RFCI-002 as “considered to be pumpable.” It is unclear how this material relates to the kaolin simulant used in the HWEE testing with respect to strength. Regardless, the HWEE kaolin would not be considered “pumpable” by conventional means, and the kaolin/plaster would not be considered “pumpable” without some form of conditioning such as grinding and use of a carrier fluid. The kaolin and kaolin/plaster HWEE simulants may therefore be more adverse for erosion (i.e., retrieval rates at a given applied stress) than Simulant 1M. The other two simulants of Shields (2011), Simulant 2 and Simulant 3, had reported retrieval rates of 90 gph (1.5 gpm) and 43 gph (0.7 gpm) respectively. Smet (2008) describes Simulant 2 as “can be pushed around by a jet but settles very rapidly and is difficult to get into the pump suction”, and reports Simulant 3 to have a compressive strength of approximately 50 psi (~ 345 kPa, or using the approximation described in Section 4, shear strength ~ 172 kPa). Although it is again emphasized that strength is potentially a poor indicator for erosion characteristics between different materials (see Section 4), the estimated shear strength of Simulant 3 is similar to that for the HWEE kaolin/plaster, and its compressive strength is nominally a factor of 40 less than the compressive strength of the HWEE K-Mag. Simulant 3 contained “chipped gravel,” thus it is most likely that particulate was larger than any employed by the Phase I HWEE testing. Test descriptions and images in Shields (2011) suggest flat simulant surfaces initially as for the beginning of the Phase I HWEE tests. Thus, it may be of interest to compare the MARS-V system simulant retrieval rates to the HWEE simulant retrieval rates.

With respect to dilution ratio, Shields (2011) reports an overall average slurry transfer rate of 86.9 gpm for Simulant 1M retrieval using the MARS-V. The resultant dilution ratio is 4.3 gpm / (86.9 – 4.3) gpm, or approximately 0.05. The dilution ratios for Simulants 2 and 3 can be similarly computed from the overall average slurry transfer rates of (Shields 2011), 96.8 and 106.5 gpm respectively, as approximately 0.02 and 0.01.

5.3.2 Aerosol Generation

Aerosol testing was conducted to visually show aerosol generation by the HWEE at two standoff distances (1/4 inch and 12 inches) and various pressures starting at 1,000 psi. This testing was performed after retrieval operations were complete. The testing was difficult to conduct because of the small size of the tank and the amount of splatter generated by the jets. Also, the kaolin and kaolin-plaster simulants were easily disperse by the waterjets, especially at higher pressure. Aerosol tests were not conducted with kaolin-plaster because the results collected for kaolin were deemed to be representative of the kaolin-plaster.

During the aerosol test, the HWEE with jet rotating was operated at 1,000 psi at a standoff distance of 1/4 –inch. The pressure was maintained for 1 minute and then increased up to the maximum available test pressure (~6,600 psi) or until excessive aerosol or splattering was reached. The HWEE was then raised 12 inches to another position over the simulant bed with similar simulant starting features. The aerosol test was repeated, starting at 1,000 psi pressure and progressing to the highest available test pressure.

Aerosol generation by HWEE waterjets impacting kaolin is shown in Figure 5.21. Minimal aerosol was generated when the stand-off distance was 0.25 inches for waterjet pressures of 1000 psi and 6600 psi. Moderate aerosol was generated when the stand-off distance was 12 inches for waterjet pressure 1000 psi and significant aerosol was generated for 6600 psi. Aerosol generation by HWEE waterjets impacting K-Mag is shown in Figure 5.22. Minimal aerosol was generated when the standoff distance was 0.25 inches for waterjet pressures of 1000 psi and 3000 psi, and moderate aerosol was generated for waterjet pressures of 5000 psi and 7000 psi. Moderate aerosol was generated when the standoff distance was 12 inches for waterjet pressure 1000 psi and 3000 psi, and significant aerosol was generated for 5000 psi and 7000 psi. At higher pressures (> 5000 psi), significantly more splatter was generated during the kaolin testing. Overall, aerosol was low to moderate when the standoff distance was 0.25 inches during kaolin and K-Mag aerosol testing.

Quantitative aerosol measurements require prototypic tank dimensions, humidity, and air circulation. Quantitative aerosol testing may occur during future phases of HWEE testing.

Stand-off Distance = 0.25 inches
Operating Pressure = 1000 psi

Stand-off Distance = 0.25 inches
Operating Pressure = 6600 psi

Stand-off Distance = 12 inches
Operating Pressure = 1000 psi

Stand-off Distance = 12 inches
Operating Pressure = 4000 psi

Figure 5.21. Aerosol Generation by HWEE Waterjets Impacting Kaolin

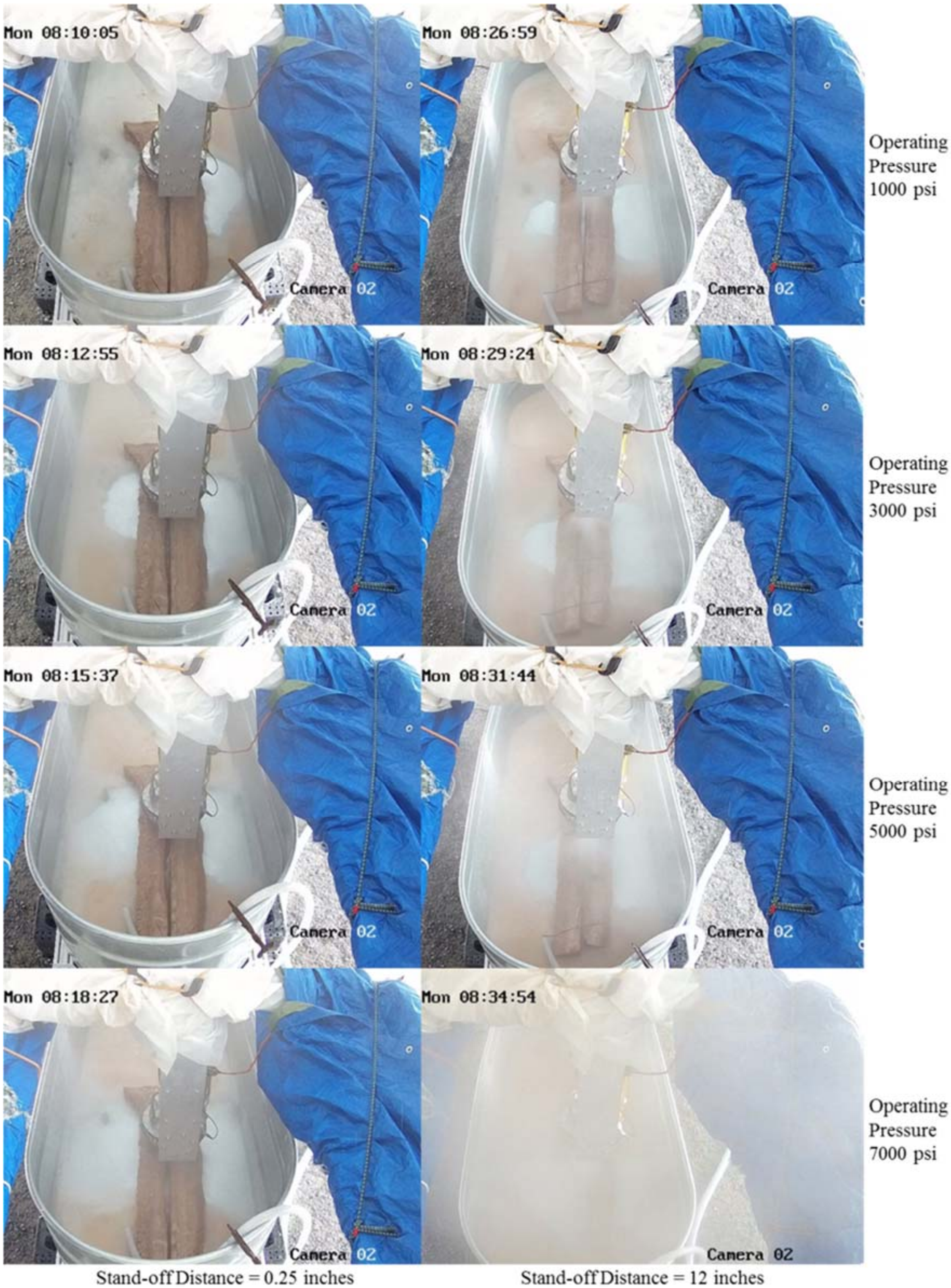

Figure 5.22. Aerosol Generation by HWEE Waterjets Impacting K-Mag

5.3.3 HWEE Reaction Forces/Torques

Reaction forces and torques were measure by a force-torque sensor between the HWEE mounting bracket and the gantry. These results can be used to determine the compatibility between the HWEE and potential deployment platforms. As shown in Figure 5.23, the Y-axis of the force-torque sensor was oriented in the vertical direction, the Z-axis was oriented in the primary direction of travel, and the X-axis was oriented in the secondary direction of travel. The distance from the measurement plane of the force-torque sensor to the center of the HWEE was 8.8 inches. A force through the center of the HWEE would be measured as a force and a torque. For example, a 10 lb vertical force would be measure by the force-torque sensor as a 10 lb force along the Y-axis and an 88.8 in-lb torque along the X-axis. Reaction forces during retrieval result from waterjet recoil, inertia, manifold rotary motion, hose weight and stiffness, suction, and slurry transport. Efforts were made to determine these forces separately, so that the forces during retrieval could be interpreted. A summary of the test condition and measured maximum and minimum forces and torques are provided in Table 5.19. The time-varying test results are provided in Appendix B and are shown in terms of force-torque measurements in the time domain and spectrum amplitudes in the frequency domain. The force-torque sensor outputs were set to zero before each of the retrieval tests was initiated, so the forces and torques that are reported are dynamic and do not include the static weight of the HWEE, the static weight of the hoses, or the reaction forces from the hoses.

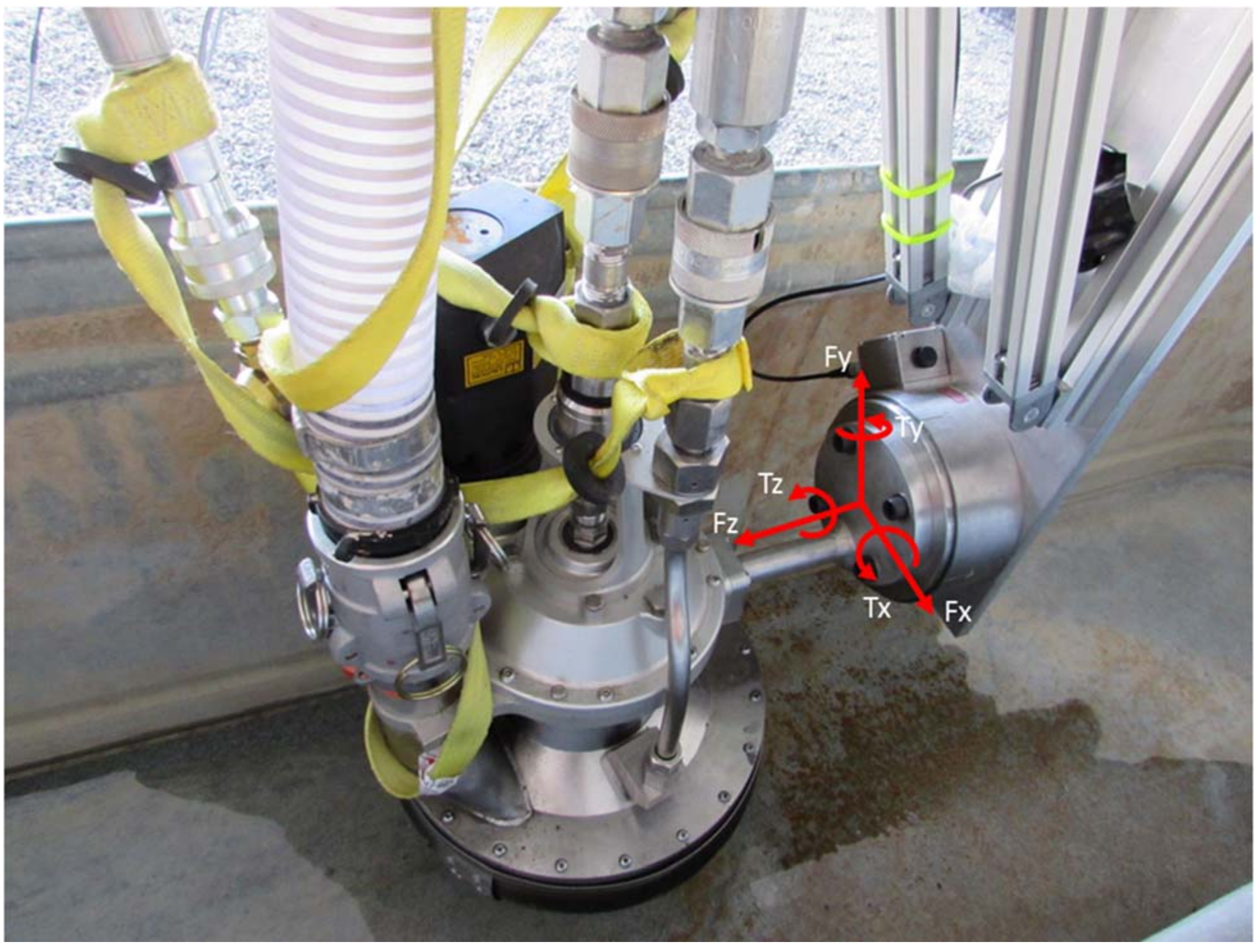

Figure 5.23. Force and Torque Measurement Orientation

Table 5.19. Maximum Forces Measured during Effectiveness Retrieval Tests

Test Type	Pass Width (in.)	WREE Nozzle Size (in.)	WREE Nozzle Pressure (psia)	Speed of Rotation (rpm)	Traverse Rate (in./min)	Extreme	Fx (lb)	Fy (lb)	Fz (lb)	Tx (in.-lb)	Ty (in.-lb)	Tz (in.-lb)
Scanning Motion Only	N/A	N/A	N/A	N/A	300	max	24	27	54	189	197	385
						min	-31	-33	-62	-189	-209	-285
Rotation Start-up and Shut-down in Air	N/A	N/A	N/A	300	N/A	Max	18	18	50	101	246	92
						Min	-18	-24	-47	-102	-228	-118
Rotation Start-up and Shut-down in Kaolin	N/A	N/A	N/A	300	N/A	Max	7	28	5	92	122	52
						min	-4	-11	-5	-230	-176	-66
Kaolin Retrieval	3.75	0.038	1000	300	300	max	54	37	64	591	480	513
						min	-30	-39	-63	-438	-299	-1091
Kaolin-Plaster Retrieval	3.75	0.038	1000	300	300	max	31	34	53	269	341	324
						min	-25	-28	-72	-194	-322	-535
K-Mag Retrieval	3.0	0.038	7000	90-100	6	max	35	31	76	320	241	193
						min	-26	-42	-76	-373	-250	-334

HWEE reaction forces versus jet pressure and flush pressure is shown in Figure 5.24 and Figure 5.25, respectively. The jet reaction force occurred primarily along the Z-axis; the maximum jet reaction force measured was 40 lb, which occurred at 10,000 psi jet pressure. The flush nozzle reaction force occurred primarily along the X and Y-axis due to the angle of the fan jet. The maximum flush nozzle reaction force measured was 9 lb, which occurred at 10,000 psi.

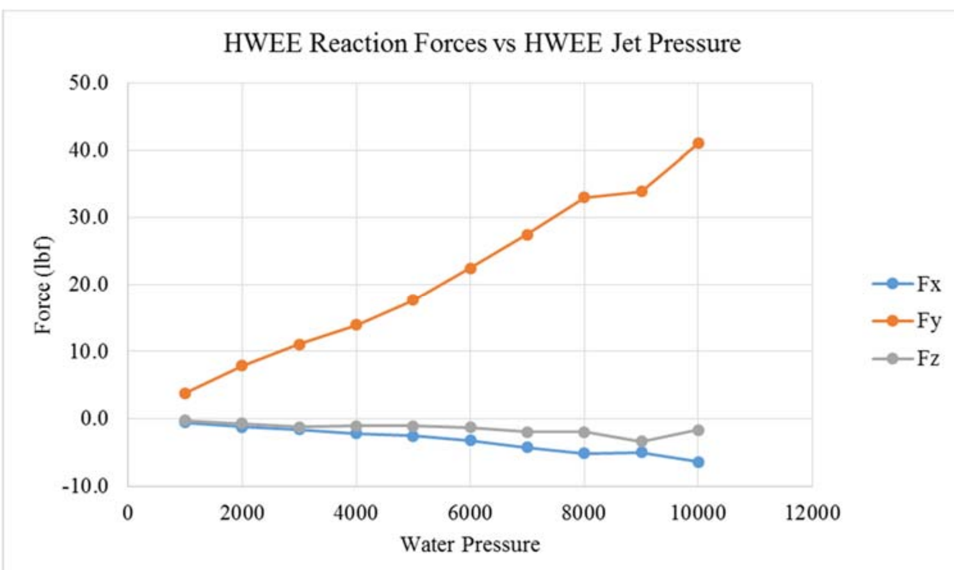

Figure 5.24. HWEE Reaction Forces versus Jet Pressure

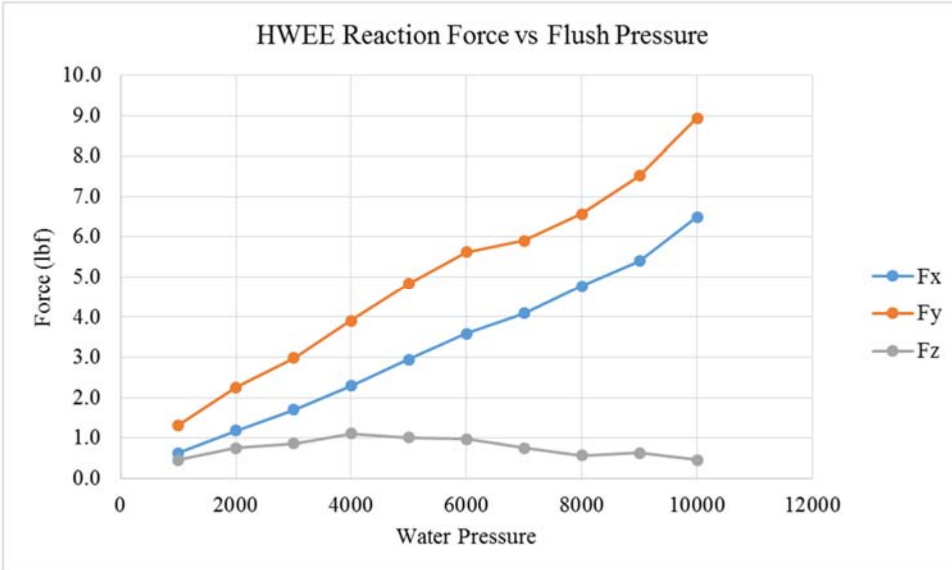

Figure 5.25. HWEE Reaction Force versus Flush Pressure

HWEE reaction forces during scanning were collected using the same mining path used for the kaolin retrieval tests. During this data collection, the high pressure pump and hydraulic power unit were not operating. Reaction forces during the scanning motion are shown in Appendix B, Figure B-1, while reaction torques are shown in Figure B-2. The torques varied more significantly than the forces, due to the changing direction of hose loading. Comparing the forces and torques measured during scanning only against the forces and torques measured during retrieval, it is apparent that hose loading contributes significantly to the overall HWEE reaction forces during retrieval.

HWEE reaction forces during hydraulic motor start-up and shut-down were measured for the condition where the HWEE is not contacting simulant (Appendix B, Figures B-3 and B-4) and for the case where the HWEE shroud was submerged in kaolin approximately 1 inches (Figures B-5 and B-6). The HWEE motor was operated for approximately 15 seconds during these tests. For the non-contact condition, the start-up and shut-down events are hard to discern in the force plots (Figure B-5), but they are readily seen in the torque plots (Figure B-6). The maximum torque measured during start-up was 228 in-lbs along the Y-axis, which is expected, since the Y-axis of the force-torque sensor is aligned with the motor rotational axis. The maximum torque during shut-down was 246 in-lbs. The frequency content of the force and torque values includes a sharp peak at 5 Hz, which corresponds to the frequency of rotation (300 RPM or 5 rotations per second). Other frequency response is probably due to the resonant of the gantry due to the shock of motor start-up.

For the case where the HWEE shroud was submerged in kaolin, the force from the reaction of the kaolin simulant was initially 28 lb in the Y-direction; this force dropped to less than 10 lb after the motor was rotated due to the fact that kaolin was expelled during the start-up process (see Appendix B, Figure B-5). The maximum torque during start-up was 176 in-lbs and occurred along the Y-axis. The maximum torque during shut-down was 122 in-lbs. These values are actually less than the torques measured in the non-contact condition. It is believed that the kaolin actually dampened the response of the HWEE because it molded to the HWEE's shroud and formed a bearing surface.

Reaction forces from the HWEE were measured during the effectiveness tests. A subset of this data was analyzed and is summarized in Table 5.19 and Figures B-7 through B-12. For kaolin and kaolin-plaster, the second layer of retrieval was analyzed. This layer was chosen because, for the first layer, the HWEE was actually 0.25 inches above the simulant bed, and during the third layer of retrieval, the simulant was significantly diluted or broken up by the waterjets. The second layer provided the best chance of collecting dragging forces between the HWEE and the simulant. For K-Mag retrieval, the first traverse was analyzed, because a significant amount of the K-Mag was retrieval in the first layer, and the traverse speed was significantly lower. The forces measured during all three retrieval tests ranged from 76 to -76 lbs. The primary differences between the retrieval tests, in terms of generating forces on the HWEE, is hardness of material, traverse speed, and waterjet pressure. Forces were highest during K-Mag retrieval and lowest during kaolin retrieval. The frequency content of the force and torque values measured during kaolin and kaolin-plaster retrieval tests include a sharp peak at 5 Hz, which corresponds to the frequency of rotation (300 RPM or 5 rotations per second). Other low frequency response is seen in all the retrieval response plots. The frequency response of the HWEE during kaolin and kaolin-plaster tests was similar, whereas the frequency response during K-Mag retrieval showed more activity around 25 Hz for the forces and torques and a sharp peak at 80 Hz for the force along the Z-axis.

5.3.4 Flushing For HWEE Screen Cleaning

The HWEE is equipped with flushing capability to clear the HWEE inlet screen if it gets clogged with debris during retrieval operations. The HWEE as designed had two flush capabilities, the HWEE flush and HWEE mole. Component water usage testing (see section 5.1.1) mapped water flow verses pressure of the HWEE flush (see section 5.1.1.2) and HWEE mole (see section 5.1.1.3). Fully flushing capabilities of the HWEE were not used during Retrieval Demonstrations (see section 5.2) because the HWEE mole was plugged after HWEE Component Testing with the HWEE flush on 8/15/2017; this HWEE mole plugging will be further explained at the end of this section.

A summary of the HWEE flushing during Retrieval Effectiveness testing is given in Table 5.20. Flushing frequency used during these tests for all simulants, including K-Mag with no flushing used, effectively kept the HWEE inlet screen adequate clean of simulants for the entire simulant mining operation. Because very little simulant was noted on the HWEE inlet screen during periodic inspections and at the end of testing these flushing times may be very conservative. To assess the ability of the HWEE flush to clean the HWEE inlet screen of simulant, a test was run in 8/22/2017 where the HWEE inlet screen what physically packed full of kaolin simulant by hand (even pushing a significant amount of material through the HWEE screen) and it was effectively cleaned with 1,000 psi and several seconds of flush with the HWEE rotating (see Figure 5.26). The HWEE waterjets were not activated during this flush test.

Table 5.20. Retrieval Effectiveness Testing Flushing Overview and Frequency

Retrieval Effectiveness Flushing Details	Simulant		
	Kaolin	Kaolin/ Plaster	K-Mag
Flush Frequency (seconds)	~ 18	~ 36	None
Test Passes on Layer for Each Flush	1	2	None
Pass Length and Pass Speed (inches and ipm)	44 / 300	44 / 300	43 / 6
Time at Flush (seconds)	~ 20	~ 10	None
Additional Flush Activation Details			
HWEE Valved Out	Yes	No	NA
HWEE Valve Closed Hold (seconds)	~ 4	NA	NA
Resulting # of Valve Sequences	4	2	NA
Valve Activation Method	Hand	Powered	NA

Note: Needle valves took approximately 5 turns to activate.
Single direction valve actuation time ~ 4 seconds manual or ~ 1 second powered (drill assist).

Figure 5.26. Screen Plug Removal Test with HWEE Flush (Kaolin)

Flushing during retrieval effectiveness testing (see section 5.2.2) show that during the initial mining path for kaolin and kaolin/Plaster (K-Mag had no flushing) the flush appeared to be well contained and possibly retrieved to some extent by the HWEE Jet Pump suction (see Figure 5.27). As mining further occurred there was more noticeable leakage of flush water outside the confines of the HWEE but much of that may have been the test configuration of the limited simulant material and ultimate penetration through the simulant and into the support form structure and out into the simulant tank

Figure 5.27. Retrieval Effectiveness Test Flushing (Kaolin right and Kaolin/Plaster left)

The HWEE flushing capabilities were not fully tested or even close to optimized for several reasons including: (a) HWEE mole flush was off; (b) flush nozzle size and spray pattern were not fully explored; (c) flushing pressure was limited to less than full 10,000 psi due to the PRM used in this test design during retrieval demonstration testing; and (d) flushing "bursts" were not available to limit water usage due to the needle valves used on the PRM. During HWEE component water usage testing (see section 5.1.1) it was noted that the flush water usage rates were a significant compared to water addition compared to the HWEE rotary mining jets water usage and was the key reason the HWEE mole flush was plugged as it operated continuously with the HWEE.

The test configuration used to operate the flushing functions for this Phase I testing did not allow the full capabilities of the HWEE flushing design to be fully utilized. The PRM used to provide a secondary lower pressure also limited the available HWEE flush maximum operating pressure (10,000 psi) to the operating limit of the HWEE rotary jet operational pressures (1,000- to 6,600 psi for this testing) and even less pressure if operated in conjunction with the HWEE rotary jet operation; for HWEE operating at 1,000 psi the addition of the flush dropped the pressure down initially to 200 psi and then rises to stabilize at 500 psi. Also, no quick acting on/off valves were used that could limit water usage; needle valves were used that required 5 turns to open and close, resulting in slower flush activation time.

During HWEE component water usage testing (see section 5.1.1), the HWEE flush testing at high pressure is believed to have damaged the HWEE inlet screen (see Figure 5.28). This HWEE screen damage is not believed to be a failure of the screen design because the screen was not it is normal operating mode of rotating during flushing; however, this screen failure may have shown that the screen weld joint is likely the weakest part of the screen design and should be reviewed for future upgrading. The HWEE flush jet discharge coincided with the HWEE screen's weld joint. The larger hole that resulted in the HWEE screen failure is surmised to have been the high pressure water causing a weld to break loose and then the loose cantilevered screen parts where buffeted by the water spray causing some of them to fatigue from this movement and fail. The HWEE screen was patched with some stainless steels screen at the PNNL machine shop and survived through the end of Phase I testing.

Figure 5.28. HWEE Screen Damage From HWEE Flush and Subsequent Repair

The HWEE mole flushing not being available for testing was a decision made by PNNL and in agreement with WRPS. Several factors played into the decision to plug the HWEE mote off but the key driver was in the recovery from the screen damage discussed previously. To remove the screen the HWEE mole had to be removed. During reassembly of the screen and subsequently the HWEE mole, the mole portion did not appear to be fully seated and this raised concerns about possible leakage and if repaired a subsequent delay in a very tight test schedule. Other factors that play against a HWEE mole functional repair was its higher than expected water usage, its design were it is constantly running with the HWEE jets or running and therefore lots of water usage not going to simulant retrieval, and finally it appeared that the jet directional spray may be only aimed to hit a small portion of the screen (or none at all) and if so it is of little use for screen flushing.

Some screen clogging did occur during the end retrieval of K-Mag but it was not because of the simulant material but because the HWEE jets had mined through the K-Mag material and the plastic and wood structure below were mined and were subsequently caught up on the screen (see Figure 5.29). This was only found after K-Mag retrieval had been completed and post-test inspections of the simulant and HWEE were done. No significant flushing was done to try and remove this material but some low pressure flushing around 1,000 psi failed to clear this material. It is plausible that HWEE flush operating at high pressure (near 10,000 psi) may have cleared the screen based on screen damage this flush did to the HWEE screen with no rotation but that was not assessed during this testing. During the K-Mag testing, no flush was operated during the entire mining sequence so periodic flush may have limited material buildup on the screen in this case.

Figure 5.29. HWEE Screen Non-Simulant Clogging at K-Mag Post Test

In conclusion, the HWEE Flush successfully kept the HWEE screen free of simulant. The flushing frequency used during retrieval effectiveness testing appeared to keep the HWEE inlet screen throughout the mining sequence but is believed to be conservative and not optimized for effective use of water. The HWEE mole flush was not a factor in this testing but may be more useful when more challenging retrieval conditions are experienced that may increase screen clogging potential. Water usage of both HWEE flush and mole seem to be high compared to the rotary jets doing the retrieval so possibly the orifice size, fan spray, and directional pointing could be optimized to reduce water and increase flush screen clearing effectiveness and efficiency. The mole flush may additional benefit from having it function not tied to the rotary jet operations (e.g. two input rotary union in HWEE) and add the ability to provide high pressure to the mole as well independent of the HWEE mining pressure. Screen clogging of non-simulant material could possibly benefit from a design modification that would mechanically scrape material off the rotating screen continuously but this would require some feasibility studies. Finally, the flush system would benefit from having quick acting valves would quickly activate and deactivate the flushing and save on water usage.

6.0 Summary of Major Test Results

6.1 Separate Effects Testing

ASTM D5852-00 was used as a guideline to assess the erosion resistance for the three simulants tested. The HWEE was operated at a fixed location over simulant that was previously undisturbed with no rotation at a set operating pressure and duration. The three jets of the HWEE thus bored three holes into the simulant surface that were then characterized for depth. Subsequent tests at new locations were at different set operating pressures and durations. The resultant data set provides a representative erosion depth as a function of operating pressure and time for each simulant. The kaolin and kaolin/plaster simulants, at significantly different shear strength of 3.6 kPa and 160 kPa respectively, were eroded to the same depth over the range of HWEE pressures tested. These results imply that the erosion behavior of the kaolin and kaolin/plaster simulants is similar for the tested HWEE operational parameters. The K-Mag simulant, at a much larger compressive strength of 12 MPa, was eroded to a substantially shallower depth than the kaolin and kaolin/plaster at the same HWEE operating pressures and times. These results imply that the K-Mag is more resistant to erosion than the kaolin and kaolin/plaster simulants. Dissolution was not a factor in these short duration tests.

6.2 Water Usage

Tests were used to determine the water usage of the HWEE jet pump, waterjets, flush jet, and mole versus operating pressure. The jet pump and the flush jet had the highest water consumption rates. Water usage data was essential to the calculation of retrieval rates and dilution ratios, provided below.

6.3 Retrieval Rates and Water Dilution Ratio

Retrieval rates were calculated using three methods. The first method, which is based on measured excavation of simulant and mining path speed, is valid for retrieval of a single pass of undisturbed, uniform simulant. The second method used the mass of material retrieved into the retrieval tank, water usage rates, simulant density, and test operation time. The third method used the volume of material retrieved from the simulant tank, simulant density, and test operation time. The second and third methods were used to calculate the retrieval rate for cumulative layers of simulant removal.

Using data from the excavated volume of a single path of undisturbed simulant, kaolin was retrieved at 14.7 gpm, kaolin/plaster was retrieved at 12.2 gpm, and K-Mag was retrieved at 0.1 gpm. Using the mass of material retrieved calculation method, kaolin was retrieved at 4.9 gpm and kaolin/plaster was retrieved at 3.0-3.2 gpm. Using the volume of material calculation method, kaolin was retrieved at 5.0 gpm and kaolin/plaster was retrieved at 3.2-4.3 gpm.

Overall, retrieval of undisturbed simulant, as calculated by the first method, yielded the highest retrieval rates. Retrieval rates based on overall mass and volume retrieved were in good agreement but are lower because these methods account for overlap of mining paths, which led to mining inefficiency in Phase I testing. The overlap distance was conservatively chosen to avoid collisions between the HWEE and the simulant. The retrieval rate limiting effects of overlap and proximity of the test tank bottom and edges would not be as significant in a large-scale deployment. Thus, it is expected the bulk retrieval in a large-scale system would be closer to the single-path retrieval rate.

These results demonstrate the potential effectiveness of the HWEE to retrieve sludge and dried sludge materials. The retrieval rate during kaolin and kaolin/plaster retrieval were reasonable and significantly higher than for K-Mag. The retrieval of K-Mag was relatively slow and indicates the need to increase the HWEE waterjet pressure (which would require redesign) or a reevaluation of the required bounding crust simulant. The water confinement was far better during kaolin and kaolin/plaster retrieval.

Table 6.1. Effectiveness Tests Results Summary

Simulant	Test Layer	Retrieval Rate(gpm) based on			Dilution Ratio based on		
		Single path	Multi path using Mass removed	Multi path using Volume removed	Single path	Multi path using Mass removed	Multi path using Volume removed
Kaolin	1st–3rd layers	14.7	4.9	5.0	0.92	0.30	0.31
Kaolin/plaster	1st–2nd layers	12.2[1]	3.0	4.3	0.75[1]	0.18	0.27
	1st–4th layers	-	3.1	3.6	-	0.19	0.22
	1st–5th layers	-	3.2	3.2	-	0.20	0.20
K-Mag	1st layer	0.1	NA[2]	0.2	0.58	NA[2]	0.01

[1] Average result. Dimensions in single path had variation, resulting in RR range 14.8 to 9.5 gpm (~36% variation), and associated dilution ratio of 0.93 to 0.59.

[2] Result not available. Complications occurred during testing due to loss of suction and jet rotation resulting in unknown water mass added to receipt vessel from jet pump.

The dilution ratio was also calculated for each simulant. Using the excavated volume and mining path speed, the dilution ratio during retrieval of kaolin, kaolin/plaster, and K-Mag was 0.92, 0.75, and 0.58 respectively. Using the mass retrieved calculation method, the dilution ratio during retrieval of kaolin and kaolin/plaster was 0.30 and 0.18–0.20, respectively. Using the volume retrieved calculation method, the dilution ratio during retrieval of kaolin and kaolin/plaster was 0.31 and 0.20–0.27, respectively.

Compared to previous results of confined sluicing end effectors shown in Hatchell et al. (2016), retrieval of kaolin was higher (14.7 gpm for the HWEE versus 7 gpm) and retrieval of kaolin/plaster was comparable (12.2 gpm for the HWEE versus 8.9-14.0 gpm). The HWEE was clearly enhanced by the refinements in the screen, skirt, and conveyance inlet, which included the addition of the fan-jet flush port. The flush port allowed the HWEE's screen to be cleared during retrieval, which greatly improved the efficiency of retrieval operations compared to prior demonstrations where a inefficient back-flush process was used. The enhanced skirt allowed the HWEE to confine the slurry and aerosol over changing topography.

The Phase I test setup and scope of work was designed to show viability of retrieval and not optimization. Some of the HWEE associated features that should be optimized to further benefit HWEE retrieval effectiveness include: (1) design features (e.g., nozzle type, size, shape); (2) operating parameters (e.g., transverse speed, standoff distance, and jet rotation); and (3) mining strategy (e.g., mining path, HWEE tilt out of horizontal plane, alternating the direction of the mining path).

6.4 Aerosol Generation

Aerosol testing was conducted to show aerosol generation by the HWEE at two standoff distances (1/4 inch and 12 inches) and various pressures starting at 1,000 psi. Overall, aerosol was low to moderate when the standoff distance was 0.25 inches during kaolin and K-Mag aerosol testing. Significant aerosol was generated when the standoff distance was 12 inches for 5000 psi and 7000 psi operating pressures.

6.5 HWEE Reaction Forces/Torques

Reaction forces and torques were measured during water usage and retrieval tests by a force-torque sensor between the mounting bracket and the gantry. These results, which are comparable to data collected during previous testing of end effectors as shown in Hatchell et al. (2016), can be used to determine the compatibility between the HWEE and potential deployment platforms

6.6 Lessons learned

The following lessons can be applied to a Phase II test campaign.

- The scanning method did not allow traversing the simulant bed in a perpendicular direction. This capability could be used to optimize the retrieval efficiency.
- There is a need to increase the dexterity of the HWEE scanner. The existing scanner lacks a rotational wrist, which made it difficult to clean next to the tank wall.
- The PRM limited the maximum water pressure to the HWEE to around 6,600 psi instead of full pressure at 10,000 psi.
- The flushing design of the HWEE needs to be evaluated with the goal to minimize water usage while maintaining effective screen cleaning. An alternate mole flush nozzle should be tested and would likely benefit from source control separated from the HWEE along with other options like higher pressure and quick valve activation.
- The jet pump, although very effective, uses significant water when operated at high pressure. Operating at a lower pressure to decrease water usage while still providing significant motivation transport force should be evaluated.
- The HWEE screen design should be reviewed in light of the failure that occurred during component testing.
- At reduced flow rates, the hydraulic power unit flow control valve diverts flow from the radiator back into the reservoir, which reduces overall fluid cooling. A workaround to this limitation needs to be identified.
- Other operational issues are listed in section 6.8.

The above list is limited to HWEE and its immediate test associated systems.

6.7 Water Remaining

Water remaining in the simulant tank was less than 1 inch after kaolin and kaolin/plaster retrieval. The water was well confined to the troughs that were cut in the simulant. The skirt contained the aerosol, jet, and slurry during kaolin and kaolin/plaster retrieval. During K-Mag retrieval, which used 6500-7000 psi waterjets, the water was not confined by the retrieval troughs and very little water was confined by the HWEE skirt.

6.8 Operational Summary

The HWEE held up well to the rigors of testing. Several operational issues occurred that were either corrected during testing or deferred for future refurbishment. During water usage testing, the screen was damaged due to prolonged exposure of the screen weld to high pressure water. The screen was repaired at the PNNL machine shop by spot welding some screen material to the damaged area. During one prolonged period of testing using 90 RPM rotation speed, the manifold temporarily seized up. This could have been due to overheating of the hydraulic fluid. Once the HWEE was allowed to cool, the manifold rotated smoothly at 300 RPM and testing continued. During retrieval testing, the skirt was damaged slightly due to contact with the dried sludge. Several of the rivets were pulled through at the interface with the support ring and the connecting plate. The rivets could have been replaced, but instead the skirt was replaced with the spare. At the end of testing, it was noted that the screen cleaning jet feed tube was dripping water. This could have come from a fitting or from the swivel. It was also noted that hydraulic fluid was leaking from the HWEE motor, although the exact location could not be determined. The operational issues did not affect the data that was collected, but should be addressed prior to Phase II testing.

6.9 Recommended Path Forward

Phase II will integrate the HWEE with support systems that collect and transfer retrieved waste out of tank. This phase will identify and develop supporting systems, including systems to position HWEE where waste is located in the tank considering in-tank obstructions. Finally, Phase II will demonstrate integrated Alternate Retrieval Technology system effectiveness. Phase III will demonstrate full-scale integrated Alternate Retrieval Technology system effectiveness in a cold simulated waste environment. Testing will include all technologies previously developed and tested in Phases I and II but at full scale. Reliability in the presence of tank environments (radiation, chemical, heat) will be a key part of Phase III.

The Phase I results will inform the development of a Phase II testing activity. A Phase II project plan will consider that following items.

- Identify and develop systems to convey mobilized waste completely out of the tank. Phase I testing included less than 10 feet of lift. A demonstration of conveyance using the full height of the tank, as a minimum, is required.
- Refine simulants retrieval of bounding hard crust simulant either through development of a more tailored simulant are using a higher pressure waterjet.
- Demonstrate retrieval of a matrix of different types of simulants.
- Demonstration retrieval of simulants with topography.

- Reduce the water usage of the flush fan jet.
- Identify or design a low water usage mole for shroud cleaning.
- Optimize the jet pump for lower water usage.
- Evaluate alternate low-water usage conveyance methods.
- Optimize mining paths to maximize the retrieval rate.
- Develop automatic screen cleaning methods. Incorporate pneumatic actuated valves for the screen flush.

7.0 References

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Appendix A: Retrieval Effectiveness Test Summary

HWEE General Test Parameters					
Simulant Retrieved	Kaolin	Kaolin/Plaster	K-Mag	Units	Comments
Date of Retrieval	8/23/2017	8/18/2017	8/25/2017		Test started and finished on this date. All data is from this date.
Simulant Test Parameters					
Test Size - Length (X-axis), Width (Y-axis), Depth (Z-axis)	58, 34, 8	58, 34, 8	58, 34, 4	inch	Size of simulant block delivered.
HWEE Adjustable Test Parameters					
Main Pump Pressure	9500	9500	10000	psi	Pressure set a NLB high pressure pump outlet/pressure gauge
Pressure Set @ Pressure Reducing Manifold (PRM)	1000	1000	6600 L1 & L3, 1000 L2	psi	Pressure set at Pressure Reducing Manifold (PRM) for HWEE & Flush
HWEE X-axis Speed	300	300	6 L1, 300 L2, 24 L3	ipm	Set X-axis speed used during test.
HWEE Rotation	300	300	80 L1, 300 L2, 90 L3	RPM	Nominal. LX is Layer X as required if changes occur between layers.
HWEE Fixed Test Parameters					
HWEE Nozzles - Size / Number of Nozzles	0.038 / 3	0.038 / 3	0.038 / 3	inch/#	Stoneage CNP2 nozzles
HWEE Jet Pump Nozzles - Size / Number on Nozzels	0.031 / 6	0.031 / 6	0.031 / 6	inch/#	Aqua-Dyne 15-118-031, Insert, .031 SS 1/8" NPT Line Mole Jet.
HWEE Flush Nozzle - Number of Nozzles	1	1	1	inch/#	NLB Fan Jet Nozzle #S-3 65 degrees
HWEE Mole Nozzle - Number of Nozzles	1	1	1	inch/#	NLB Rotating Jet Mole #RJM-2 nozzle. PLUGGED AND NOT USED IN ALL RETRIEVAL TESTING.
HWEE Jet Cone Inward Angle from Simulant Surface	35	35	35	degrees	From HiLine as-built drawing 11BMD019. Applies to this test condition when HWEE is perpendicular to simulant surface.
HWEE Jet Cone Width at HWEE Metal Base	4.42	4.42	4.42	inches	Two times radius 2.2095 inches to get diameter.
HWEE Jet Cone Width 0.25" Below HWEE Metal Base	4.77	4.77	4.77	inches	Two times radius 2.3846 inches to get diameter.
HWEE Jet Cone Convergence Below HWEE Metal Base	3.41	3.41	3.41	inches	Vertical distance below HWEE where HWEE rotating jets converge and then below that dirverge again.
Hose from Pressure Set to HWEE	50 + PRV + NV	50 + PRV + NV	50 + PRV + NV	feet	Additional pressure loss components unaccounted for by pressure gauge reading
Hose from Pressure Set to Flush	50 + PRV + NV	50 + PRV + NV	50 + PRV + NV	feet	Additional pressure loss components unaccounted for by pressure gauge reading
Hose from Pressure Set to Jet Pump	200 + FP+PRV	200 + FP+PRV	200 + FP+PRV	feet	Additional pressure loss components unaccounted for by pressure gauge reading
Layer 1 Parameters					
Drop height from previous layer	Start - Zero	Start - Zero	Start - Zero	inches	Relative drop distance from previous layer
Position from original simulant surface	0.25	0.25	0.25	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	6	6	7	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	~ 40 - 44	44	43	inches	
Y-Axis Offset Between Serpentine Paths on Layer	3.75	4.3	3	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.
Flushing per Layer	End of each pass [1]	End of return pass [2]	None [3]		Details of how flushing was done (see notes if tagged)
Flush Time	2 to 3	18 - 24	None	seconds	Approximate flush time for valve off and on (see notes if tagged)
Flush Pressure	500	0 - 1000	None	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Drill	Manual	Manual		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Cut Measurement Width	Not Taken	Not Taken	4	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	Not Taken	Not Taken	1.03 to 1.8 KM:	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	Not Taken	Not Taken	Start - Zero	inches	Mining measurement to fluid surface (-S) or ridge (-R).

Measurement Comment	NA	NA	KM:		KM: Mining left trough with ridges between passes. Measurements of depths recorded at three high point locations: Ridges at 1.03, 1.8, and Mound 1.22 inches and Troughs to bottom (4 inches).
Receipt Tank (Fluid Depth - Opposing corners) - Comment	Not Taken	Not Taken	Pass 1: None Pass 2: (15.5, 14) Pass 3: 15, 13) Pass 4: (15, 13.5) Pass 5 (15, 13.25) Pass 6: (11.75, 12.75) Pass 7: (14, 12.25)		KM: Due to slow transverse speed, retrieval tank was pumped at the end of each of the 7 passes within layer.
Comment	NA	NA	KM:		KM: Transverse speed 6 ipm and HWEE pressure 6600 psi and rotation 80 rpm.
Layer 2 Parameters					
Drop height from previous layer	1	1	1.25	inches	Relative drop distance from previous layer
Position from original simulant surface	-0.75	-0.75	-1	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	6	5	7	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	~ 40	42	~ 43 (est)	inches	
Y-Axis Offset Between Serpentine Paths on Layer	3.75	4.3	3	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.
X-Axis Offset Inward from Original Serpentine Path	None	1	None	inches	Distance HWEE moved inward in X-axis *both ends) from original serpentine path on layer 1
Y-Axis Offset Inward from Original Serpentine Path	None	1	None	inches	Distance HWEE moved inward in Y-axis *both ends) from original serpentine path on layer 1
Flushing per Layer	End of each pass [1]	End of return pass [2]	3rd & 7th pass		Details of how flushing was done (see notes if tagged)
Flush Time	2 to 3 [1]	18 - 24	2 to 3 [1]	seconds	Approximate flush time for valve off and on (see notes if tagged)
Flush Pressure	500 [1]	0 - 1000	500 [1]	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Drill	Manual	Drill		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Cut Measurement Width	NA	NA	NA	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	Not Taken	5 - 5.33	4 (Bottom)	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	Not Taken	1.37 - 2.5	2.8 - R	inches	Mining measurement to fluid surface (-S) or ridge (-R).
Measurement Comment	NA	KP:	KM:		KP:Mining left trough with ridges between passes. Measurements of depths recorded at two locations: 1) Trough 5.33 inches & Ridge 1.37 inches and 2) Trough 5 inches & Ridge 2.5 inches. KM: Mining to remove ridges. Measurements of depths recorded at three high point locations: Ridges at 1.03, 1.8, and Mound 1.22 inches and Troughs to bottom (4 inches).
Receipt Tank (Fluid Depth - Opposing corners) - Comment	Not Taken	Not Taken	(6, 4.5)		
Comment	NA	NA	KM:		KM: A higher tranvers speed (300 ipm) and lower pressure (1000 psi) and higher rotation (300 rpm) was done to knock down ridges from previous path and to retrieve simulant sand left. At end of run some ridges remain but loose from the sides and bottom.
Layer 3 Parameters					
Drop height from previous layer	1	1	1	inches	Relative drop distance from previous layer
Position from original simulant surface	-1.75	-1.75	-2	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	5	4	6	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	~ 40	34	~ 43 (est)	inches	
Y-Axis Offset Between Serpentine Paths on Layer	3.75	4.3	3	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.
X-Axis Offset Inward from Original Serpentine Path	None	3	1.5	inches	Distance HWEE moved inward in X-axis *both ends) from original serpentine path on layer 1
Y-Axis Offset Inward from Original Serpentine Path	None	3	1.5	inches	Distance HWEE moved inward in Y-axis *both ends) from original serpentine path on layer 1
Flushing per Layer	End of each pass [1]	End of return pass [2]	End of each X path		Details of how flushing was done (see notes if tagged)
Flush Time	2 to 3 [1]	18 - 24	2 to 3 [1]	seconds	Approximate flush time for valve off and on (see notes if tagged)

Flush Pressure	500 [1]	0 - 1000	500 [1]	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Drill	Manual	Drill		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Flush Note	NA	NA	KM:		At end of run, screen was clogged with wood and plastic. Flush as 500 psi did not clear. Flush pressure increased to 2500 psi and did not clear. Wood and plastic particles were manually removed from the HWEE screen.
Cut Measurement Width	NA	NA	NA	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	8	6.99	4(Bottom)	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	2.25 - FS	3.46	NA	inches	Mining measurement to fluid surface (-S) or ridge (-R).
Measurement Comment	K:	KP:	KM: End of mining.		K: Mined to the bottom of simulant (~ - 8 inches) but light slurry level at - 2.25 inches. KP: Mining left trough with ridges between passes. Measurements of depths recorded at one locations: 1) Trough 6.99 inches & Ridge 3.46 inches. KM: Mining trough left is through the simulant to wood form (4 inches) and no ridges left.
Receipt Tank (Fluid Depth - Opposing corners) - Comment	Not Taken	Not Taken	(19.25, 17.5) KM:	inches	KM: Only measured on last pass (7th). All other passes not measured and fluid dumped.
Comment	K:	NA	KM:		K: End of WRPS Demonstration. No measurements taken on previous two layers. KM: Tranvers speed lower (24 ipm) and pressure higher (6600 psi) and rotation lower (90 rpm) was done to knock down and pick up loose ridges and simulant sand. KM: Mining complete. End of Test.
Layer 4 Parameters	Suction Only				
Drop height from previous layer	1	1	Test Ended	inches	Relative drop distance from previous layer
Position from original simulant surface	-2.75	-2.75	Test Ended	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	5	4	Test Ended	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	~ 40	34	Test Ended	inches	
Y-Axis Offset Between Serpentine Paths on Layer	3.75	4.3	Test Ended	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.
X-Axis Offset Inward from Original Serpentine Path	None	3	Test Ended	inches	Distance HWEE moved inward in X-axis *both ends) from original serpentine path on layer 1
Y-Axis Offset Inward from Original Serpentine Path	~ 1 inward	3	Test Ended	inches	Distance HWEE moved inward in Y-axis *both ends) from original serpentine path on layer 1
Flushing per Layer	End of each pass [1]	End of return pass [2]	Test Ended		Details of how flushing was done (see notes if tagged)
Flush Time	2 to 3 [1]	18 - 24	Test Ended	seconds	Approximate flush time for valve off and on (see notes if tagged)
Flush Pressure	1000 [1]	0 - 1000	Test Ended	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Drill	Manual	Test Ended		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Cut Measurement Width	NA	NA	Test Ended	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	Not Taken	Not Taken	Test Ended	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	Not Taken	Not Taken	Test Ended	inches	Mining measurement to fluid surface (-S) or ridge (-R).
Measurement Comment	NA	NA	Test Ended		
Receipt Tank (Fluid Depth - Opposing corners) - Comment	Not Taken	Not Taken	Test Ended		
Comment	K:		Test Ended		K: All passes on this layer were suction only (HWEE off) with flushing at end of each pass.
Layer 5 Parameters					
Drop height from previous layer	1	1	Test Ended	inches	Relative drop distance from previous layer
Position from original simulant surface	-3.75	-3.75	Test Ended	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	5	4	Test Ended	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	~ 40	34	Test Ended	inches	
Y-Axis Offset Between Serpentine Paths on Layer	3.75	3.75	Test Ended	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.

X-Axis Offset Inward from Original Serpentine Path	None	3	Test Ended	inches	Distance HWEE moved inward in X-axis *both ends) from original serpentine path on layer 1
Y-Axis Offset Inward from Original Serpentine Path	1.75	3	Test Ended	inches	Distance HWEE moved inward in Y-axis *both ends) from original serpentine path on layer 1
Flushing per Layer	End of each pass [1]	End of return pass [2]	Test Ended		Details of how flushing was done (see notes if tagged)
Flush Time	2 to 3 [1]	18 - 24	Test Ended	seconds	Approximate flush time for valve off and on (see notes if tagged)
Flush Pressure	500 [1]	0 - 1000	Test Ended	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Drill	Manual	Test Ended		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Cut Measurement Width	NA	NA	Test Ended	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	Not Taken	8	Test Ended	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	Not Taken	5.74 -R	Test Ended	inches	Mining measurement to fluid surface (-S) or ridge (-R).
Measurement Comment	NA		Test Ended		
Receipt Tank (Fluid Depth - Opposing corners) - Comment	Not Taken	17, 15.5	Test Ended		KP: Filled 13-1/4 inches on average from opposing corner measurements (17 & 5-1/2 inches) with noticeable interface layer 6 inches on average from opposing corner measurements (9 & 7 inches).
Comment	NA	KP:	Test Ended		KP: Screen 90% clear
Layer 6 Parameters					
Drop height from previous layer	1	1	Test Ended	inches	Relative drop distance from previous layer
Position from original simulant surface	-4.75	-4.75	Test Ended	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	4	4	Test Ended	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	~ 40	34	Test Ended	inches	
Y-Axis Offset Between Serpentine Paths on Layer	3.75	3.75	Test Ended	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.
X-Axis Offset Inward from Original Serpentine Path	None	3	Test Ended	inches	Distance HWEE moved inward in X-axis *both ends) from original serpentine path on layer 1
Y-Axis Offset Inward from Original Serpentine Path	1.75	3	Test Ended	inches	Distance HWEE moved inward in Y-axis *both ends) from original serpentine path on layer 1
Flushing per Layer	End of each pass [1]	End of return pass [2]	Test Ended		Details of how flushing was done (see notes if tagged)
Flush Time	2 to 3 [1]	18 - 24	Test Ended	seconds	Approximate flush time for valve off and on (see notes if tagged)
Flush Pressure	500 [1]	0 - 1000	Test Ended	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Drill	Manual	Test Ended		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Cut Measurement Width	NA	NA	Test Ended	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	Not Taken	Not Taken	Test Ended	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	Not Taken	Not Taken	Test Ended	inches	Mining measurement to fluid surface (-S) or ridge (-R).
Measurement Comment	NA	NA	Test Ended		
Receipt Tank (Fluid Depth - Opposing corners) - Comment	Not Taken	Not Taken	Test Ended		
Comment	NA	NA	Test Ended		
Layer 7 Parameters					
Drop height from previous layer	1	1	Test Ended	inches	Relative drop distance from previous layer
Position from original simulant surface	-5.75	-5.75	Test Ended	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	4	4	Test Ended	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	~ 40	34	Test Ended	inches	
Y-Axis Offset Between Serpentine Paths on Layer	3.75	3.75	Test Ended	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.
X-Axis Offset Inward from Original Serpentine Path	None	3	Test Ended	inches	Distance HWEE moved inward in X-axis *both ends) from original serpentine path on layer 1
Y-Axis Offset Inward from Original Serpentine Path	1.75	3	Test Ended	inches	Distance HWEE moved inward in Y-axis *both ends) from original serpentine path on layer 1

Flushing per Layer	End of each pass [1]	End of return pass [2]	Test Ended		Details of how flushing was done (see notes if tagged)
Flush Time	2 to 3 [1]	18 - 24	Test Ended	seconds	Approximate flush time for valve off and on (see notes if tagged)
Flush Pressure	500 [1]	0 - 1000	Test Ended	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Drill	Manual	Test Ended		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Cut Measurement Width	NA	NA	Test Ended	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	Not Taken	8 (to bottom)	Test Ended	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	7.22 -S	NA	Test Ended	inches	Mining measurement to fluid surface (-S) or ridge (-R).
Measurement Comment	End of mining	End of mining	Test Ended		K: Slurry level at -7.22 inches. About 0.75 inches of liquid in tank with some clumps left. KP: Mining trough left is through the simulant to wood form (4 inches) and no ridges left.
Receipt Tank (Fluid Depth - Opposing corners) - Comment	(11,9.5)	Not Taken	Test Ended	Inches	K: Associated with e-file 009. Light milkshake consistency with no large particles or clumps.
Comment	K:	KP:	Test Ended		K: Completion of mining. Test Ended KP: Completion of mining. Test Ended.
Layer 8 Parameters					
Drop height from previous layer	Test Ended	Test Ended	Test Ended	inches	Relative drop distance from previous layer
Position from original simulant surface	Test Ended	Test Ended	Test Ended	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	Test Ended	Test Ended	Test Ended	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	Test Ended	Test Ended	Test Ended	inches	
Y-Axis Offset Between Serpentine Paths on Layer	Test Ended	Test Ended	Test Ended	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.
X-Axis Offset Inward from Original Serpentine Path	Test Ended	Test Ended	Test Ended	inches	Distance HWEE moved inward in X-axis *both ends) from original serpentine path on layer 1
Y-Axis Offset Inward from Original Serpentine Path	Test Ended	Test Ended	Test Ended	inches	Distance HWEE moved inward in Y-axis *both ends) from original serpentine path on layer 1
Flushing per Layer	Test Ended	Test Ended	Test Ended		Details of how flushing was done (see notes if tagged)
Flush Time	Test Ended	Test Ended	Test Ended	seconds	Approximate flush time for valve off and on (see notes if tagged)
Flush Pressure	Test Ended	Test Ended	Test Ended	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Test Ended	Test Ended	Test Ended		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Cut Measurement Width	Test Ended	Test Ended	Test Ended	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	Test Ended	Test Ended	Test Ended	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	Test Ended	Test Ended	Test Ended	inches	Mining measurement to fluid surface (-S) or ridge (-R).
Measurement Comment	Test Ended	Test Ended	Test Ended		
Receipt Tank (Fluid Depth - Opposing corners) - Comment	Test Ended	Test Ended	Test Ended		
Comment	Test Ended	Test Ended	Test Ended		
Layer 9 Parameters					
Drop height from previous layer	Test Ended	Test Ended	Test Ended	inches	Relative drop distance from previous layer
Position from original simulant surface	Test Ended	Test Ended	Test Ended	inches	Position of metal bottom of HWEE from original simulant surface. Tolerance ± 0.25 inches.
Passes per Layer	Test Ended	Test Ended	Test Ended	passes	Number of X-axis passes to complete mining/retrieval of this layer.
X-Axis Traverse	Test Ended	Test Ended	Test Ended	inches	
Y-Axis Offset Between Serpentine Paths on Layer	Test Ended	Test Ended	Test Ended	inches	Distance HWEE moves over in Y-axis before moving alongside the previous X-axis path in return.
X-Axis Offset Inward from Original Serpentine Path	Test Ended	Test Ended	Test Ended	inches	Distance HWEE moved inward in X-axis *both ends) from original serpentine path on layer 1
Y-Axis Offset Inward from Original Serpentine Path	Test Ended	Test Ended	Test Ended	inches	Distance HWEE moved inward in Y-axis *both ends) from original serpentine path on layer 1
Flushing per Layer	Test Ended	Test Ended	Test Ended		Details of how flushing was done (see notes if tagged)

Flush Time	Test Ended	Test Ended	Test Ended	seconds	Approximate flush time for valve off and on (see notes if tagged)
Flush Pressure	Test Ended	Test Ended	Test Ended	psi	Maximum flush pressure. When flush valve is first opened, pressure drops low and then rises.
Flush Method	Test Ended	Test Ended	Test Ended		Method used to actuate flush needle valve (~ 5 turns each direction). Time may include some hold at max flush pressure.
Cut Measurement Width	Test Ended	Test Ended	Test Ended	inches	Mining HWEE single path cutting width. NA for multiple path cuts.
Cut Measurement Depth (To Undisturbed)	Test Ended	Test Ended	Test Ended	inches	Mining measurement to lowest undisturbed depth.
Cut Measurement Depth (Fluid Surface or Ridges)	Test Ended	Test Ended	Test Ended	inches	Mining measurement to fluid surface (-S) or ridge (-R).
Measurement Comment	Test Ended	Test Ended	Test Ended		
Receipt Tank (Fluid Depth - Opposing corners) - Comment	Test Ended	Test Ended	Test Ended		
Comment	Test Ended	Test Ended	Test Ended		

Notes:

[1] Flush water was activated at the end of each X-axis path during Y-axis jog using an electric drill while HWEE jets remained running. Flush valve quickly opened and closed with no pause at open. Maximum flush pressure at half HWEE operating pressure but some lag noted while water filled line and pressure was almost zero when first opened and then would build to maximum.

[2] Flush water was activated by hand. To start flushing HWEE flush valve opened with HWEE jet valve still running, HWEE jet valve shut, Hold for about 4 seconds at full HWEE pressure through HWEE flush valve only, open HWEE jet valve, close HWEE flush valve. During the process when both HWEE jet and HWEE flush valves were open, flush and HWEE pressure at first droped to zero and then normalized at half HWEE jet operating pressure.

[3] No flush water was activated during run.

[4] Data in main body of report may have slightly modified values based on final review of testing notes, photos, and video

Appendix B: Force/Torque Plots

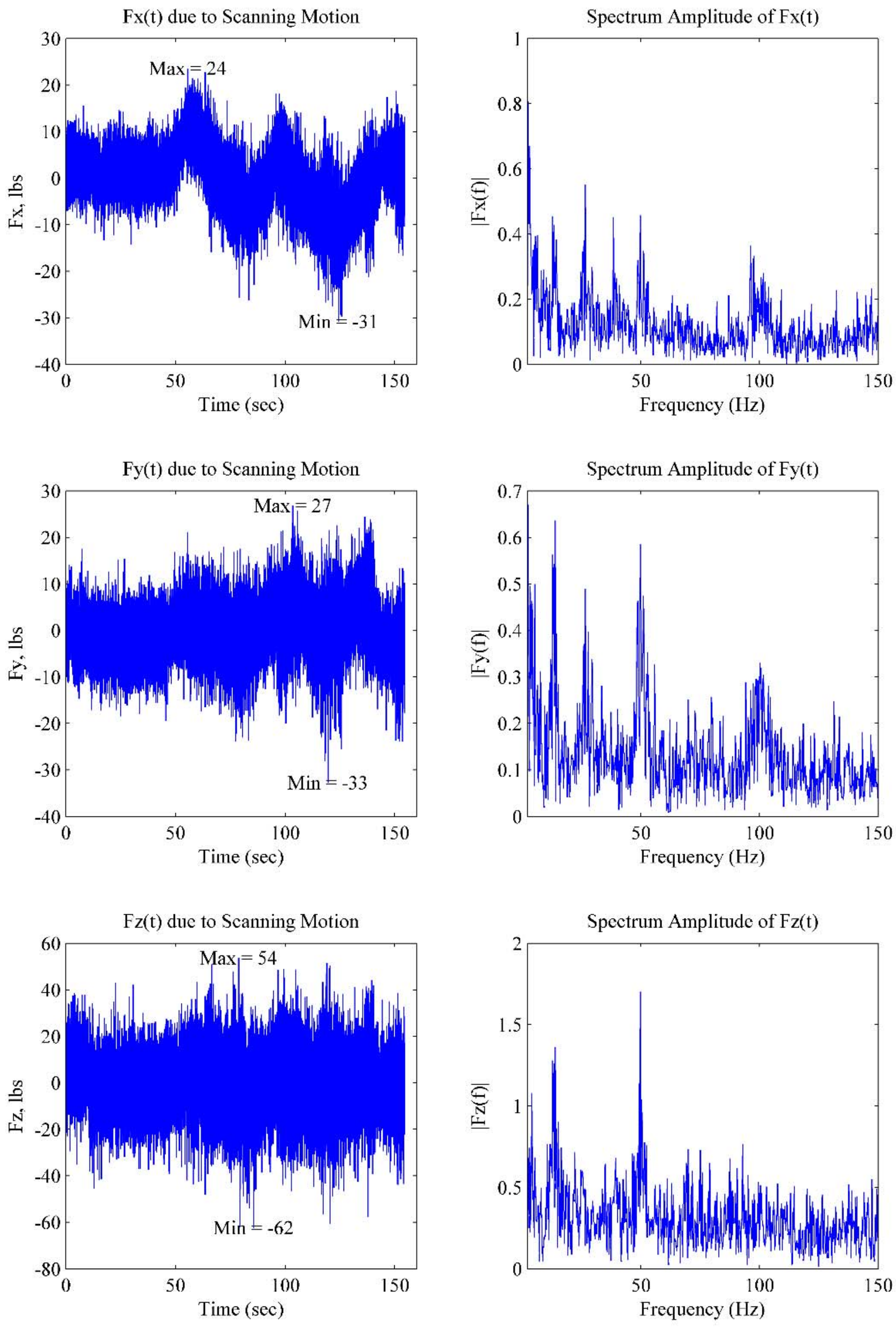

Figure B-1. HWEE Forces, Scanning Motion

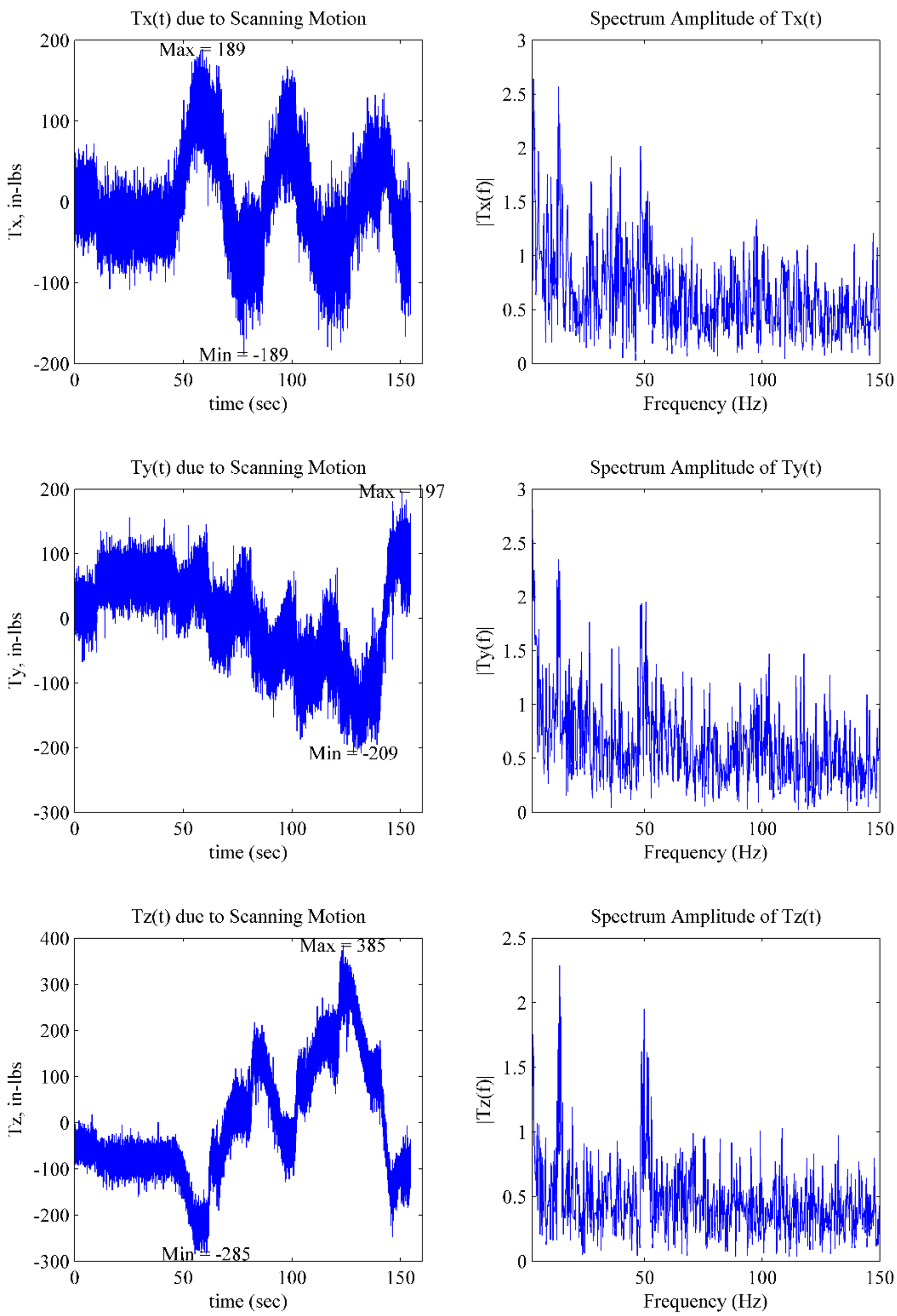

Figure B-2. HWEE Torques, Scanning Motion

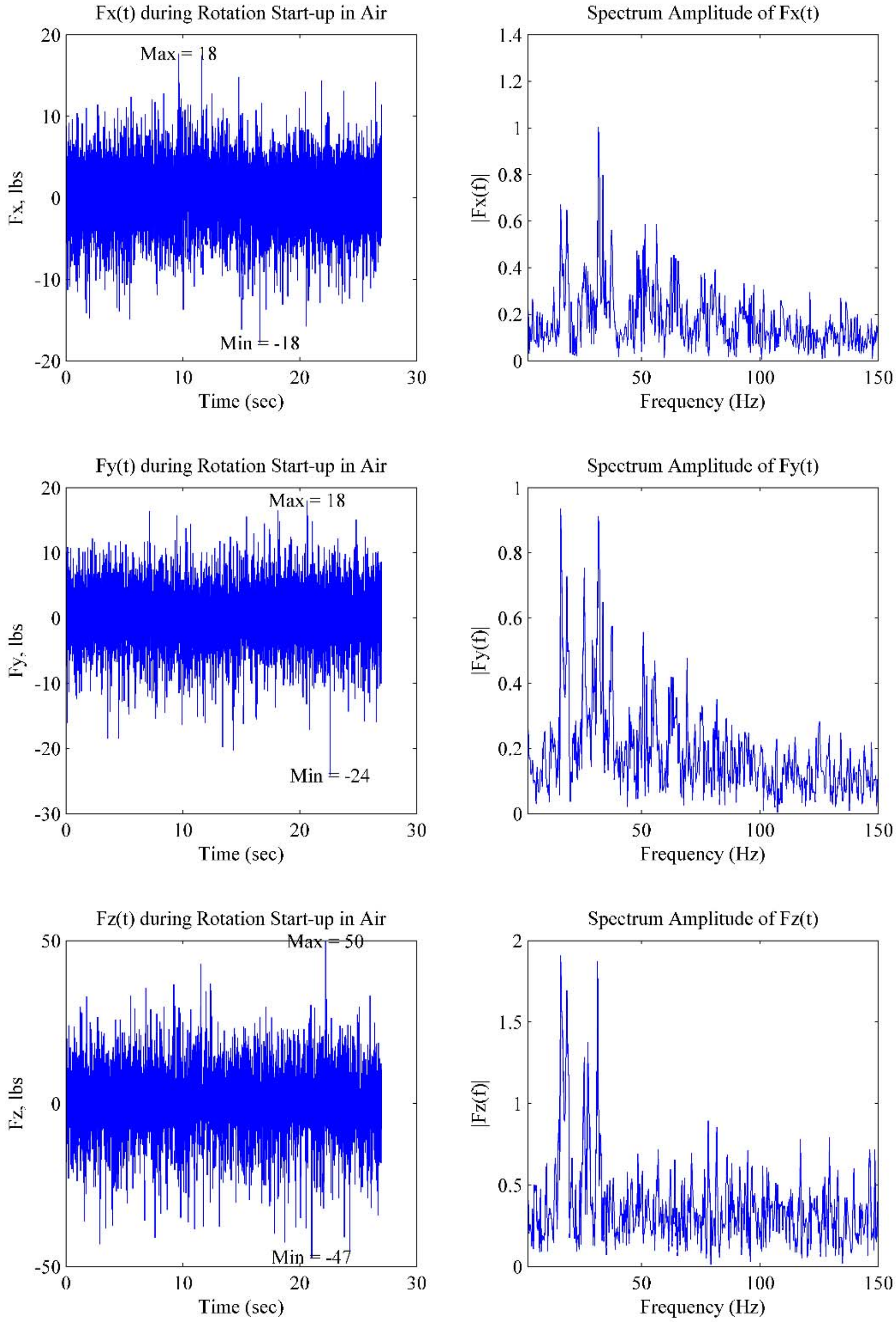

Figure B-3. HWEE Force Plots, Rotation Start-up and Shut-down in Air

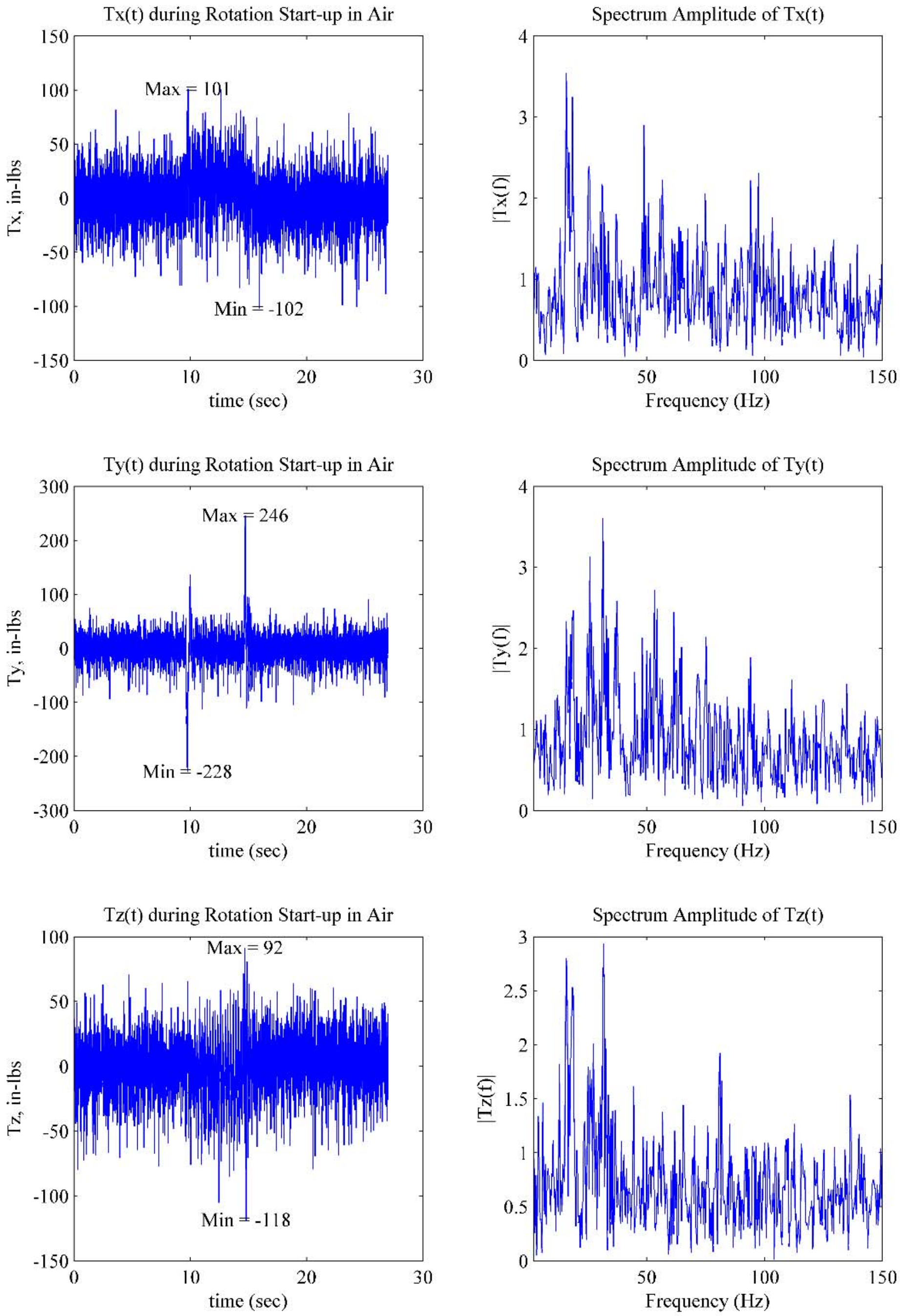

Figure B-4. HWEE Torque Plots, Rotation Start-up and Shut-down in Air

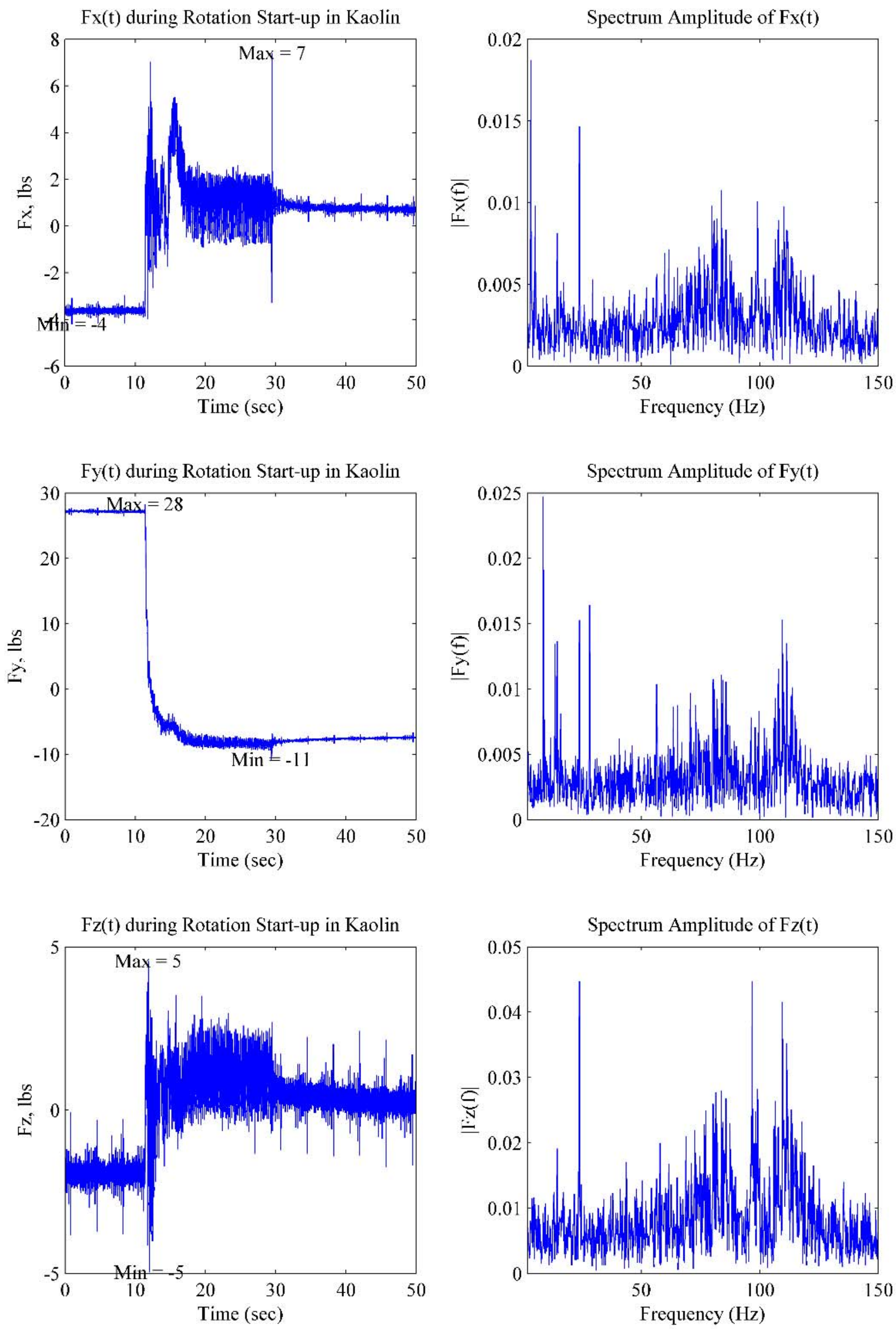

Figure B-5. HWEE Force Plots, Rotation Start-up and Shut-down in Kaolin

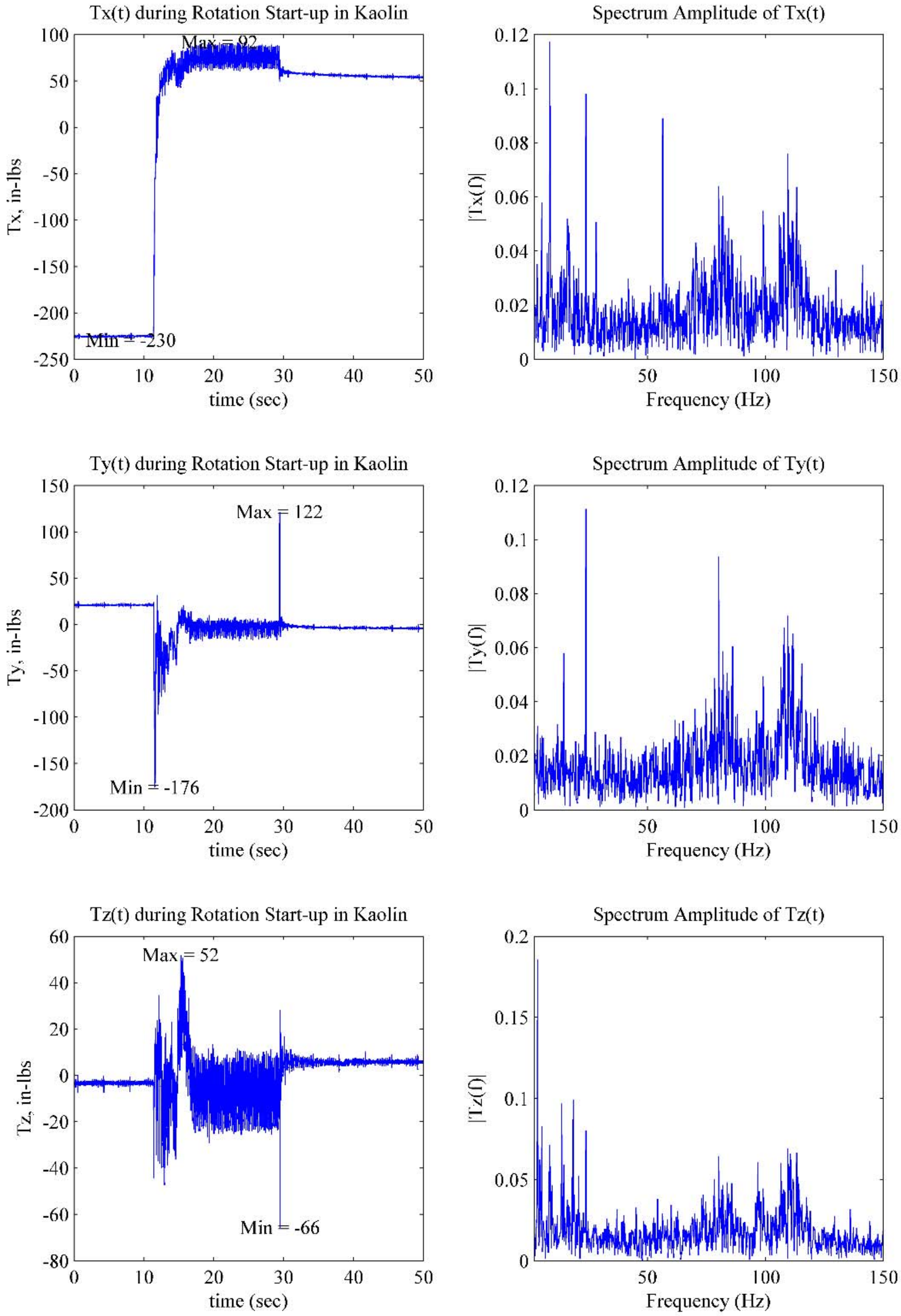

Figure B-6. HWEE Torque Plots, Rotation Start-up and Shut-down in Kaolin

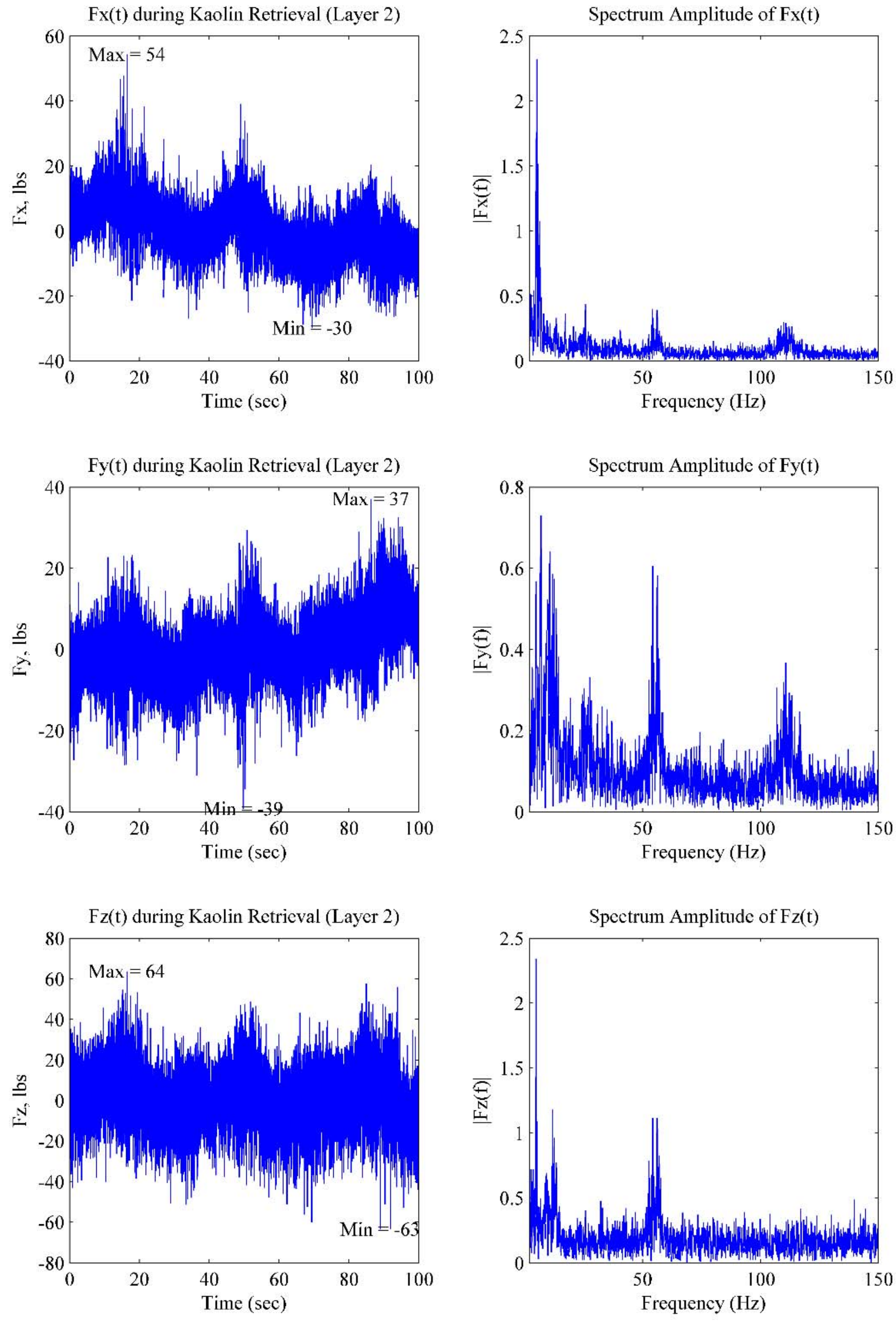

Figure B-7. HWEE Force Plots, Kaolin Retrieval

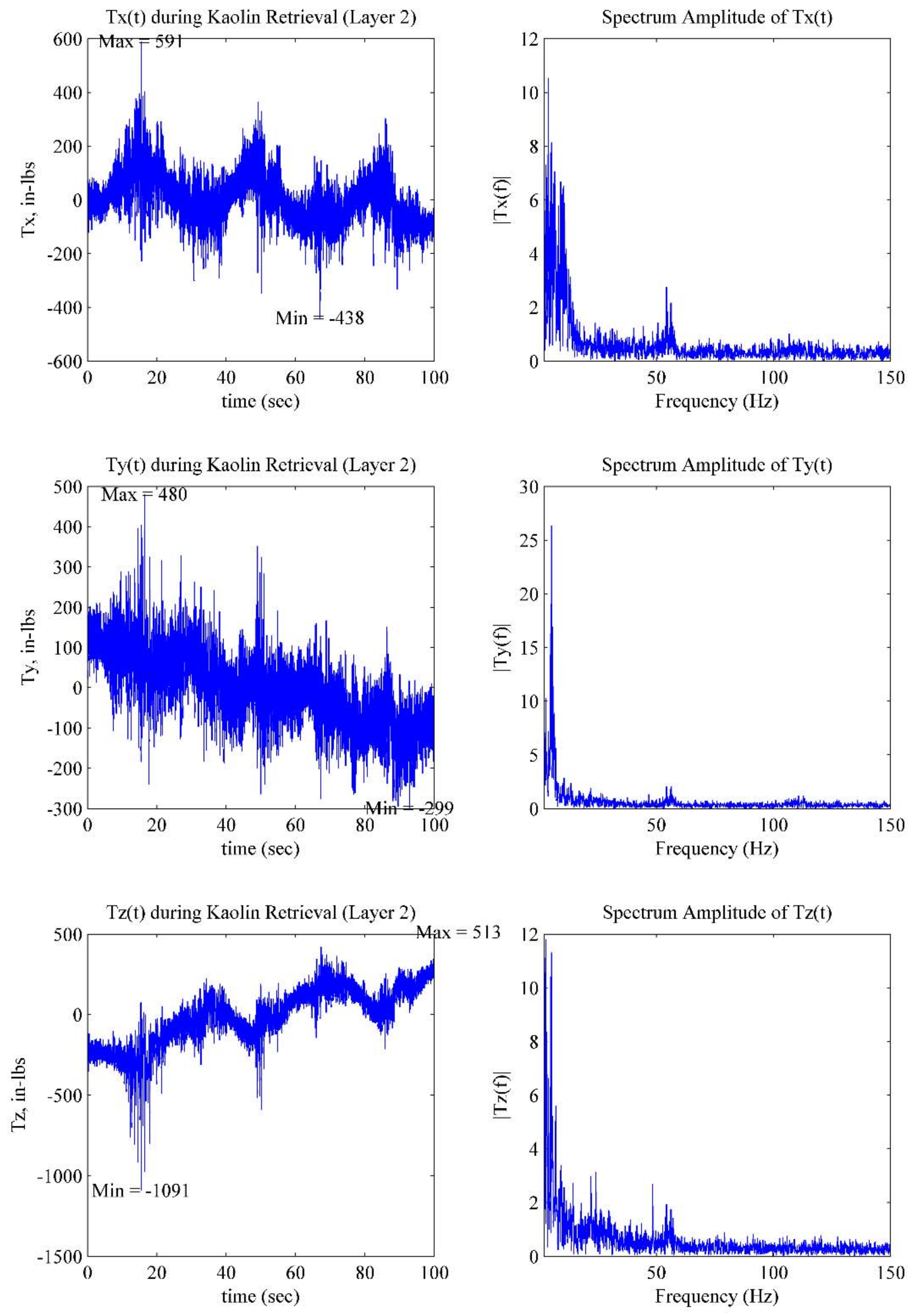

Figure B-8. HWEE Torque Plots, Kaolin Retrieval

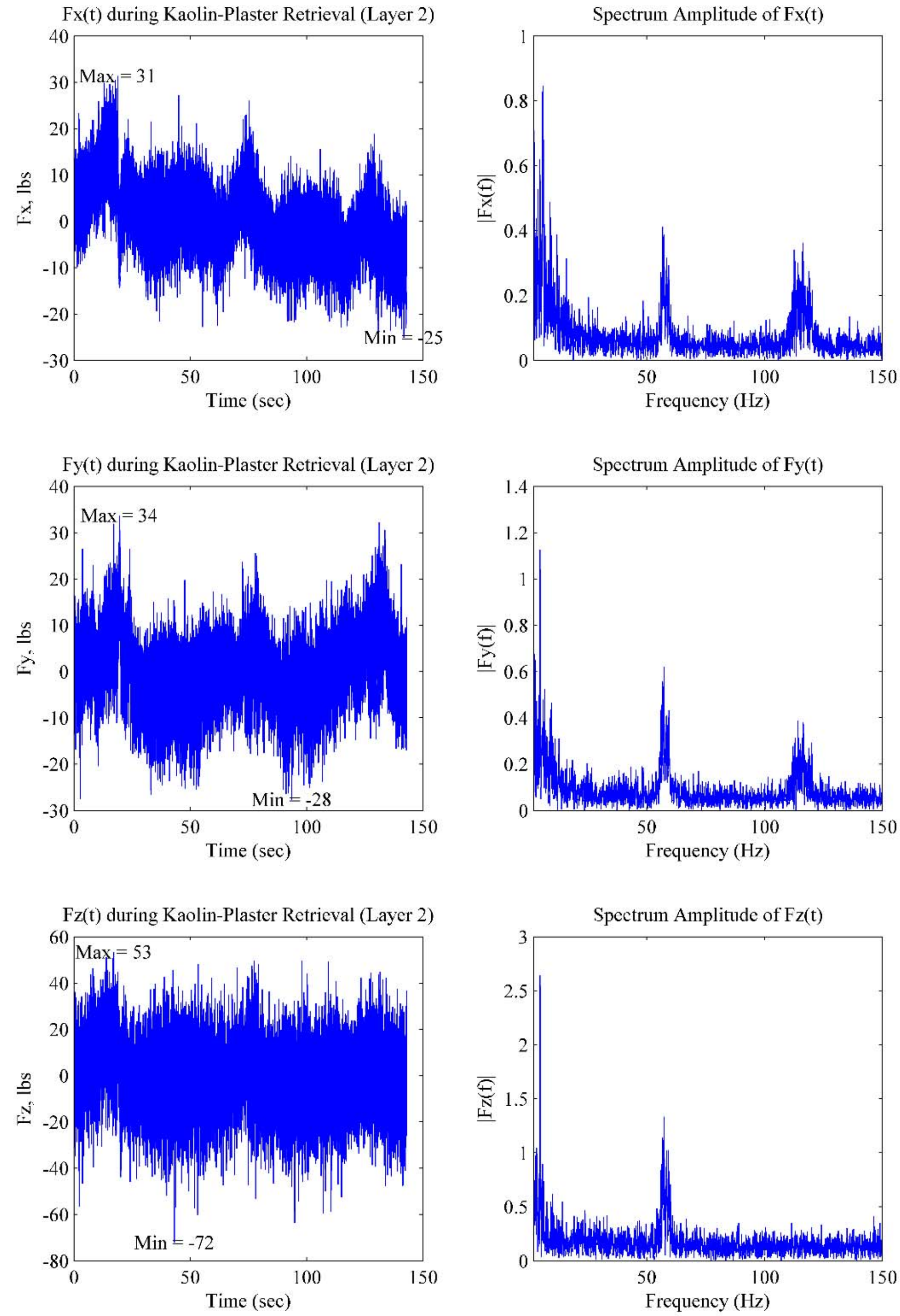

Figure B-9. HWEE Force Plots, Kaolin-Plaster Retrieval

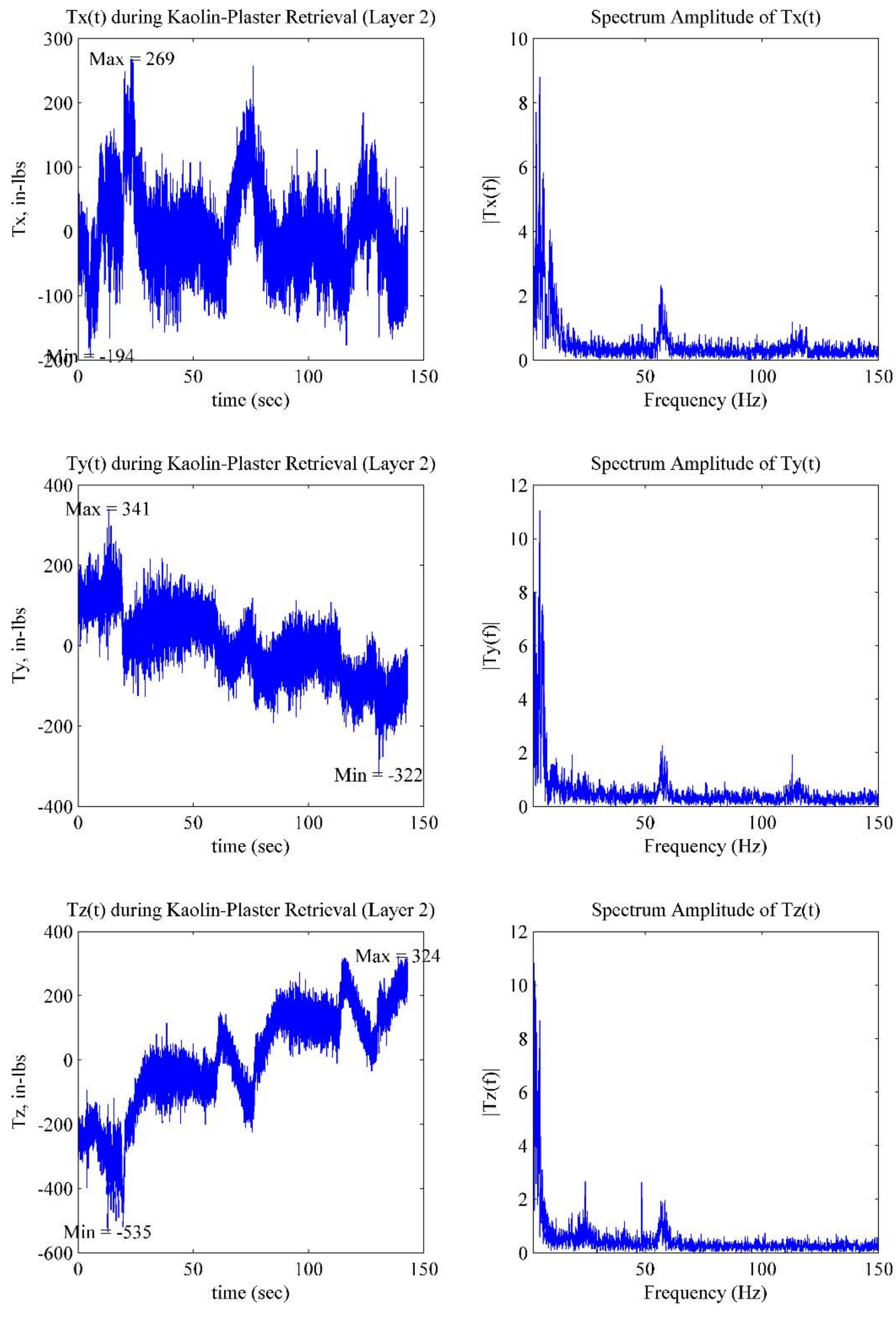

Figure B-10. HWEE Torque Plots, Kaolin-Plaster Retrieval

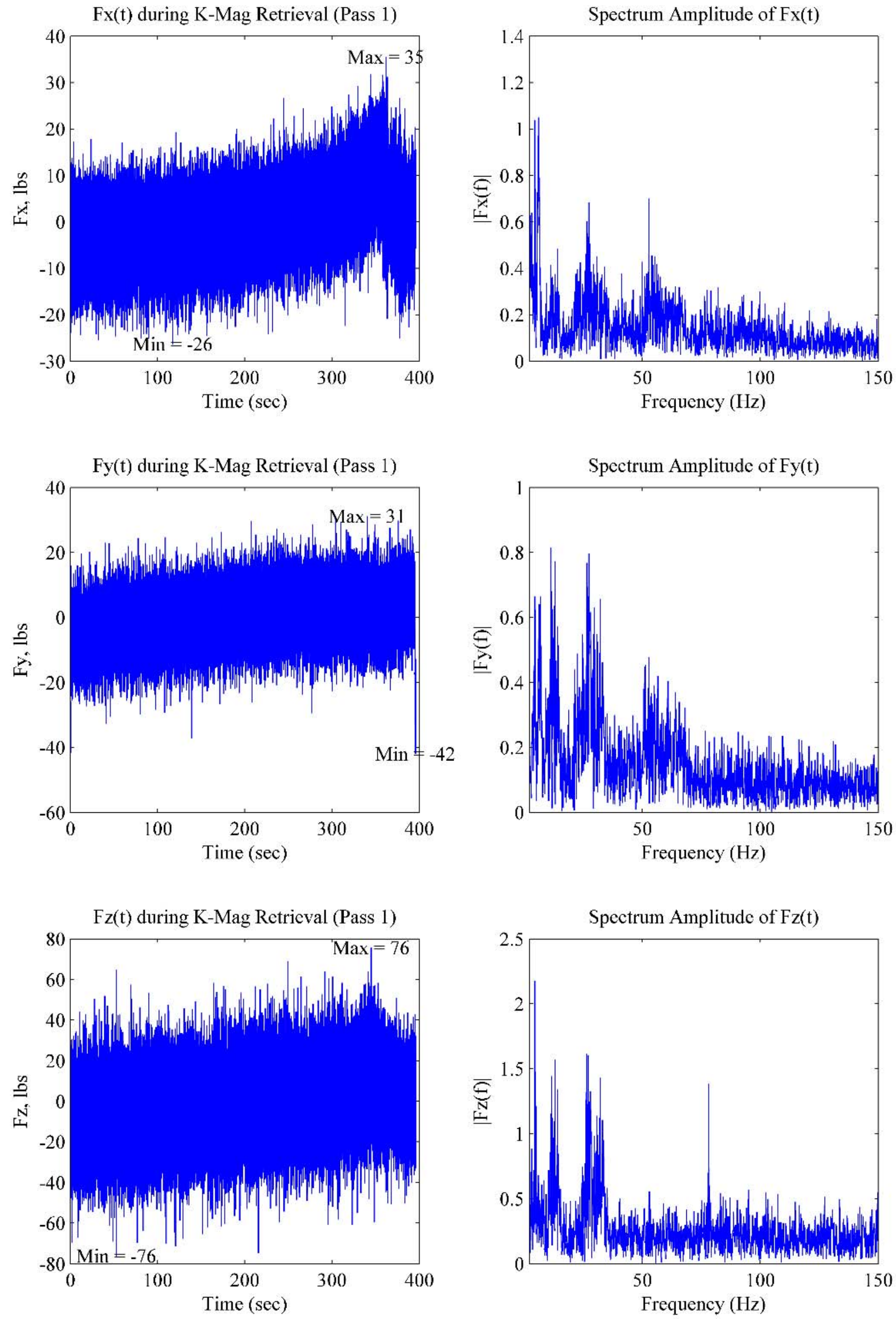

Figure B-11. HWEE Force Plots, K-Mag Retrieval

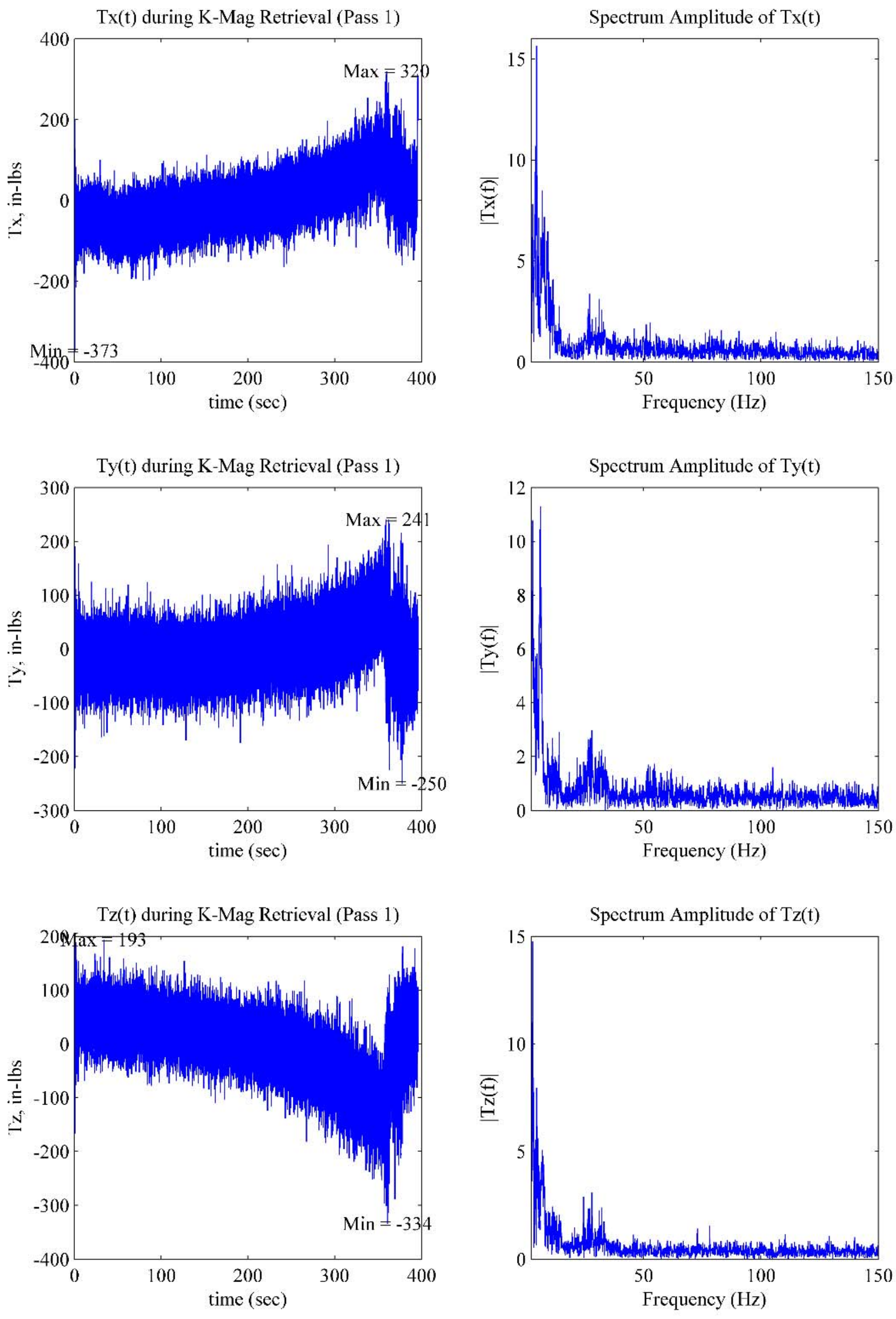

Figure B-12. HWEE Torque Plots, K-Mag Retrieval

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