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The Hanford Waste End Effector Phase II Test Report

August 2018

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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 II testing program of the Hanford Waste End Effector (HWEE) at the Washington River Protection Solutions Cold Test Facility (CTF). Phase II testing builds on the completed Phase I development testing (PNNL-26856) to address some key actual waste challenges as outlined in the Phase II test plan (PNNL-27422). This testing demonstrated retrieval of a mixed layered simulant and retrieval of uneven simulant profiles like that found near tank walls. A separate demonstration using only the HWEE conveyance jet pump assessed the lifting capabilities of this device for transporting waste out of an underground tank. The Pacific Northwest National Laboratory (PNNL)-designed robotic gantry system and associated systems (e.g., tanks, high-pressure water delivery and valves, instruments, etc.) used at CTF during Phase I were modified and upgraded to implement the Phase II test program and measure various process parameters. The tests demonstrated retrieval of water and Kaolin (sludge) simulant to determine pumping rate, dilution factors, and screen fouling rate.

This report will first describe the test equipment, instrumentation, simulant preparation procedures, and testing methodology. Testing results presented include HWEE water usage versus operating pressure of modified components from Phase I, simulant characterization data, dilution ratios, and retrieval rates. Reaction forces and other factors that would affect the remote operation of the HWEE will also be presented. Results of the separate jet pump vertical lift demonstration to a fixed height of at least 35 feet¹ are also presented.

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

- Demonstrate an end effector with minimal in-tank water usage in layered Kaolin simulant.

Success. The HWEE successfully retrieved the layered simulant without the need to modify the HWEE operating parameters. The retrieval rate calculated for Phase II was significantly higher than Phase I results (7.6 gpm versus 4.9 gpm), and the dilution ratio was slightly lower (0.24 versus 0.3). Minimizing the amount of liquid waste preserves limited double-shell tank space. As layers of simulant were retrieved, higher strength material at a raised elevation would slump slightly into the lower strength material, but the effect was not significant and did not impact the performance of the HWEE.

- Demonstrate an end effector with minimal in-tank water usage that can be used in a leaking tank in Kaolin simulant with a topographic profile as may be found at a tank wall.

Success. The HWEE successfully retrieved the simulant with topographical features using the predetermined mining strategy. The water was well contained during the feature removal, but it was noted that the skirt was dragged across the simulant bed, which created a small pathway for liquid to drain into the lower level of simulant. The retrieval rate calculated for Phase II during the topographical retrieval test was somewhat lower than Phase I results (3.1 gpm versus 4.9 gpm), and the dilution ratio was significantly lower (0.11 versus 0.3). It was noted that when performing

¹ The lift required to retrieve material from a Hanford single-shell tank is 35 feet for a 500,000-gallon tank and 60 feet for a 1,000,000-gallon tank.

retrieval with a tilted HWEE, the suction inlet was inclined with respect to the level of the simulant. This resulted in a loss of suction.

- Demonstrate potentially higher retrieval effectiveness with lower dilution.

Success. The HWEE Phase II tests demonstrated a retrieval rate of 7.6 gpm and a dilution ratio of 0.24 during the layered simulant retrieval test. The HWEE Phase I results for the similar Kaolin simulant during active retrieval were a retrieval rate of 4.9 gpm and dilution ratio of 0.3. The weakest material used for the MARS-V system testing, likely an easier to erode simulant than the higher shear strength Kaolin employed herein, had a retrieval rate of 4.3 gpm and dilution ratio of 0.05.

- Demonstrate the vertical lift capabilities of the jet pump to at least 35 feet, the lift required to retrieve material from a Hanford 500,000-gallon single-shell tank.

Success. The jet pump vertical testing demonstrated that the HWEE jet pump operating in its current configuration can transport simulant at least 39 feet including 6.5 feet of suction lift.

Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
CTF	Cold Test Facility
DACS	data acquisition and control system
HWEE	Hanford Waste End-Effector
imp	inch per minute
MARS	Mobile Arm Retrieval System
MARS-V	Mobile Arm Retrieval System-Vacuum
PNNL	Pacific Northwest National Laboratory
PRM	pressure-reducing manifold
WRPS	Washington River Protection Solutions

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1.0 Introduction

This report describes the Phase II testing program of the Hanford Waste End Effector (HWEE) at the Washington River Protection Solutions Cold Test Facility (CTF). Phase II testing builds on the completed Phase I development testing (PNNL-26856) to address some key actual waste challenges as outlined in the Phase II test plan (PNNL-27422). Work was performed under TOC subcontract 36437-220.

This testing demonstrated retrieval of a mixed layered simulant and retrieval of uneven simulant profiles like that found near tank walls. A separate demonstration using only the HWEE conveyance jet pump assessed the lifting capabilities of this device for transporting waste out of an underground tank. The Pacific Northwest National Laboratory (PNNL)-designed robotic gantry system and associated systems (e.g., tanks, high-pressure water delivery and valves, instruments, etc.) used at CTF during Phase I were modified and upgraded to implement the Phase II test program and measure various process parameters. The tests demonstrated retrieval of water and Kaolin (sludge) simulant to determine pumping rate, dilution factors, and screen fouling rate.

This report will first describe the test equipment, instrumentation, simulant preparation procedures, and testing methodology. Testing results presented include HWEE water usage versus operating pressure of modified components from Phase I, simulant characterization data, dilution ratios, and retrieval rates. Reaction forces and other factors that would affect the remote operation of the HWEE will also be presented. Results of the separate jet pump vertical lift demonstration to a fix height of at least 35 feet, the lift required to retrieve material from a Hanford 500,000-gallon single-shell tank, is also presented.

1.1 Background

The HWEE is a water-based scarifier originally developed by PNNL for U.S. Department of Energy tank retrieval systems 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). In 1998, as part of the Hanford Tanks Initiative (HTI) Project, a contractor team led by Foster Wheeler proposed to deploy the technology with a remote crawler to remove sludge and hardpan from Tank 241-C-106 during a retrieval demonstration. The prototype was fabricated by Oceaneering International and tested by PNNL using wet sludge and hardpan to measure baseline performance. Development of the HWEE was not deployed in favor of other competing technology, such as the Mobile Arm Retrieval System (MARS) (Shields 2011).

Currently, 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 background, history and design of the HWEE is described in HWEE Phase I documentation including the test report (PNNL-26856) and test plan (PNNL-26549).

The HWEE used for the Phase II testing was initially fabricated by HiLine Engineering and Fabrication, Inc. based on the procurement specification RPP-SPEC-61356 for Phase I and then inspected, modified, and reassembled after Phase I for Phase II.

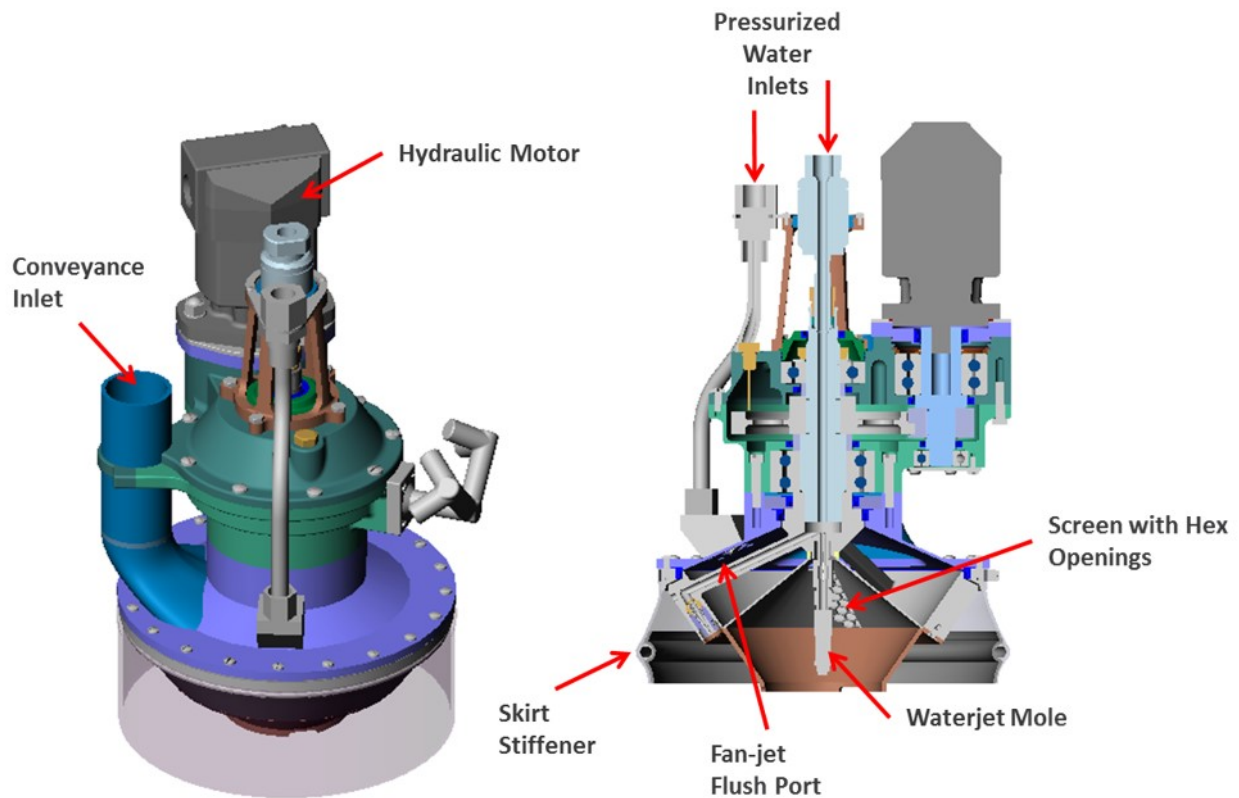


Figure 1.1. Hanford Waste End Effector Concept

The following equipment and test setup modifications/upgrades from HWEE Phase I testing included the following:

HWEE modifications by either PNNL or HiLine:

1. The HWEE was refurbished, including disassembly and inspection of non-welded components and internal seals, bearings, and nozzles. Seals in the hydraulic motor were replaced to correct a leak that occurred during low-speed operation (HiLine).
2. Mole was removed and inlet plugged (HiLine).
3. The flush jet was changed out to smaller nozzle to reduce flush water usage (HiLine).
4. Inlet screen with hex openings was refabricated to be more robust and eliminate the screen failure that occurred during Phase I testing (HiLine).
5. One-directional tilting capability was added along the x-axis plane to allow more flexible mining paths, including wall cleaning (PNNL).

HWEE retrieval test setup by PNNL:

6. Remotely activated high-pressure water valves were added to allow quick on/off activation of the HWEE jets, the HWEE flush, and, for some testing, the HWEE conveyance jet pump.
7. Position sensors were added on the remotely activated high-pressure water valves.
8. Level sensor was added to the retrieval tank to allow better monitoring of tank fill/tank fluid volume.
9. Temperature sensor was added to the retrieval tank to allow simulant density to be more accurately assessed.
10. Linear string pots were added to monitor gantry 3D motion and HWEE head tilt.

Jet pump vertical lift test setup by PNNL:

11. This was a completely new test setup that used some equipment and instrument components from the retrieval testing to monitor a jet pump lift demonstration to a CTF tank platform.

1.2 Governing Documents

Governing documents associated with this work are

- *Hanford Waste End Effector Prototype Test Plan – Phase II* (Berglin et al. 2018, PNNL-27433), referred to as the Test Plan in this document
- *Standard Operating Procedures for the Hanford Waste End Effector Test System* (Neill 2018)
- *Statement of Work for Alternate Retrieval Technology Concept Testing Definition of the Hanford Waste End Effector, Phase II*, WRPS Requisition 305847, Revision 2, June 25, 2018
- *Off-Site Risk Management Plan for Alternate Retrieval Technology Concept Testing Definition Phase II*, Pacific Northwest National Laboratory, March 29, 2018
- *Pressure Systems Permit for Alternate Retrieval Technology Concept Testing Definition Phase II*, PSP-70000-01, Pacific Northwest National Laboratory, August 1, 2017

The key governing document for test execution and reporting is the final Test Plan that was generated and approved by Washington River Protection Solutions (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 II Data Requirements

Data Requirement	Data Type	Target Accuracy Objective
Retrieval		
Determine slurry retrieval rate and slurry dilution ratio for different test material configurations, including:	Test data Video record	+/-10%
1. Kaolin (sludge) in layered configuration 2. Kaolin (sludge) with uneven surfaces		
Measure HWEE tool reaction forces and frequency content during retrieval operation.	Test data Video record	+/- 5%
Conveyance (Jet Pump)		
Measure water usage from jet pump conveyance activities during retrieval activities.	Test data	+/- 15%
Lift (Jet Pump)		
Demonstrate jet pump total lift capability of at least 35 feet.	Test data Video record	+/-10% Qualitative
Simulant Production		
Measure density and strength of test simulants to ensure consistency. Where multiple simulants are used, measure each simulant separately.	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 re-erected the mobile testing platform at the CTF off Horn Rapids Road in Richland, Washington, with a few modifications for Phase II testing as described in Test Plan Section 4.0 (Test Approach). WRPS supplied the Phase II reconditioned/modified HWEE by HiLine Engineering and CTF services (water, air, electrical), structure (tent anchor blocks, operations trailer, disposal basin), support (operators, forklift, man lift), and CTF-associated erection of piping and electrical for the jet pump vertical lift testing. 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 April 2018 and was completed in early May 2018. Phase II testing was started and completed in May 2018. The following sections provide a description of the test equipment and instrumentation used.

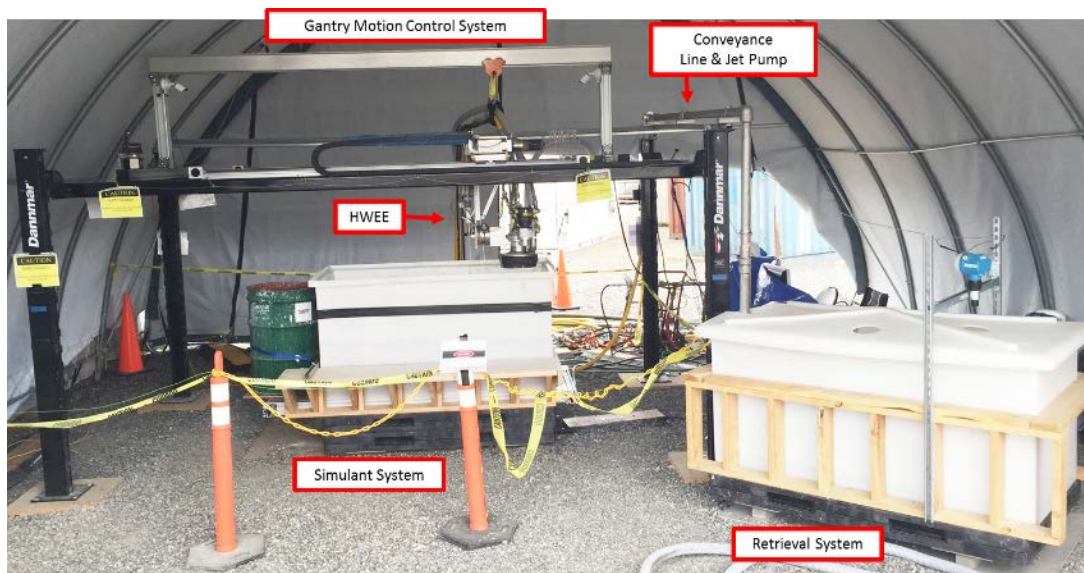


Figure 2.1. HWEE Test System inside Tent

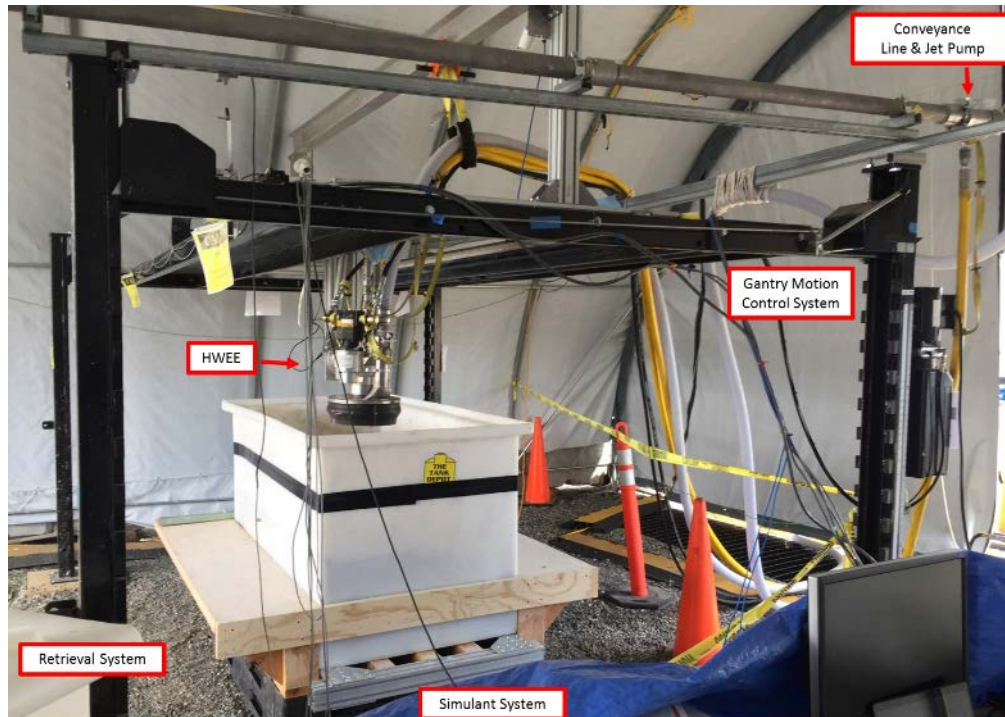


Figure 2.2. HWEE Test System inside Tent (Retrieval Tank to Right Not Shown)

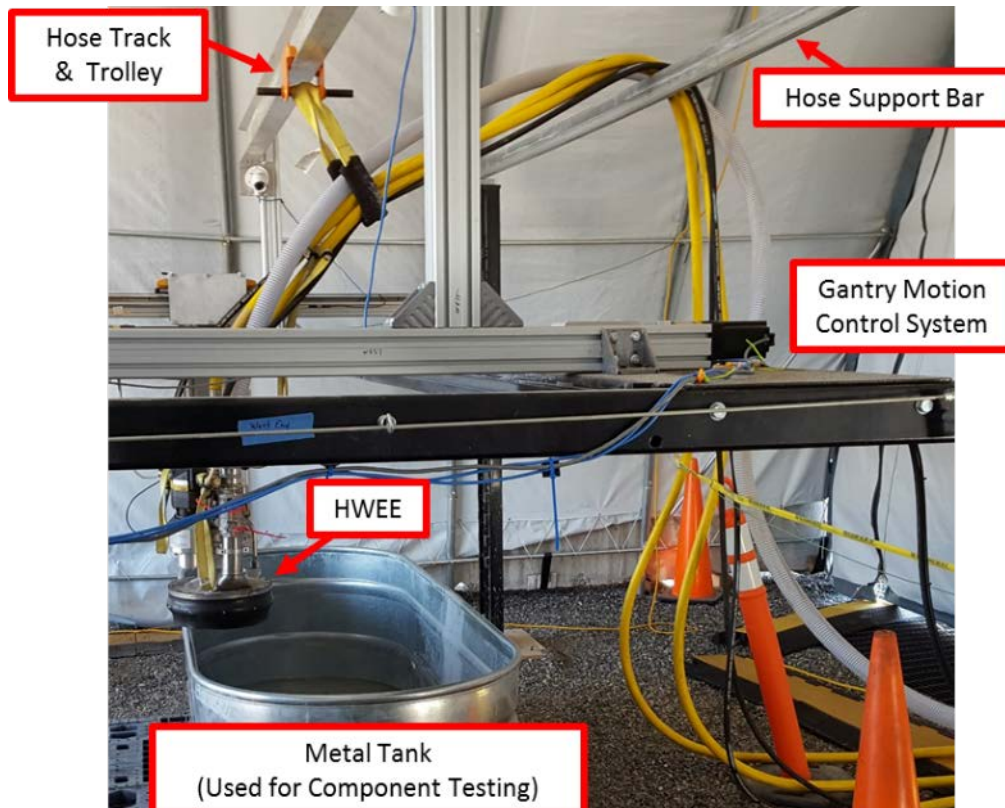


Figure 2.3. HWEE Test System – HWEE Attachment and Hose Management System

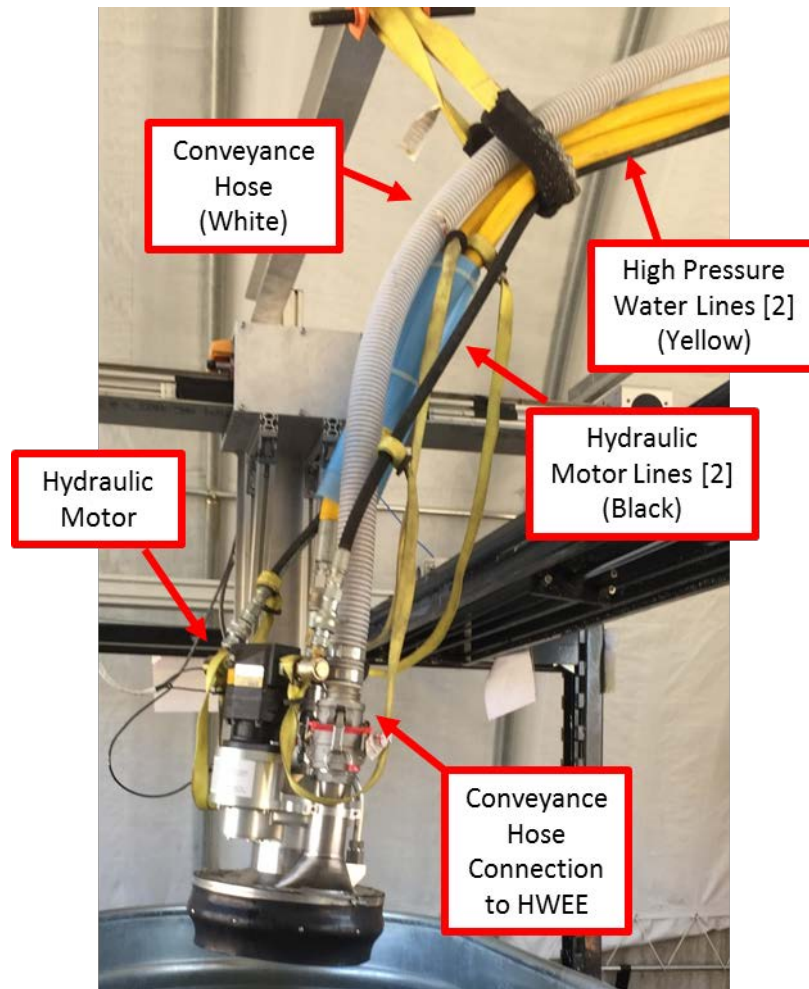


Figure 2.4. HWEE Test System – HWEE Connections

Test setup and associated equipment and instrumentation used for HWEE Phase II testing are initially described in the Test Plan; see Sections 4.1 to 4.3, Test Setup, and 4.4, Test Equipment and Instrumentation.

For retrieval testing, 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 were located in the tent enclosure.

For jet pump vertical lift testing, the tent enclosure was not used and all equipment was located outside. A small portable tent was utilized near the CTF simulated tank structure to provide weather protection and operator shielding associated with the data acquisition system.

2.2 Units under Test

Items under test include the HWEE with jet pump during retrieval testing and only the jet pump during vertical lift testing. For retrieval test (see Section 5.3), the HWEE and jet pump are connected by hose and work together to allow transport of materials through the HWEE and out the jet pump using the jet pump's suction force. For vertical jet pump lift testing (see Section 5.4), the jet pump operates by itself drawing fluid through a HWEE on the inlet hose and up into a vertical conveyance pipe.

2.2.1 Hanford Waste End Effector

The HWEE used in Phase II was the same as used in Phase I with some minor changes that were previously briefly described in Section 1.1. Background and design are detailed in the Phase II test plan Section 3.0. The minor changes included the following:

- The HWEE was refurbished by HiLine, which included disassembling and inspecting non-welded components and internal seals, bearings, and nozzles. Seals in the hydraulic motor were replaced to correct a leak that occurred in Phase I testing during low-speed operation.
- A tilt mechanism was added that allowed the HWEE to be pivoted $\pm 35^\circ$ from the vertical downward position (i.e., 0° used during Phase I testing) to allow demonstration of wall cleaning.
- The internal flush jet size was changed to reduce water flow (Hatchell 2018 letter report). The new flush jet nozzle installed by HiLine was NLB part #S-3-6504. Water flow rate through this nozzle was specified by NLB to be 6.3 gpm at 10,000 psi. The Phase I HWEE internal flush nozzle (believed to be the NLB part #S-3 65° or possibly the NLB S3-1515) had a flow rate of 22.53 gpm at 10,000 psi (Hatchell 2018).
- The external mole flush nozzle was removed (Hatchell 2018).
- The inlet screen was redesigned and fabricated by HiLine Engineering to be more robust due to failure in Phase I testing. The new screen has 20% more bar thickness (depth of hexagonal cell openings) and 5.5% less open area (now 0.1150 in² per cell).

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 at around 300 rpm at 35 degree cone angle as shown in Figure 2.5 and Figure 2.6. Two high-pressure water hoses supplied water to the HWEE rotary jets and HWEE flush and two hydraulic hoses supplied power 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 pressure drop along the length of high-pressure hoses, which were 150 ft long, was small and did not affect performance. The operating pressure of 1000 psi used for Phase II testing was chosen primarily to provide adequate dilution of the simulant while providing sufficient depth of cut.

The HWEE connected to the gantry using an attachment bracket that sandwiched the force/torque sensor to the gantry down structure. This attachment bracket was modified for Phase II to allow the HWEE tilt apparatus to be installed. To achieve the tilt capability, the HWEE was mounted to a large rotational thrust bearing (McMaster Carr Item 2010N260). Rotation was achieved by the use of an electro-mechanical actuator (McMaster Carr Item 9005K120) that pushed/pulled a pivot bar mounted to the rear of the thrust bearing. Limit switches were installed at $\pm 35^\circ$ to allow the HWEE to be accurately

positioned for tank wall cleaning. A string potentiometer measured the length of the actuator. Knowing the length that corresponded to a level orientation, the test operator was able to easily position the HWEE at 0° by going to a known location indicated by the string potentiometer. For the topographical retrieval test, only one direction of tilt was needed, so the second limit switch was repositioned at the 0° orientation. This switch made it easier for the operator to go to the level orientation during the test. Testing during Phase I was conducted with the HWEE in the vertical down position only (i.e., 0°). HWEE configuration used during testing is shown in Figure 2.7 through Figure 2.9.

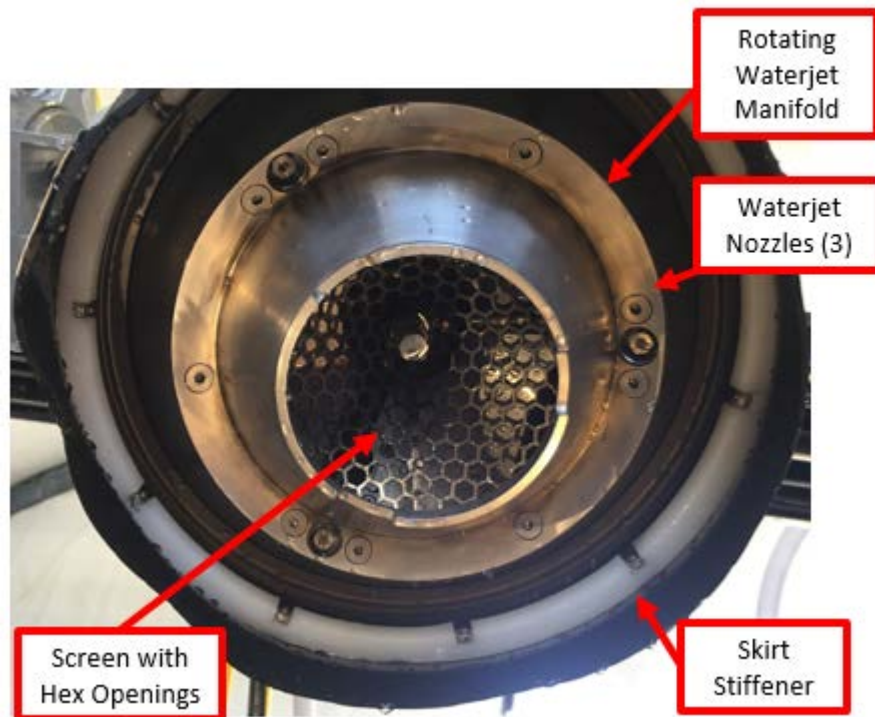


Figure 2.5. HWEE Testing Configuration—Bottom View of the HWEE

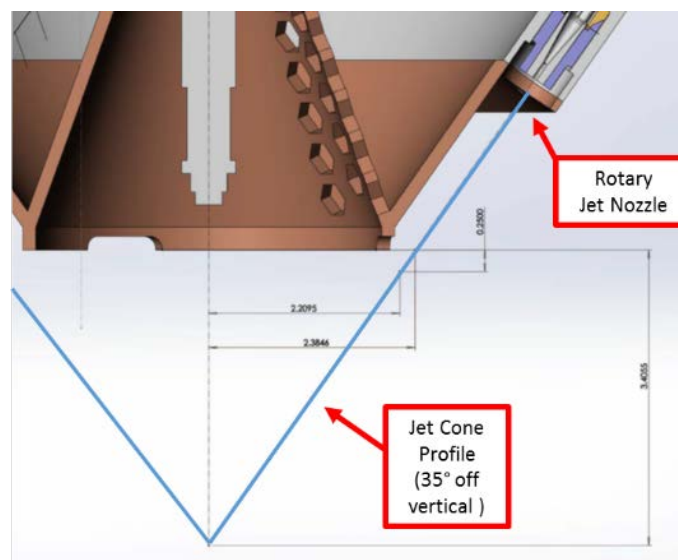


Figure 2.6. HWEE Jet Trajectory (35° Degree Angle)

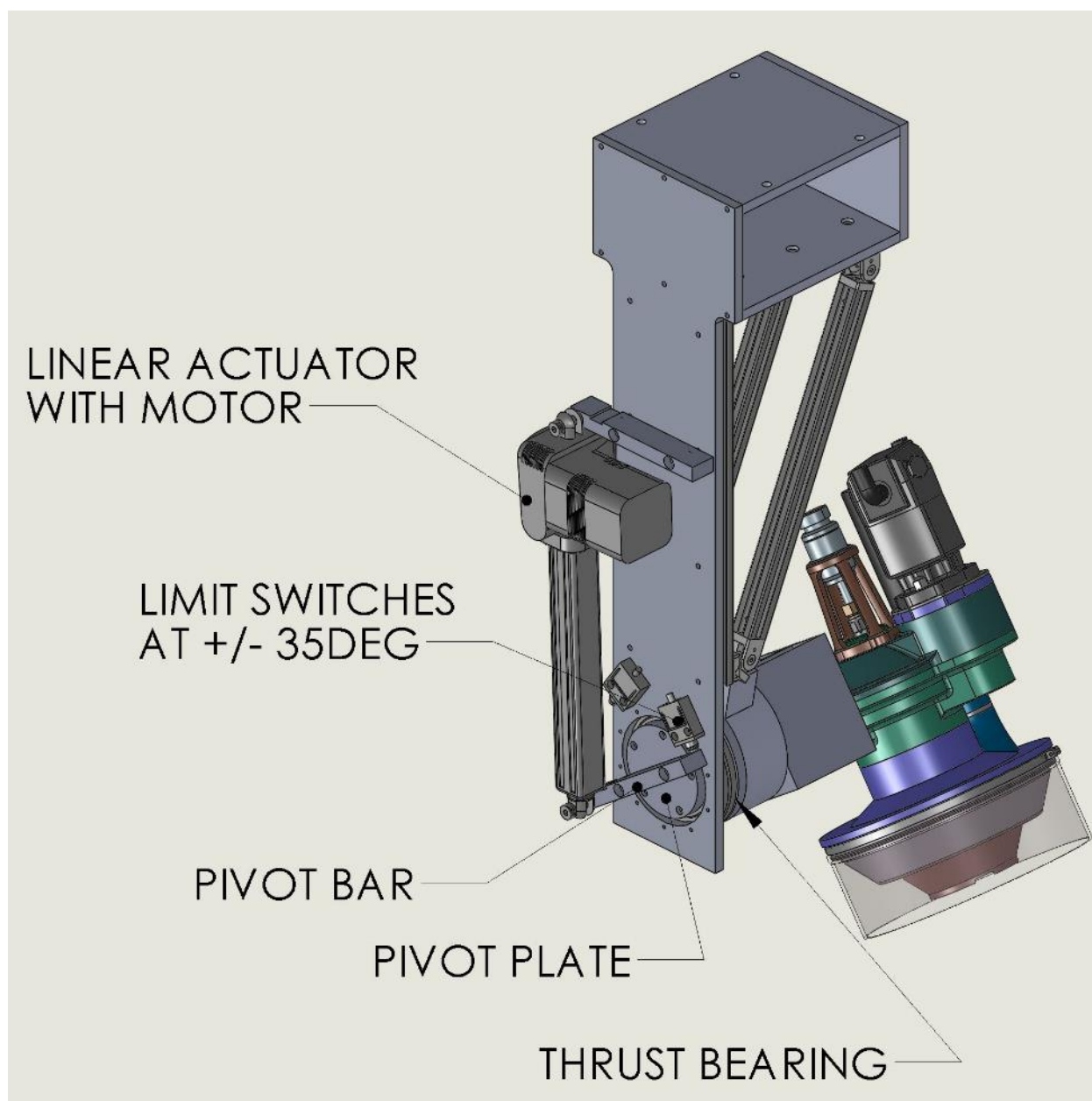


Figure 2.7. HWEE Tilt Design and Components

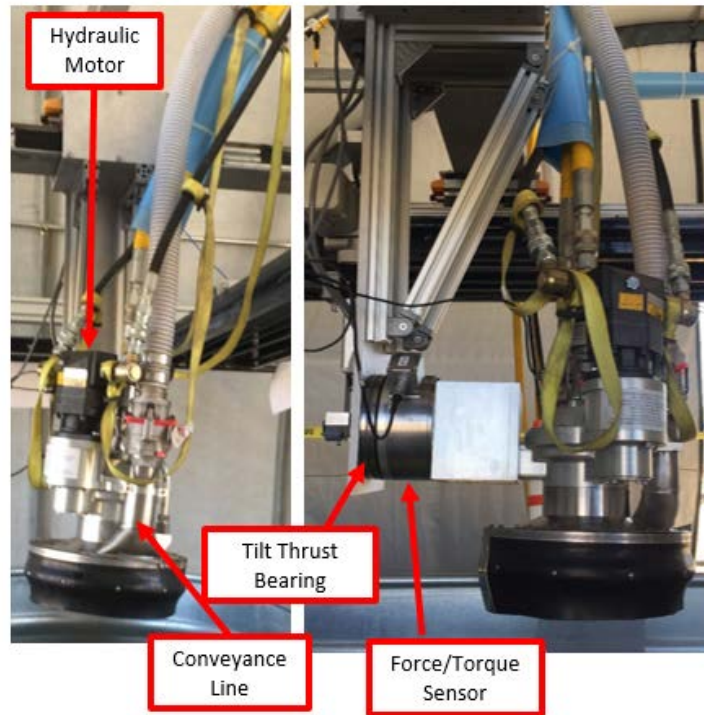


Figure 2.8. HWEE Testing Configuration—Front and Side View



Figure 2.9. HWEE Testing Configuration—Back View and Tilts

2.2.2 Jet Pump

The jet pump was the same configuration used during HWEE Phase I testing with standard operating pressure in the range of 9,000 to 10,000 psi maximum. During jet pump testing, a range of jet pump operating pressure could be used to observe pump performance/operation limits. 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 (see Figure 2.10).



Figure 2.10. Jet Pump

2.3 Equipment

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

2.3.1 High-Pressure Water System

The high-pressure water system was essentially the same one used in Phase I testing; however, for retrieval testing, the on/off high-pressure water control of the individual HWEE components (HWEE rotary jets, flush, and jet pump) was enhanced by adding in-line pneumatically actuated fast-acting remote-operated valves to better control water usage. The rented NLB 225 Series high-pressure pump (300 hp diesel motor with 10K psi plungers installed) was a newer pump unit (see Figure 2.11) than the one used in Phase I but supplied the same water pressure and flow (up to 10,000 psi and 43 gpm).



Figure 2.11. NLB Corporation 225 Series Pump

The high-pressure water system supported Phase II retrieval testing and jet pump vertical lift testing. The retrieval testing setup was the more complex system because it had the capability to operate the jet pump at high pressure and to step down the pressure to the HWEE rotary jet/flush components via a pressure-reducing manifold (PRM) along with various pressure components (i.e., manual and automatic valves, etc.) as detailed in the retrieval piping and instrumentation design schematic (see Figure 2.12 and Appendix A). The jet pump vertical testing was a much simpler system as the high-pressure pump was connected directly to the jet pump with minimal valving (see Figure 2.13 and Appendix A).

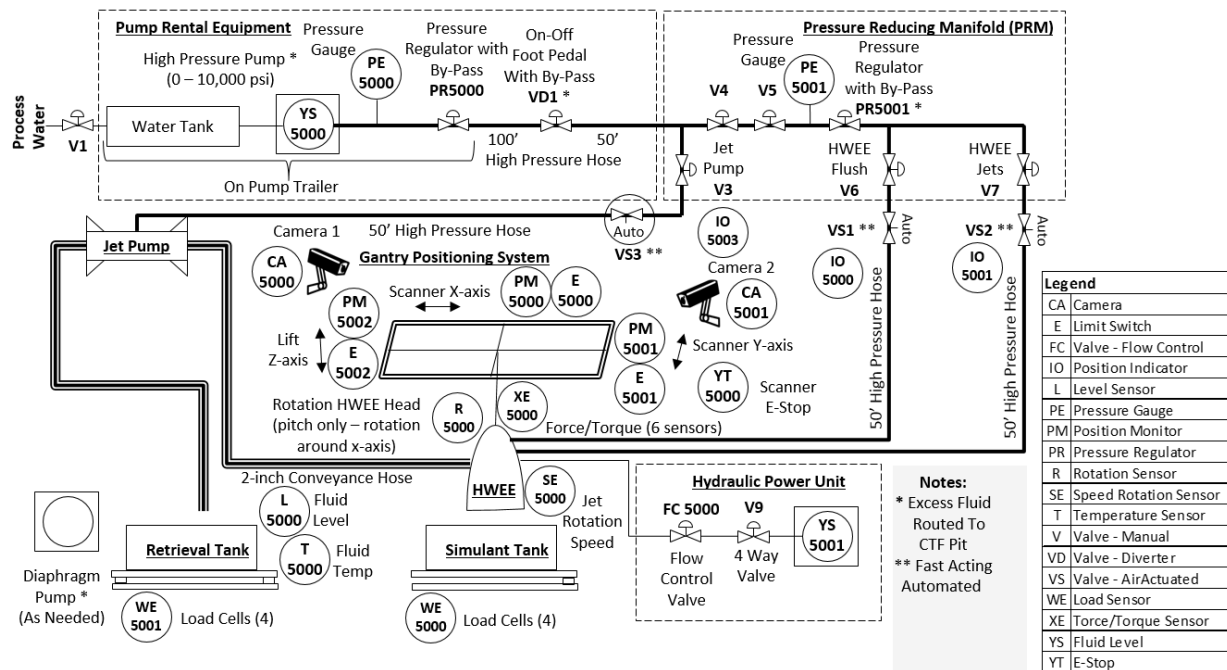


Figure 2.12. HWEE Test System Schematic—Retrieval Tests

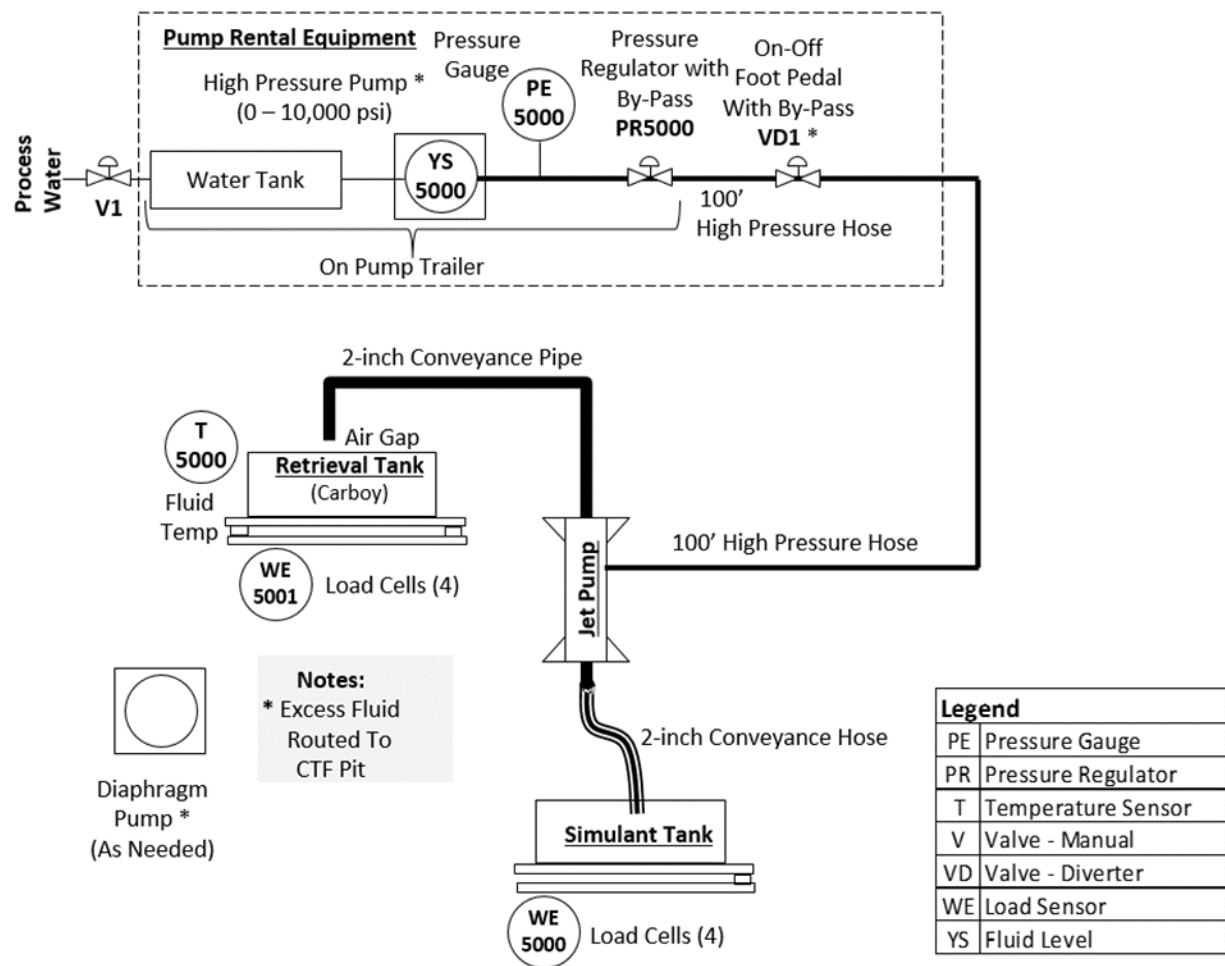


Figure 2.13. HWEE Test System Schematic—Jet Pump Vertical Lift Test

High-pressure pump operating pressure during test operations was typically set at 9,000 to 10,000 psi maximum as measured at the main pressure pump. For retrieval testing, a reduced pressure was set at the PRM for the HWEE rotating jet and flush devices. PRM pressure set was done with only the HWEE rotary jets operating. The foot pedal valve was used to interrupt flow from the high-pressure pump as applicable to conserve water when jet pump and/or HWEE operations were not required. During retrieval testing, the HWEE rotary jets could be shut off individually, typically using the new automatic valves, even when the foot pedal valve was engaged. During the first layered retrieval test only, an automatic valve was installed that also allowed the jet pump to be shut off individually like the HWEE components.

Retrieval Test Operations

During retrieval operations, whenever the jet pump was operating, its water flow and any flow drawn in by suction at the HWEE inlet screen was deposited into the retrieval tank. The jet pump and HWEE rotating jets operated during the retrieval test sequencing that included various sequences of serpentine paths to mine the simulants in layers. HWEE flushing occurred periodically and was generally activated at the end of an x-axis mining length when HWEE motion stopped and y-axis motion was activated. To conserve water used in the retrieval process, the HWEE rotating jet, HWEE flush, and jet pump were shut

off when not specifically needed. The clean, depressurized water that was diverted by the valves was discharged into the Cold Test Facility (CTF) basin.

Jet pump water flow occurred during pressure setup operations, just prior to the start of retrieval operations, during the retrieval operation sequence, 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 $\frac{1}{4}$ inch above the simulant surface at the start of retrieval testing. The conveyance hose between the HWEE and jet pump was approximately 54 feet (648 inches) of 2-inch conveyance hose and 9 inches of 2-inch pipe. Conveyance line downstream of jet pump was all 2-inch schedule 80 pipe consisting of approximately 136 inches of horizontal pipe at a downward slope of around 2 degrees, then 66 inches of vertical drop, and then into the horizontal dispersion pipe apparatus (see Figure 2.20) in the retrieval tank that extended 9.5 inches and 25 inches to each tee respectively with 9-inch arms with 90-degree elbows at end to exhaust contents downward into retrieval tank.

The PRM (see Figure 2.14) allowed reduced pressure operation of the HWEE rotary jets and the HWEE flush. 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. For Phase II testing, the manual needle valves were not used for shutting the HWEE components on or off as they proved to be too slow to operate (10 to 20 seconds) during Phase I and were therefore left in full open position during all retrieval testing operations.

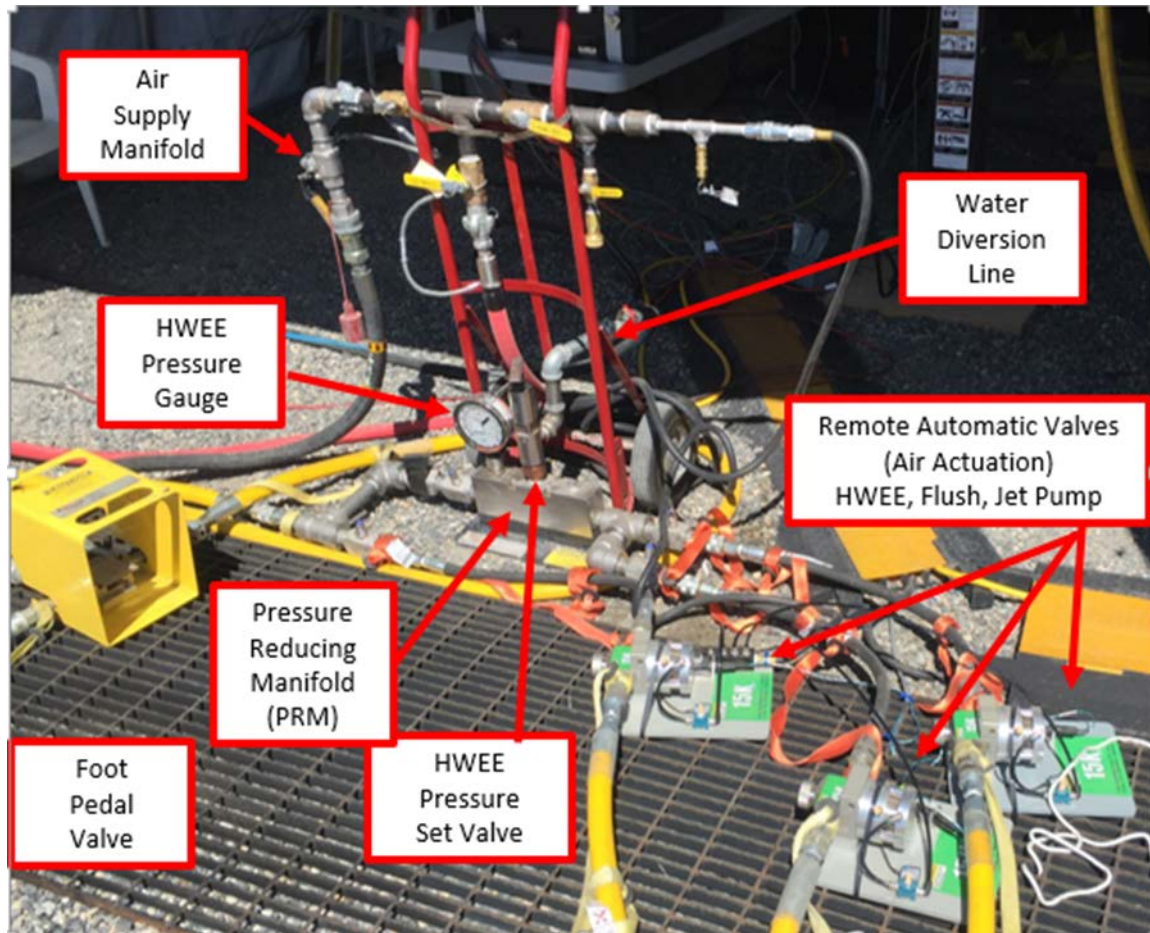


Figure 2.14. Pressure Reducing Manifold Details

The high-pressure pump provided a fixed flow rate of 43 gpm. Because the total flow was not required for the HWEE system, excess low-pressure water was diverted by the valves. Due to a limitation on water release to the ground by CTF administrative procedures, 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. In an actual retrieval system, this clean, diverted water would be recycled back into the pump.

The new remote activated on/off valves added downstream of the PRM allowed quick on/off activation (less than a second) during testing of the HWEE rotary jets (all retrieval tests), HWEE flush (all retrieval tests), and HWEE jet pump (first layered waste retrieval test only). These remote valves were pneumatically activated using up to 120 psi air and had a position sensor installed so that the valve on/off position could be viewed by the operator and recorded by the data acquisition and control system (DACs). The remote valves were supplied by Advanced Pressure Systems (61-010-306 Air Diverter Valve, 15K Dry Shutoff w/Base Plate) and inserted into the high-pressure water system using quick connect fittings just downstream of the last manual shutoff valve before the applicable HWEE component. Each of the remote valve assemblies on a plate had a short 27-inch high-pressure hose added to aid in connecting and positioning. The pneumatic system components supplied by Buchanan Automation Inc. used a MAC 3-way, 24VDC solenoid valve (part # 35A-AAA-DDAA-1BA) for activating the remote valves (see Figure 2.15 and associated Figure 2.13). Air supply to the remote valves used CTF air with air on/off control valves mounted on the PRM cart.

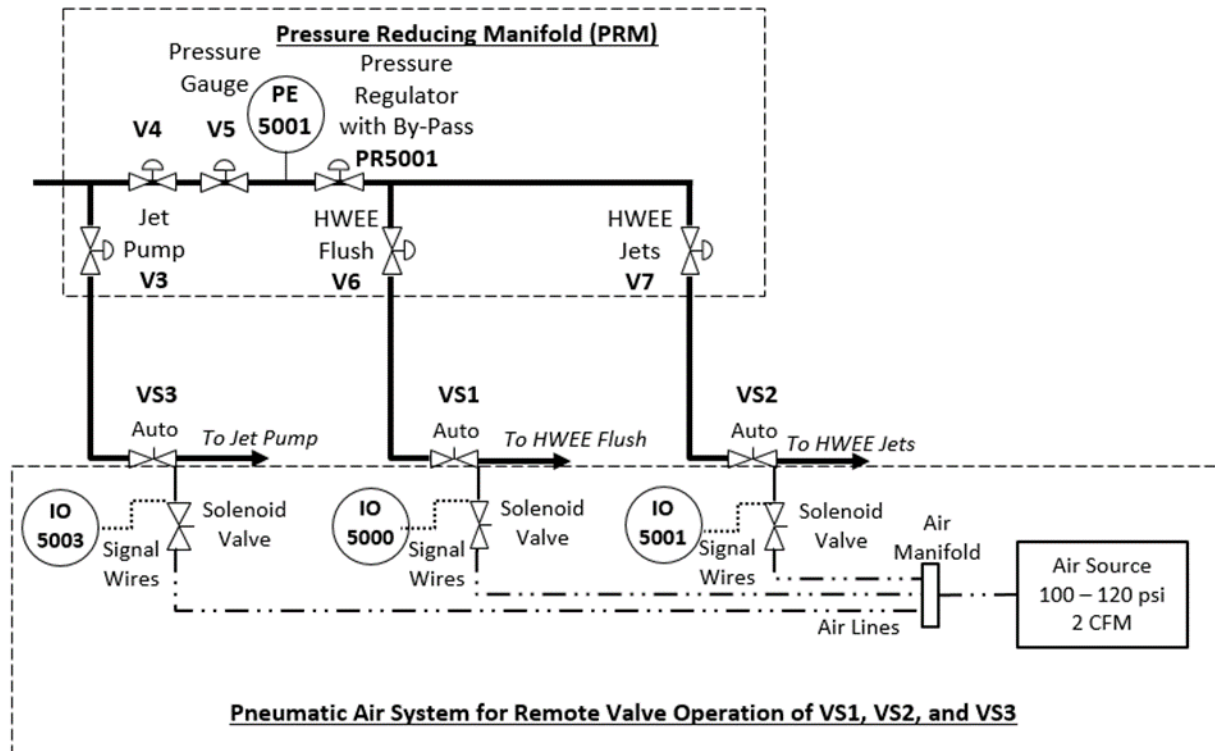


Figure 2.15. HWEE Test System Schematic—High-pressure Pneumatic Remote Shutoff Valves

2.3.2 Hydraulic Power for HWEE Jet Rotation

A small hydraulic power unit from Foster Manufacturing Company (see Figure 2.16 and Figure 2.17) 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, two-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 2.16. Hydraulic Power for HWEE Jet Rotation Control—Pump

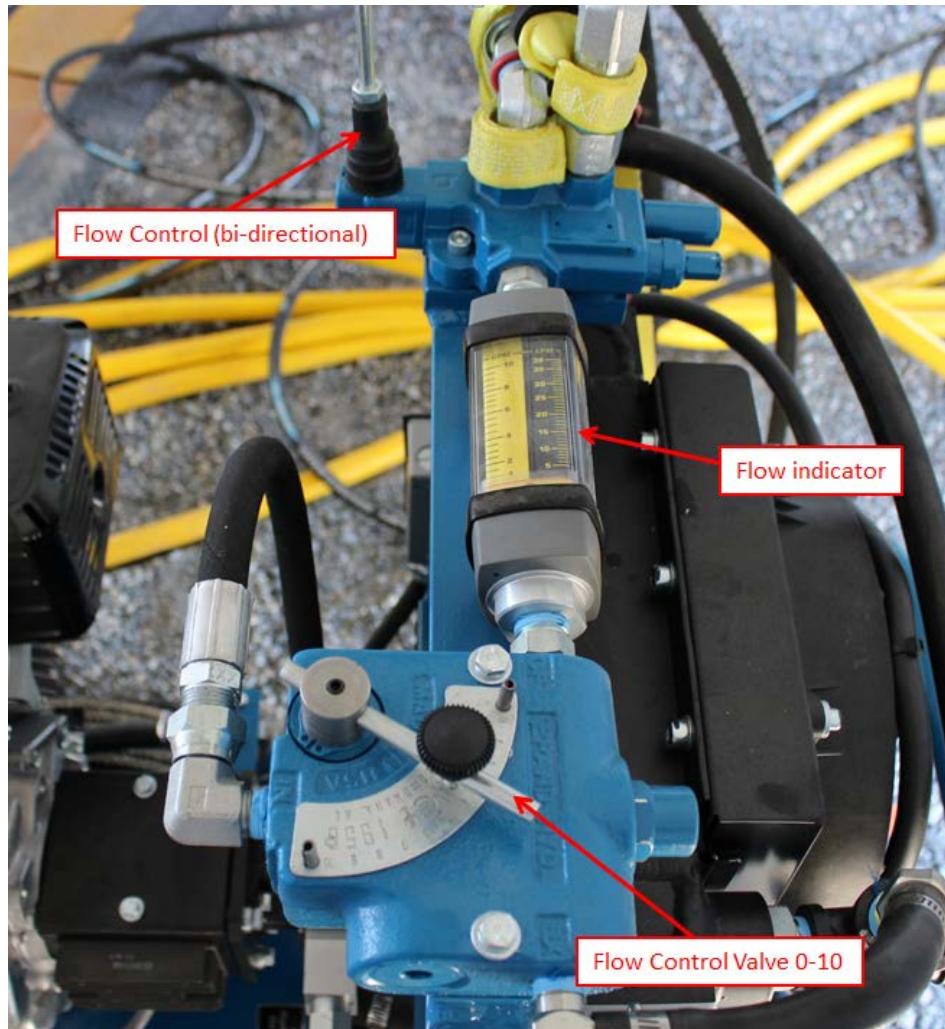


Figure 2.17. Hydraulic Power for HWEE Jet Rotation Control Details

2.3.3 Gantry Motion Control System

The gantry system (see Figure 2.18) 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.

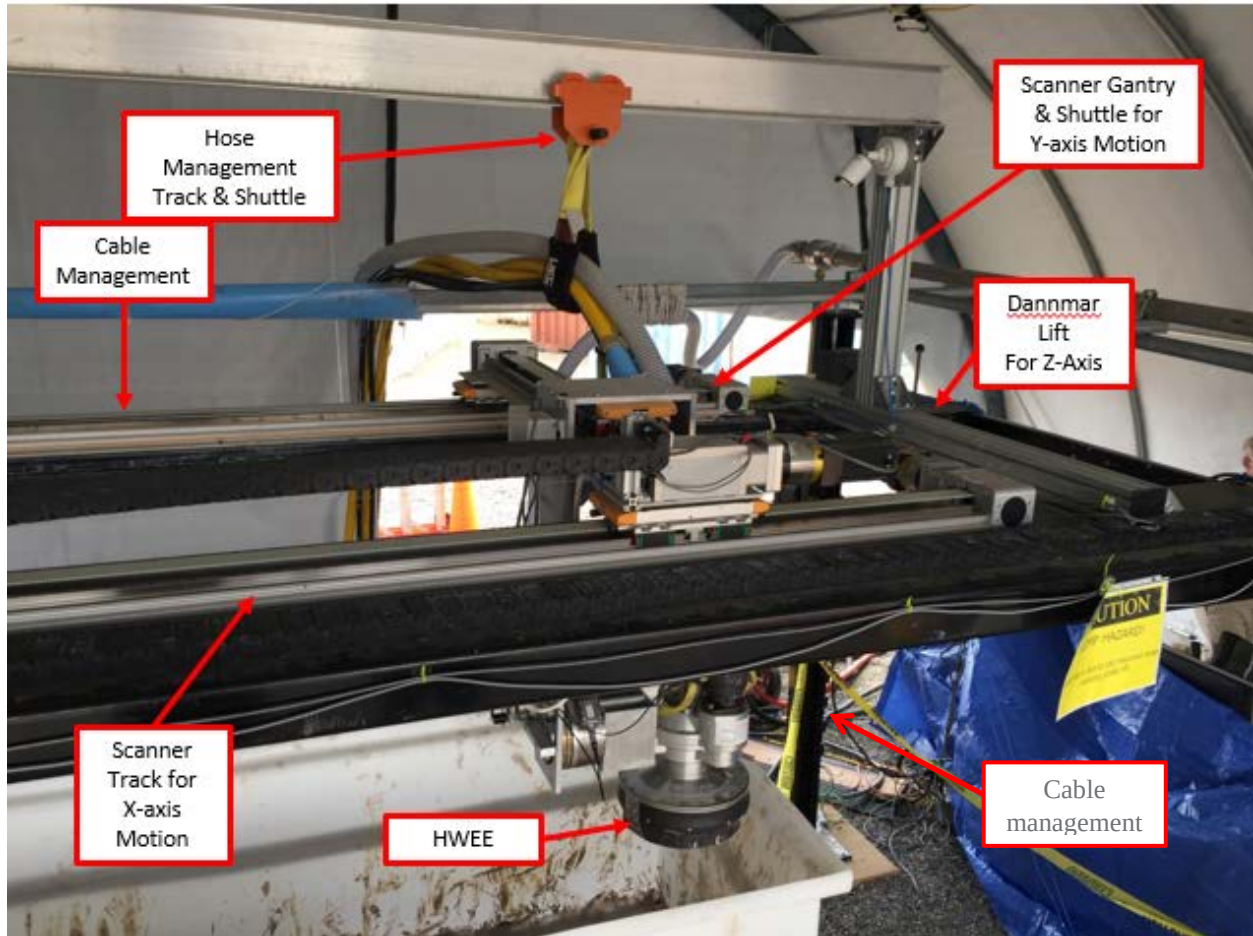


Figure 2.18. Gantry Motion Control System

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. The 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. 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 Dannmar Equipment vehicle lift was used, which 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 high. 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 extends 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. For Phase II testing, the drop bracket was

modified to allow the insertion of the HWEE tilt mechanism. 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 were bundled and attached to the trolley using a nylon strap with swing length of 12 to 24 inches. Motion along the x-axis was the long direction and was assisted by the trolley rolling motion in the same direction. Motion along the y-axis was shorter and was assisted by the swinging motion of the trolley strap side-to-side. Motion along the z-axis was assisted by having the beam portion of the trolley directly connected to the lift; a secondary static bar was mounted on the lift frame to provide additional vertical support.

2.3.4 Simulant System

The simulant system consisted of a simulant tank (See Figure 2.19) mounted on a pallet and a matching pallet supported by load cells under the gantry. The simulant tanks were Chem-Tainer Industries R367236AB/CD plastic rectangular tanks about 6 feet long, 3 feet wide, and 3 feet high with a capacity of approximately 400 gallons. This Phase II simulant tank was larger and taller, but shorter in length, than the Phase I metal stock tank chosen to accommodate the larger and deeper simulant bed while eliminating the void space where simulant/water was trapped and could not be accessed during Phase I testing. The PNNL simulant crew made up the simulants and packed them into the simulant tank at PNNL. For the second topographic retrieval test simulant profile, a wooden frame was fabricated and used to form a topographic sawtooth shape and hold this shape into position until retrieval testing started. Simulant tank and/or material were delivered to CTF as needed for testing operations. Separate simulant tanks were used for the two retrieval tests. During testing, we found that the larger simulant tank did not allow the HWEE to fully access the bottom of the simulant tank because the car-lift opening of the HWEE gantry system was smaller than the width of the simulant tank. This interference condition was solved by mining into the simulant tank as far as the simulant tank would allow and then removing the top 11 inches of the simulant tank (see “tank cut line” in Figure 2.19) to allow the remaining mining to take place.

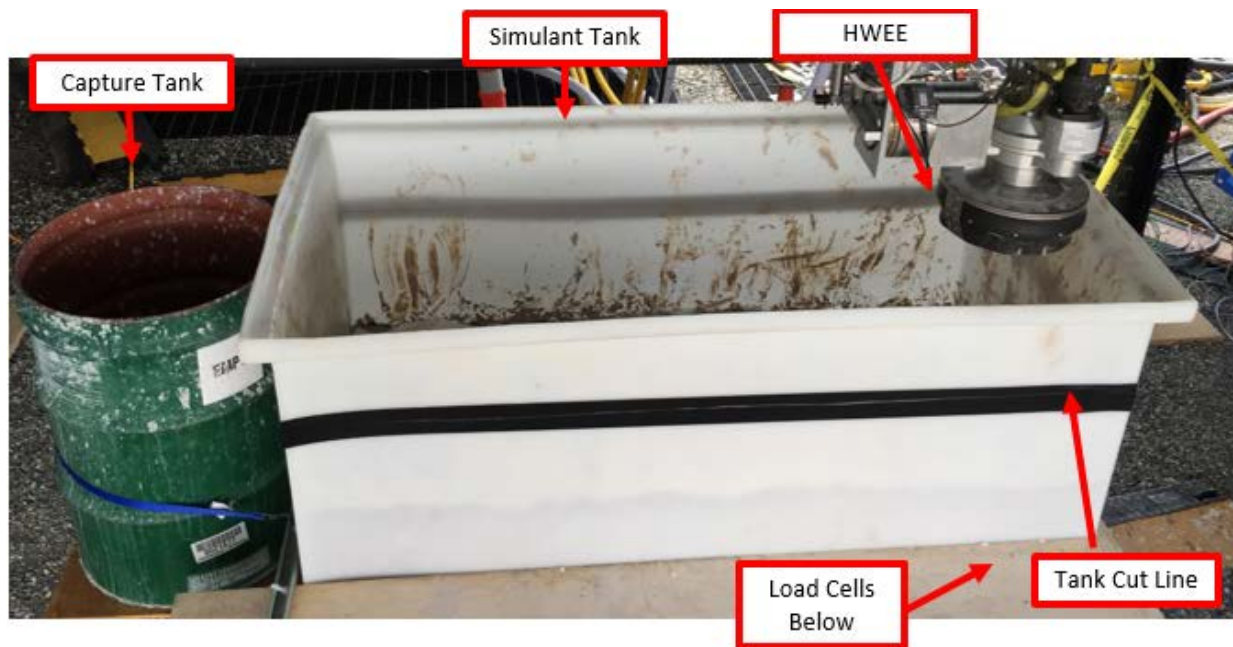


Figure 2.19. Simulant Tank System (with Green Capture Tank on Left End)

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, an open 55-gallon metal drum “capture tank” that was mounted on one end of the simulant tank pallet and butted up to the short end of the simulant tank on the pallet was used to set water pressure on the various HWEE components to meet test conditions. Because this water in the capture tank was not associated with test retrieval operations, it was occasionally evacuated from the tank using a diaphragm pump. 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 was exposed to the HWEE screen and conveyance port where the water may be drawn up via the jet pump and transported.

During pauses of simulant retrieval operations, the retrieval progress could be viewed and photographed. After retrieval testing was completed, 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 were removed from simulant load cell pallet and moved/stored as appropriate.

2.3.5 Retrieval System

The retrieval system starts at the HWEE suction port with screen and ends 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 2.20. From the jet pump, metal pipe and fittings were used to transport and then dissipate transport energy before depositing contents in the rectangle poly retrieval tank, which has internal dimensions of approximately 72-3/4 inches long, 36 inches wide, and 35 inches high. The sides of the retrieval tank were reinforced with wooden braces to eliminate bulging as the tank was filled with liquid. Because some of the retrieval calculations are based on the tank volume, bulging of the tank would have resulted in inaccuracies.

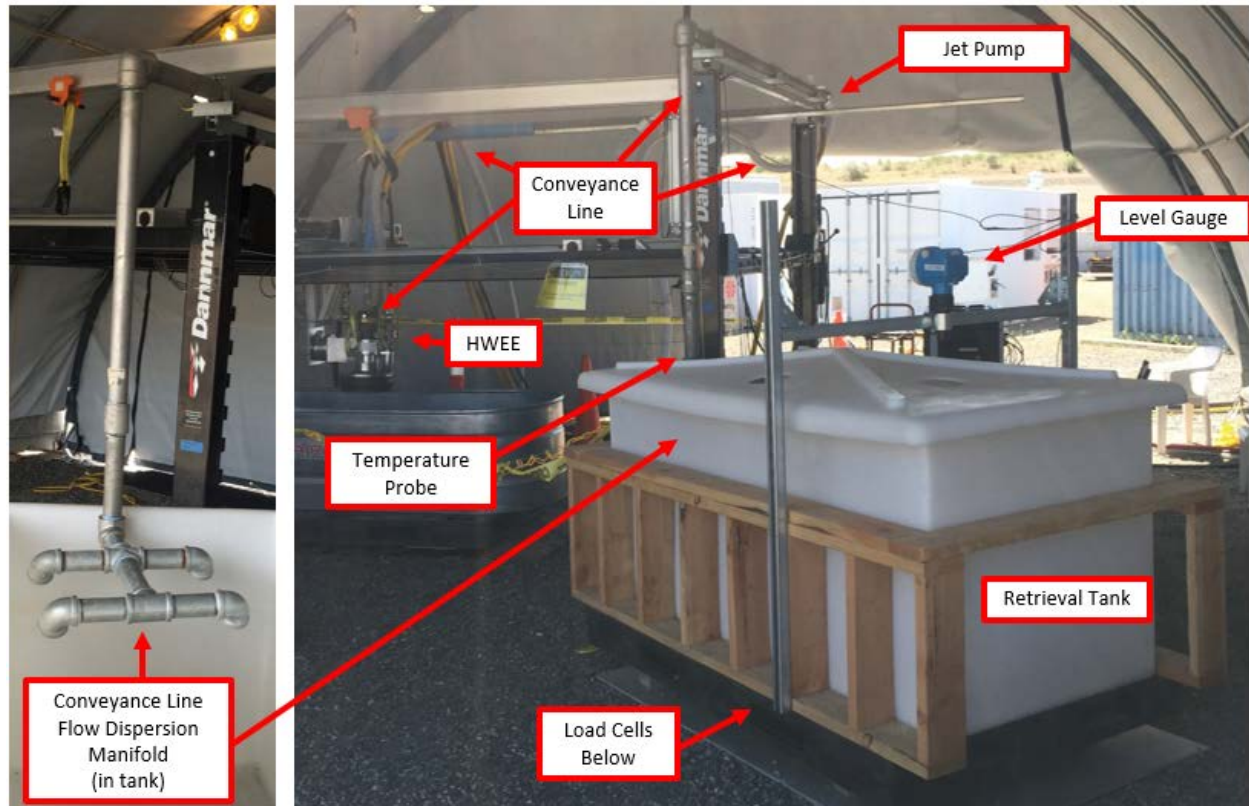


Figure 2.20. Overview of Retrieval System with Jet Pump

The HWEE jet pump (see Section 2.2.2) operating pressure during retrieval operations was typically 9,000 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 before retrieval operations start, during all retrieval operations, and often for a period after retrieval that included dewatering operations.

Before a simulant retrieval operation, the retrieval tank was cleaned, pumped down to about 3 inches of water, 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. For Phase II testing, the energy dispersion pipe was modified to be shorter (to make room for level measurements) and raised up slightly to allow more retrieval capacity in

the tank. Capacity of the retrieval tank was limited by the height of the dispersion pipe above the bottom of the tank (approximately 33 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.

2.3.6 Tent Enclosure

A tent enclosure from Rhino Shelter (see Figure 2.21) 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 an elliptical-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 open end was used for forklift operations to set up HWEE equipment and move simulant tanks in and out as required for testing. Due to enclosure door damage during Phase I testing, new door ends were ordered and installed.



Figure 2.21. Tent Enclosure

2.3.7 Jet Pump Vertical Lift System

The jet pump vertical lift system design is detailed in the Phase II test plan Sections 4.3 and 5.4 and schematically in Figure 2.13. Details of the actual jet pump vertical lift system are shown in Figure 2.22 through Figure 2.25 and Appendices A and D. The vertical lift conveyance starts at the simulant tank where the 2-inch conveyance hose like the one used in retrieval testing was fitted with an HWEE inlet screen to mimic inlet conditions. The inlet hose at the simulant tank was attached to a unistrut apparatus that allowed the inlet to be positioned at various levels including manual active movement in and out of the simulant tank fluid to simulant multiple flow phase conditions as would be seen in actual retrieval

operations. In the maximum down position, the tip of the inlet HWEE screen cone was approximately three inches off the simulant tank bottom and the inlet hose flange was approximately seven inches; this location was used when flooded inlet water transport testing was performed.

The inlet hose is routed to the vertically oriented jet pump at an elevation that is close to the suction lift used in Phase I and II retrieval testing—around 6.5 feet. At the jet pump, the vertical conveyance continues in 2-inch Schedule 80 steel pipe up to the CTF first platform level to an elevation that allows conveyed contents to be deposited into the retrieval tank (in this case, a 330-gallon carboy) with a 4-inch air gap to break any syphoning tendencies. About 12.5 feet of horizontal transport was required on the first platform to get to the retrieval tank top inlet. The conveyance outlet had a down pipe installed to direct the conveyed contents into the retrieval tank top inlet. The conveyance outlet had a 45-degree cut in the pipe as suggested in literature for air gap design. In the final configuration, total vertical conveyance lift was 39 feet—1.5 inch to the bottom of the air gap. Note that the lift required to retrieve material from a Hanford single-shell tank is 35 feet for a 500,000-gallon tank and 60 feet for a 1,000,000-gallon tank.

During pre-testing of vertical conveyance, it was found that conveyed liquids were being conveyed back out of the retrieval tank inlet resulting in not all fluid being captured in the retrieval tank. Upon investigation of problem, it was determined that retrieval tank inlet opening was too small to channel all the conveyed media and that additional retrieval tank venting was needed to remove transported gas; this problem increasingly worsened as the tank filled with liquid and overall air space in the tank was reduced. This small inlet opening was remedied by fitting a modified tapered traffic cone on the retrieval tank inlet, which effectively increased the inlet diameter. The air venting was remedied by cutting a flap hole on the top corner of the retrieval tank to allow air other than the retrieval tank inlet port.

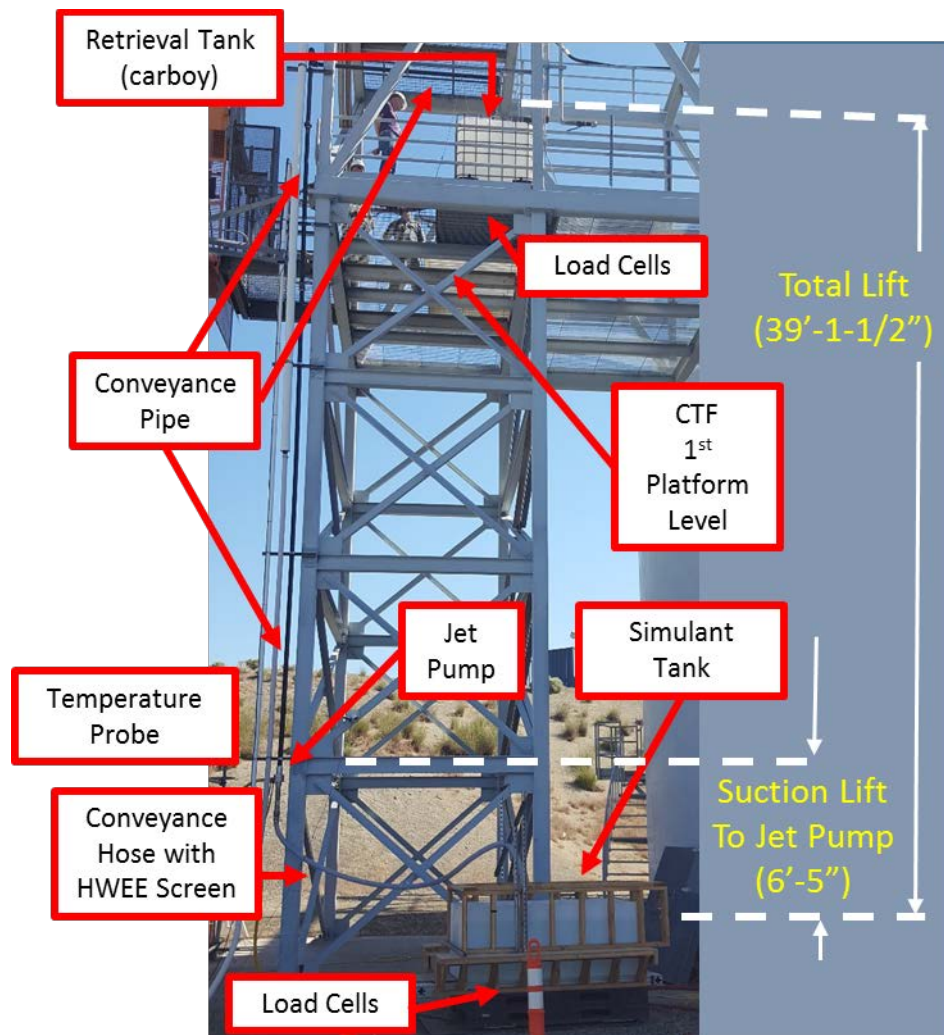


Figure 2.22. Jet Pump Vertical Lift—Overall/General (see also Appendix D)

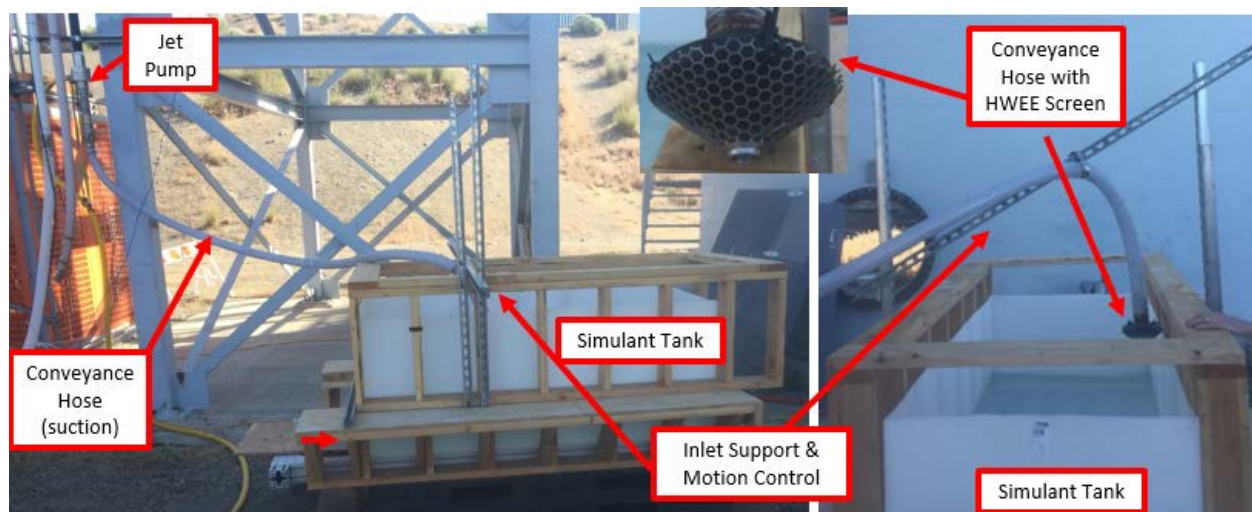


Figure 2.23. Jet Pump Vertical Lift—Simulant Tank—Ground Level

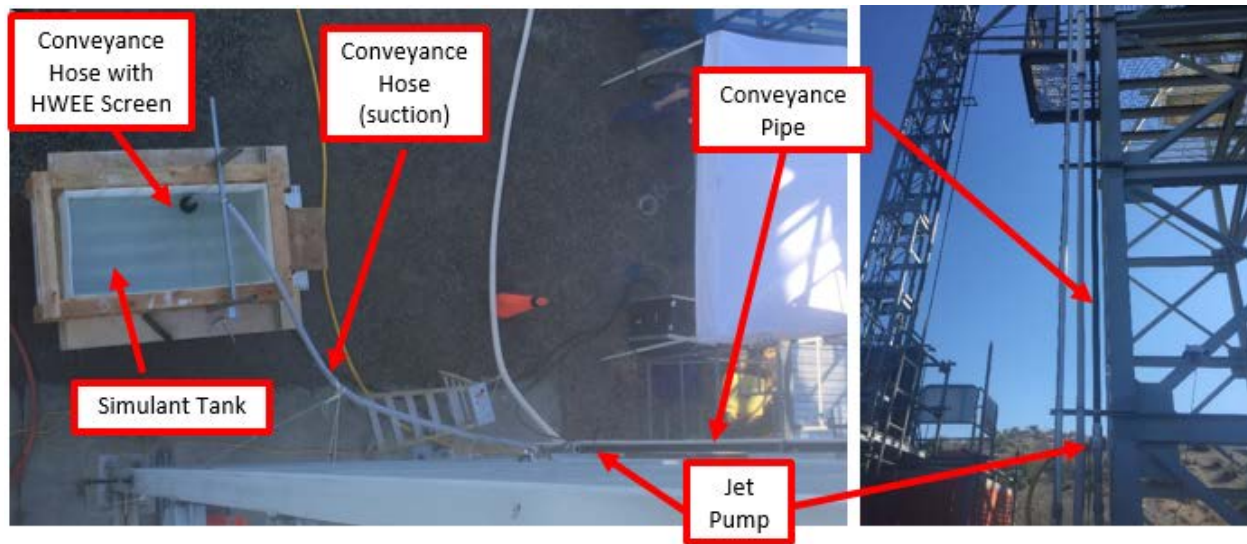


Figure 2.24. Jet Pump Vertical Lift—Vertical Conveyance—Lifting

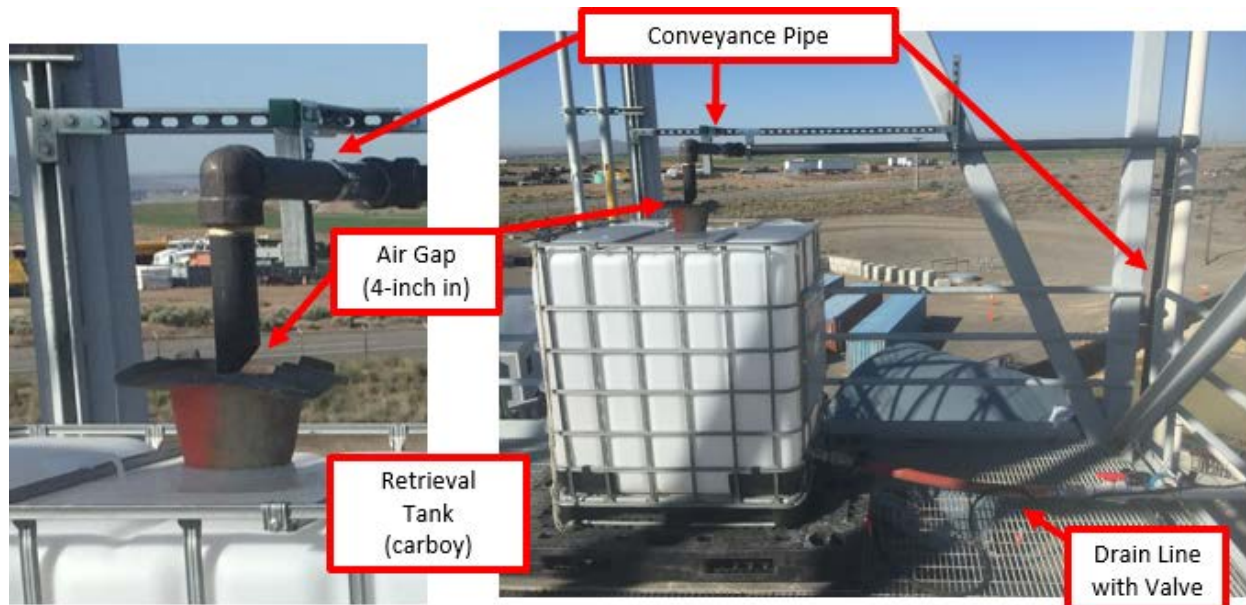


Figure 2.25. Jet Pump Vertical Lift—Retrieval Tank—Platform Level

2.4 Instrumentation

A measurement and test equipment list is 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 that 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 could be used to set the discharge pressure. A second visual pressure gauge was included on the PRM 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, 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 sensors (x-, y-, z-axis, and tilt).** 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. Limit switches were installed on the x and y actuators to avoid collisions between the HWEE and the tank walls.

The x-, y-, and z-axis positions of the gantry were also monitored absolutely using new linear position transducers (models HX-PA-100-S10-N1S-1BC for the long x-axis and model HX-PA-50-S10-N1S-1BC for the shorted y-, z- axis manufactured by UniMeasure, Inc.). Manual z-axis positioning of the lift used a visual scale attached to the fixed lift structure and scale pointer attached to the lift movable structure.

The new tilt feature on the HWEE was measured absolutely using the linear potentiometer (model SP1-25, manufactured by Measurement Specialties); this was formerly used in Phase I to track the gantry vertical z-axis lift. For the tilt measurement, only three positions were important (vertically down – 0 degrees, and tilt 35 degrees in two directions), and therefore correlation between linear and rotation measurements was not necessary.

- **Retrieval tank fluid level sensor.** Fluid level in the retrieval tank was monitored ultrasonically using a model Prosonic-M FMU40-ANB2A4 manufactured by Endress + Hauser. The sensor monitored fluid level through a hole cut in the retrieval tank lid and spaced away from internal tank structures (walls and piping) per installation instructions.
- **Retrieval tank fluid temperature sensor.** The temperature of the fluid in the retrieval tank was measured with model AD590 temperature sensor manufactured by Analog Devices. The AD590 uses a fundamental property of the silicon transistors from which it is made to realize its temperature proportional characteristic. The AD590 is particularly useful in remote sensing applications. The

device is insensitive to voltage drops over long lines due to its high impedance current output. For this application, the sensor was installed in a 6 ft stainless steel tube and sealed with silicon adhesive. The sensor was placed 1-inch from the bottom of the tank in order to measure temperature at low liquid levels.

- **Retrieval tank fluid temperature sensor.** The sensor monitored fluid temperature in the bottom of the tank and was spaced about $\frac{1}{4}$ to $\frac{1}{2}$ inch above the tank floor. A minimum fluid level of about 3 inches was maintained in the tank so that the thermocouple was always measuring a liquid/slurry fluid temperature.

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 re-released Test Plan that reflects the actual test methods used. Table 3.1 describes the tests that were completed.

Table 3.1. HWEE Prototype Phase II Tests

Test Phase	Test Focus	Test Parameter	Key Data Expected
Instrumentation Verification and Check-out Tests	Controls and Instrumentation Calibration	Performance check of sensors with known weights, pressures, etc. Verify controls operation	Performance check of sensors in the installed condition
HWEE Component Tests	Water Usage of Components at Pressure, Baseline Water Retrieval	Test ability of re-jetted HWEE internal flush to clear HWEE screen Baseline water usage at various pressures to determine operating characteristic of components Baseline water retrieval with HWEE flooded suction Baseline retrieval tank volume to level sensor	Simulant packed in HWEE screen is cleared. Water usage at pressure of various high-pressure HWEE components Water retrieval rate of HWEE with flooded suction at HWEE Phase II retrieval operating conditions Water volume in retrieval tank per vertical fluid level
HWEE Retrieval Tests	Kaolin (Sludge) Retrieval Tests	Tests with layered Kaolin (sludge) of strong and weak shear strengths Stepped topography with Kaolin (sludge) of strong shear strength	Verify basic operating parameters Identify plugging problems Water usage Slurry density Slurry output rates
Jet Pump Vertical Lift Tests	Demonstrating Jet Pump Lift Capabilities	Test with water and simulant	Verify basic operating parameters Water and simulant lift demonstrations

4.0 Simulants

As described for the Phase II HWEE test plan (Berglin et al. 2018), simulants used in Phase I were to be used to represent key waste formations that were not previously addressed:

- Layered waste (e.g., strong crust over weaker sediment)
- Topography that is representative of tank waste (uneven surface)

WRPS specified that the waste in A-106 was to inform the selection of key waste formations. Historical information from A-106 waste, including tank history, sampling reports, and images, was investigated in Berglin et al. (2018) as follows:

- Waste layering: Existing data will be reviewed to determine waste strength with depth. Following the Phase I approach, waste shear strength is used as an erosion characteristic metric.
- Waste surface topography for selected tank: Existing images will be reviewed to determine if there are predominant and challenging waste topography that could be difficult to retrieval with the HWEE.

Simulant targets that are representative of the A-106 waste as described in Berglin et al. (2018) were selected therein for layered waste and topographical features for Phase II testing of the HWEE. The simulant configurations selected in Berglin et al. (2018) are summarized below.

4.1 Layered Waste Simulant

The layer waste simulant target is based on the A-106 waste shear strength with depth. Following the Phase I approach, waste strength was used for erosion characteristic metric. The A-106 waste sediment is reported to have higher shear strength material at the top and bottom surrounding a lower shear strength middle layer. Phase I testing of the HWEE indicated that, for the same HWEE operating conditions (i.e., pressure, rotation rate, translation rate, and standoff distance), retrieval rates were decreased by increased simulant shear strength; the HWEE jet penetration into the simulant was reduced by increased simulant shear strength (Berglin et al. 2017). The HWEE retrieval rate and dilution ratio performance in layered waste is therefore tested for a “step-change” of shear strength rather than a gradient. The selected step-change maximizes the shear strength difference from the maximum upper bound extrusion length estimate of 3,375 Pa to the lower bound extrusion length estimate of 284 Pa. Based on the Phase I testing performance in the simulants and the test system configuration (Berglin et al. 2017), 4-inch layers at 3,375 Pa above and below a 6-inch layer of 284 Pa, depicted in Figure 4.1, is the selected simulant configuration for waste layering testing of the HWEE in A-106 waste. The dimensions are selected from the HWEE Phase I testing performance so that breakthrough of the jets into middle layer can be expected. This is postulated as a condition of interest for the HWEE as the added water from the jet breakthrough may be lost in the lower shear strength middle layer until the HWEE interacts directly with that layer.

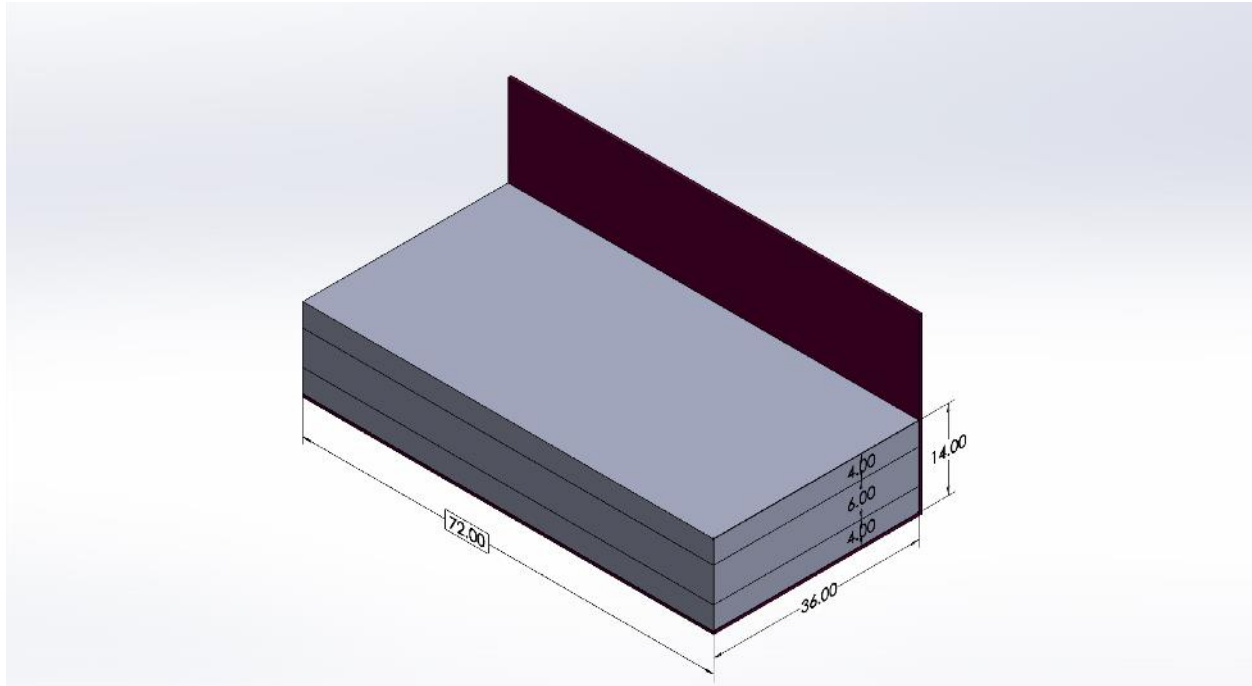


Figure 4.1. Simulant Configuration for Waste Layering Test

4.2 Waste Topography Simulant

The A-106 topographical features are used, in conjunction with the HWEE Phase I testing performance and test system configuration (Berglin et al. 2017), to define the simulant target for the waste topography test. A vertical elevation change along the test vessel wall with a “saw-tooth” front face is selected, as shown in Figure 4.2. To represent the higher shear strength upper sediment of A-106, the maximum upper bound extrusion length estimate of 3,375 Pa is used.

As shown in Figure 4.2, the lower level is 6 inches deep, and the upper level is 8 inches deep. The “saw-tooth” front face of the upper level is 10 inches between peaks and 4 inches deep. These dimensions are selected based on the HWEE Phase I testing performance (Berglin et al. 2017) such that multi-layer cuts will likely be required.

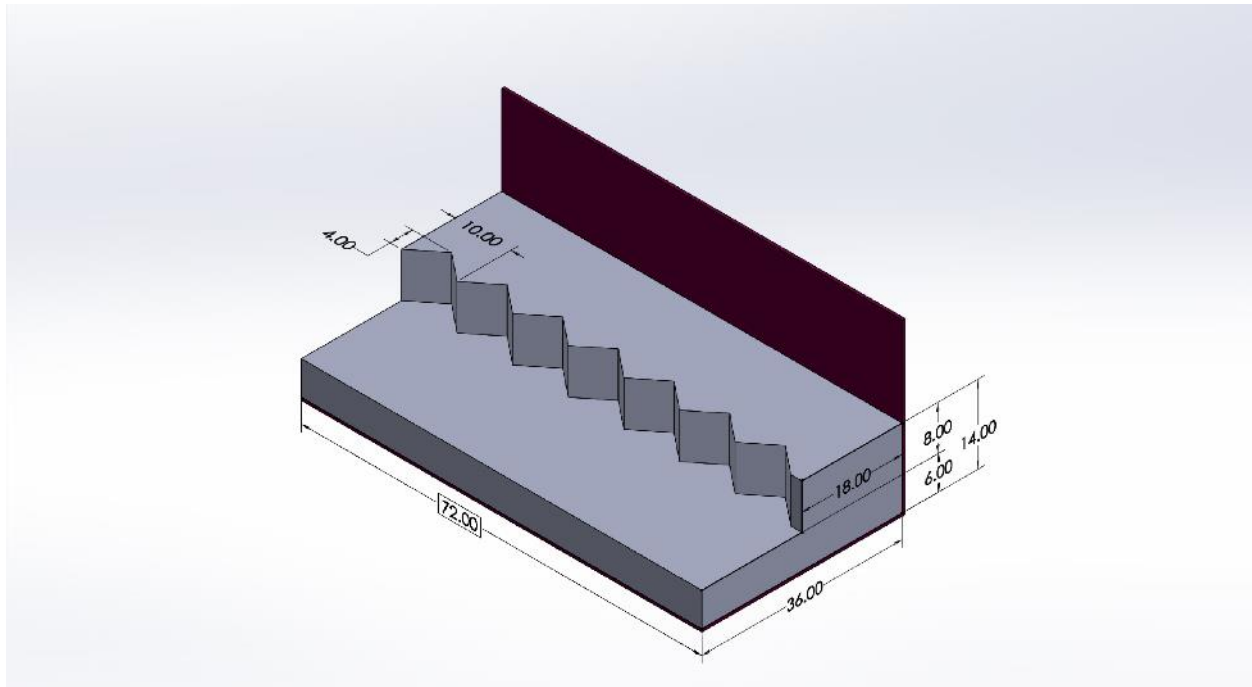


Figure 4.2. Simulant Configuration for Waste Topography Test

The Kaolin simulant of Phase I is appropriate for the selected shear strengths. The HWEE Phase II simulant recipes and characterizations are summarized in Section 4.1.

4.3 Simulant Preparation and Characterization

The simulants used in Phase II testing are described below.

- **Higher Strength Kaolin Simulant:** The Kaolin/water with a nominal strength of $\sim 3,500$ Pa was selected because it was used during HWEE Phase I testing performance and test system configuration (Berglin et al. (2018)). This simulant was used for both the strong crust of the layered waste and for the upper and lower layers of the waste topography simulant. The as-prepared simulant properties are summarized in Table 4.1.
- **Lower Strength Kaolin Simulant:** The Kaolin/water with a nominal strength of ~ 284 Pa was selected for the weaker sediment (middle layer) of the waste layering test. This simulant was selected because it could be readily achieved using Phase I simulant materials. The as-prepared simulant properties are summarized in Table 4.1.

The previously prepared Kaolin simulant, $\sim 3,500$ Pa recipe was prepared as specified for Phase I testing. The Kaolin, ~ 284 Pa simulant was prepared after conducting bench top experiments to evaluate the shear strength of a range of Kaolin slurries (see Schonewill et al, 2014).

Table 4.1. Phase II HWEE Simulants

Simulant	Solids	Phase II Recipe⁵	Density (g/mL)	Strength⁴ (Pa)
Kaolin (~3,500 Pa)	EPK Pulverized Kaolin Clay ¹	64 wt% Kaolin clay 36 wt% Richland city water	1.649 ²	3700
Kaolin (~284 Pa)	EPK Pulverized Kaolin Clay ¹	51.5 wt% Kaolin clay 48.5 % Richland city water	1.469 ³	267

1 Feldspar Corporation (Edgar, Florida)

2 Measurement Device: Micromeritics AccuPyc II 1340 pycnometer. Procedure: (Burns 2017)

3 Measurement device: Glass pycnometer. Procedure: (Daniel 2011)

4 Measurement Device: Haake VT550 Viscometer. Procedure: (Daniel 2007)

5 Weights of simulants solids were made for as-received materials.

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

- Kaolin ~ 3,500 Pa – 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 ~284 Pa – Multiple batches of approximately 5.5 gallons each were sequentially prepared in a 6-gallon bucket with the aid of a mechanical mixer. Small batches were necessitated to ensure consistent mixing of the clay slurry. The Kaolin slurry was aged for a minimum of 5 days prior to use. The individual batches were mixed with the aid of a spatula prior to gently pouring into the test vessel.

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 new HWEE flush jetting. Because water usage of the HWEE and jet pump was done in Phase I, only spot checking of the performance of these components was done to allow comparison to Phase I water usage testing. Jet pump component testing is also included in this section.

5.1.1 Water Usage

This water usage testing was done to fulfill data requirements in the Test Plan (Section 6.2, Water Usage of HWEE) for the HWEE flush with new jetting as well as spot checking water usage performance of the HWEE and jet pump previously done in Phase I as 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:

$$\text{Water Weight Collected (steady state) / Collection Time} = \text{Water Usage Rate}$$

Data were collected over a range of operating pressures, typically from 1,000 to 10,000 psi in 1,000 psi increments and repeated twice (HWEE flush only). This testing configuration had pressure measured at PRM for the HWEE flush and rotary jets and at the main high-pressure pump for the jet pump. High pressure water to the jet pump was delivered through 150 feet of high-pressure hose (0.50-inch inner diameter), a foot pedal, and additional 50 feet of high-pressure hose. The HWEE flush and rotary jets used the jet pump setup but had the addition of the PRM and another 50 feet of high-pressure hose.

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

The HWEE standoff distance from the water collection tank metal bottom was about 22 inches. 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) reduce or eliminate water spray and splash considerably. The HWEE manifold was not rotating during the water usage tests. Because lower pressure testing was done for the HWEE components, no tarping of tanks to contain water spray was necessary.

The water usage composite summary data from Phase I testing are shown in Figure 5.1 and Table 5.1 for reference.

REFERENCE – Phase I HWEE Component Water Flow

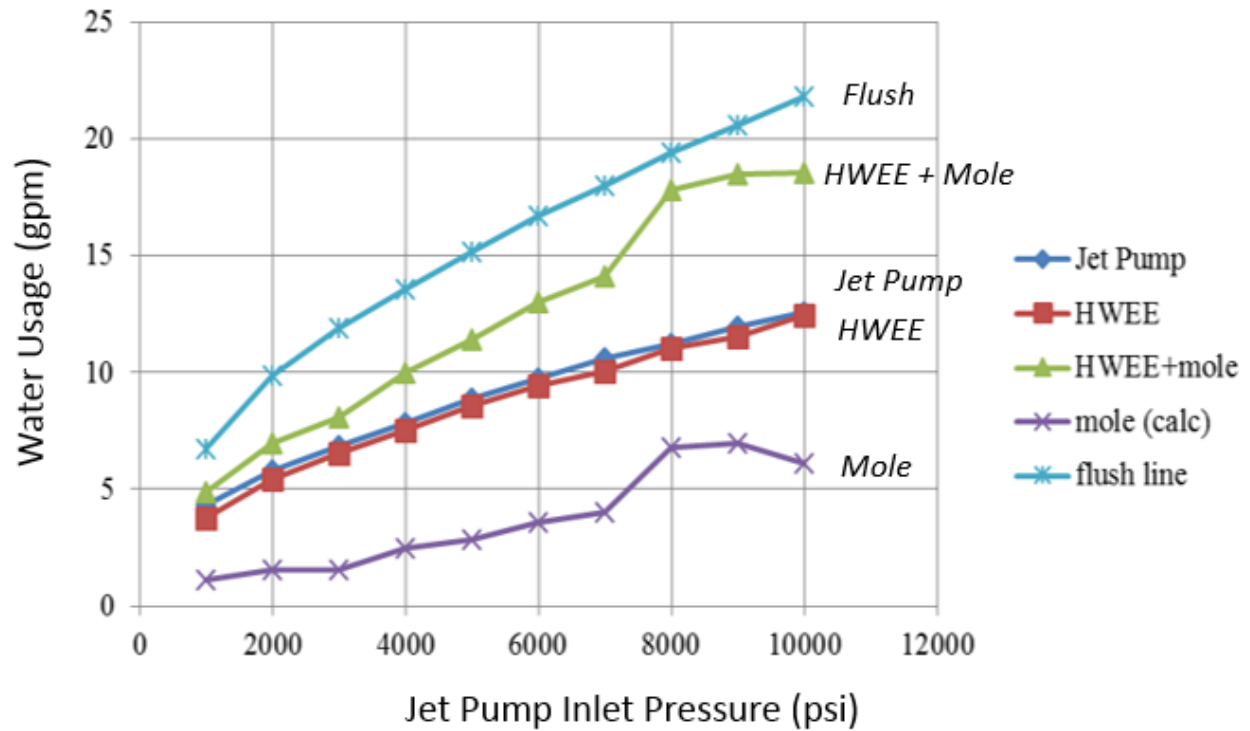


Figure 5.1. Water Usage Composite Summary Graph—Phase I Reference

Table 5.1. Water Usage Composite Summary Data—Phase I Reference

Pressure (psi)	Water Usage (gpm)		
	Jet Pump	HWEE	Flush Line
1000	4.33	3.74	6.72
2000	5.81	5.42	9.84
3000	6.84	6.52	11.89
4000	7.85	7.54	13.58
5000	8.88	8.56	15.18
6000	9.72	9.44	16.68
7000	10.63	10.06	18.03
8000	11.23	11.01	19.42
9000	11.97	11.52	20.6
10000	12.59	12.45	21.83

5.1.1.1 HWEE Rotating Jets

Water usage of only the HWEE rotating jets is shown in Figure 5.2 and Table 5.2. A single run up to 6,000 psi with one-minute hold points was performed on May 2, 2018. HWEE rotary jet configuration was the same as Phase I where HWEE rotary jet water usage was fully characterized. HWEE pressure pump was set at 9600 psi and the PRM manifold was used to adjust the HWEE rotary jet pressure during testing. Using the PRM with the addition of new remote valves added downstream of the PR, the maximum HWEE rotary jet pressure that could be obtained was 6,000 psi. It is suspected that the PRM with new remote valves installed downstream may have caused the pressure limitation, but this was not verified. Higher HWEE rotary jet pressure testing could have been achieved if the PRM was bypassed as done in Phase I component testing. Due to limited time to reconfigure and conduct additional testing, the data correlation to 2,000 psi was deemed acceptable as HWEE rotary jet operation for Phase II retrieval testing in Kaolin was 1,000 psi based on Phase I testing.

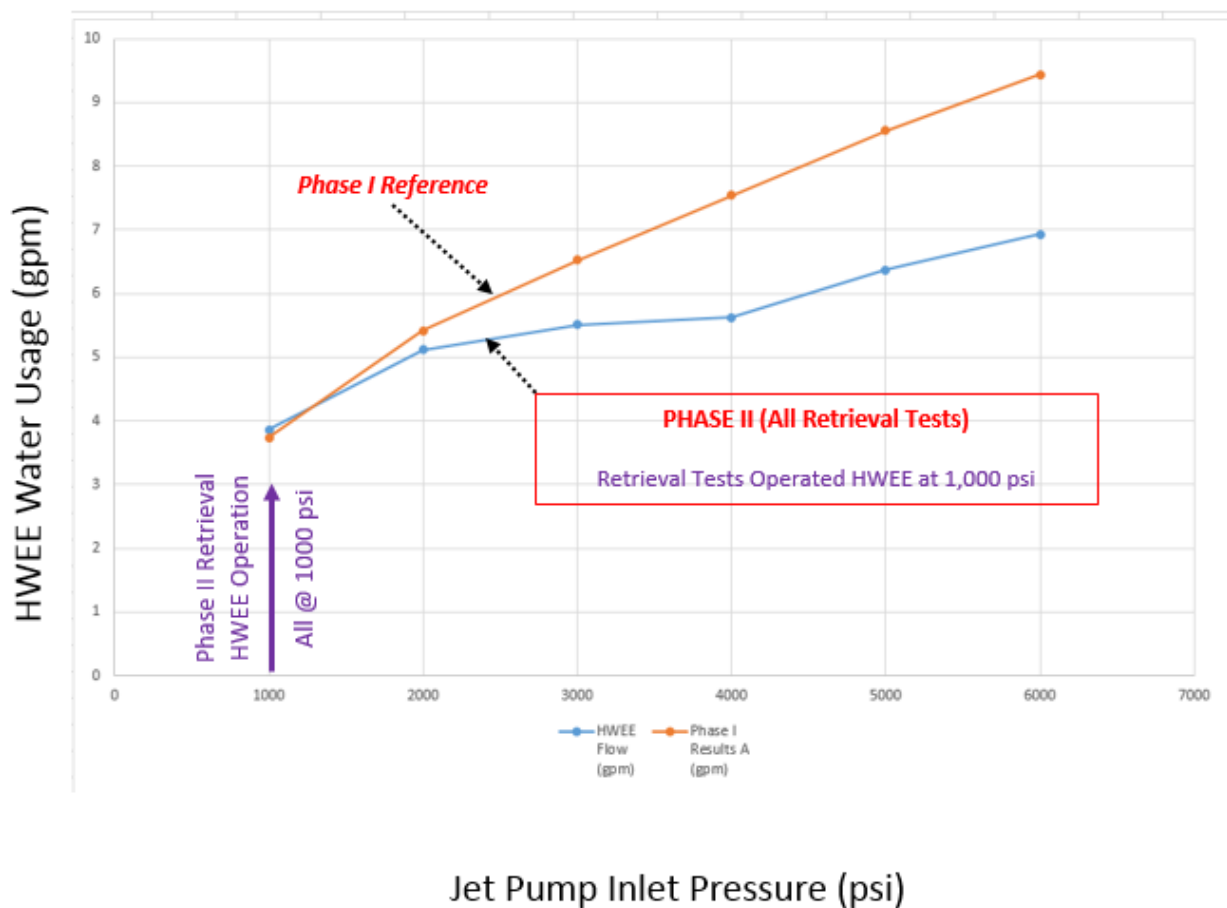


Figure 5.2. Water Usage HWEE and Comparison to Phase I Results

Table 5.2. Water Usage HWEE and Comparison to Phase I Results

	Phase II Water Usage	Phase I Reference
Jet Pump Inlet Pressure (psi)	HWEE Flow (gpm)	HWEE Flow (gpm)
1000	3.86	3.74
2000	5.12	5.42
3000	5.51	6.52
4000	5.62	7.54
5000	6.37	8.56
6000	6.93	9.44

5.1.1.2 HWEE Flush

A new smaller fan jet was installed in the HWEE flush port based on Phase I testing that indicated the HWEE flush may be using more water than was needed. Before characterizing the HWEE by testing, a screen cleaning demonstration was done to prove this new jet could adequately clear the screen (see Section 5.3.3 for additional details).

Water usage of the HWEE flush jet located inside the HWEE screen is shown in Figure 5.3 and Table 5.3 using data taken on May 2, 2018. HWEE flush data are different from Phase I data because a smaller fan jet was installed to limit water usage. A one-minute hold was done at each flush pressure point. HWEE pressure pump was set at 9600 psi and PRM was used to adjust the flush pressure during testing. Using the PRM with new remote valves installed downstream, the maximum flush pressure that could be obtained was around 5,000 psi. It is suspected that the PRM with new remote valves installed downstream may have caused the pressure limitation, but this was not verified. Higher HWEE flush pressure testing could have been achieved if the PRM was bypassed as was done in Phase I component testing. Due to limited time to reconfigure and conduct additional testing, the 6,000 psi maximum data point was deemed acceptable as HWEE flush operation for Phase II retrieval testing in Kaolin is around 1,000 psi based on Phase I testing.

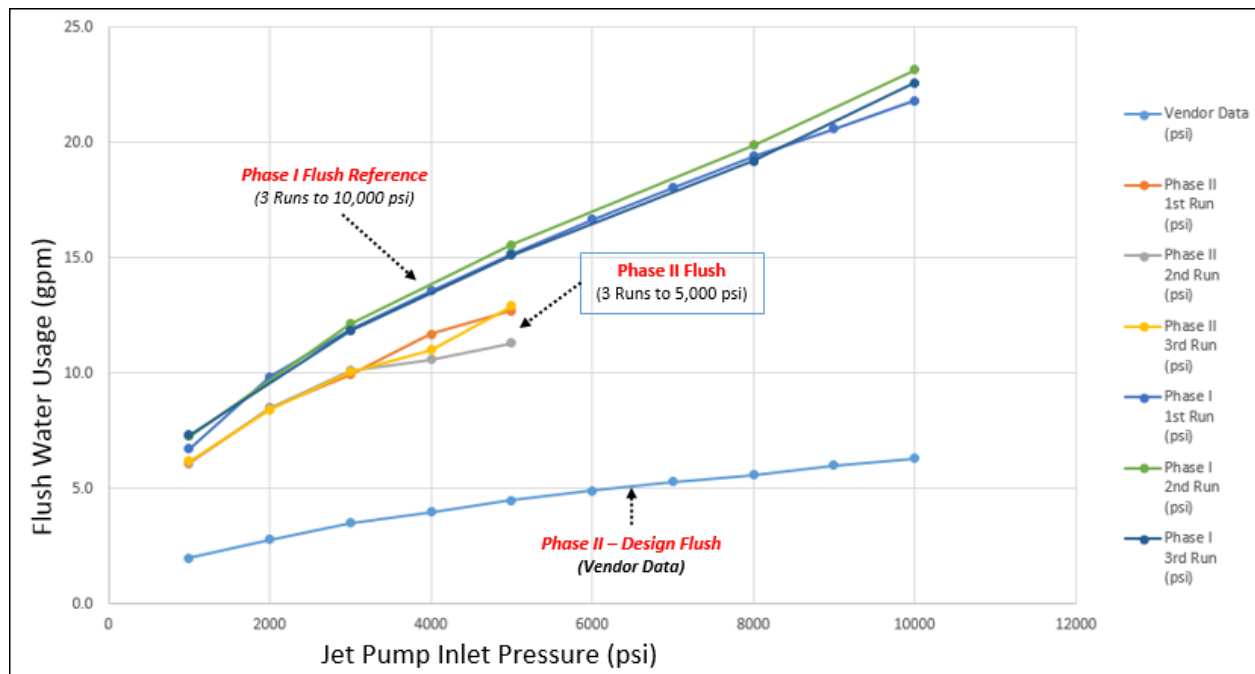


Figure 5.3. Water Usage of HWEE Flush with Repeat Runs and Comparison to Phase I Results

Table 5.3. Water Usage of HWEE Flush with Repeat Runs and Comparison to Phase I Results

Jet Pump Inlet Pressure (psi)	Phase II Water Usage					Phase I Reference					Vendor
	1st Run (gpm)	2nd Run (gpm)	3rd Run (gpm)	Average (gpm)	Std Dev (gpm)	1st Run (gpm)	2nd Run (gpm)	3rd Run (gpm)	Average (gpm)	Std Dev (gpm)	Design Data (Expected) (gpm)
1000	6.11	6.14	6.19	6.15	0.04	6.72	7.26	7.32	7.10	0.33	2.00
2000	8.48	8.50	8.42	8.47	0.04	9.84					2.80
3000	9.94	10.13	10.05	10.04	0.10	11.89	12.15	11.84	11.96	0.17	3.50
4000	11.69	10.60	11.02	11.10	0.55	13.58					4.00
5000	12.71	11.31	12.92	12.31	0.88	15.18	15.57	15.12	15.29	0.24	4.50
6000	(A)	(A)	(A)	(A)	(A)	16.68					4.90
7000	(A)	(A)	(A)	(A)	(A)	18.03					5.30
8000	(A)	(A)	(A)	(A)	(A)	19.42	19.89	19.19	19.50	0.36	5.60
9000	(A)	(A)	(A)	(A)	(A)	20.60					6.00
10000	(A)	(A)	(A)	(A)	(A)	21.83	23.17	22.60	22.53	0.67	6.30

A – Higher pressure was limited by the remotely actuated valves for Phase II

The HWEE internal flush flow rate measured in Phase II was significantly more than expected. The expected flow rate from fan jet NLB S-3-6504 was taken from page 102 of the NLB Nozzle Catalogue (NLB 2017) and is shown in the right column of Table 5.3 (see also (Hatchell Berglin 2018)). The flush nozzle change from Phase I to an NLB S-3-6504 should have given much lower flow usage rates—about 70% reduction instead of about 15% reduction measured (see Table 5.4). With the nearly instantaneous operating valves installed for Phase II, water usage for a “2 second” flush still used significantly less water than during Phase I, where it required 4 – 8 seconds to cycle the manual valves.

Table 5.4. Comparison between Flush Water Flow Measure and Expected—Phase I to Phase II

Pressure (psi)	Phase II Average (gpm)	Phase I Average (gpm)	Vendor Data S-3-6504 (gpm)	Measured Water Use Reduction Phase I to II (%)	Expected Water Use Reduction Phase I to II (%)
1000	6.15	7.1	2	13.43%	71.83%
2000	8.47				
3000	10.04	11.96	3.5	16.05%	70.74%
4000	11.10				
5000	12.31	15.29	4.5	19.47%	70.57%

In conclusion, the HWEE flush worked acceptably for Phase II testing needs; however, any future development of the HWEE may want to further explore flush nozzle modifications to reduce flush water usage. For this project, it was out of scope to diagnose or test various flush nozzle options.

5.1.1.3 HWEE Jet Pump

Water usage of only the HWEE jet pump is shown in Figure 5.4 and Table 5.5 with initial run data taken on May 7, 2018. Looking at the initial data (Run 1) and comparing it to Phase I data, a noticeable drop in water usage was seen; water usage should have been the same. The jet pump was removed and inspected and found to have a clog in one of its jets. The jet obstruction was removed and the water usage testing was rerun (Run 2) on May 10, 2018, resulting in an improvement in water usage but still not quite up to Phase I water usage. Due to limited schedule time, determining why the HWEE water usage is slightly lower in Phase II (Run 2) than Phase I was not explored.

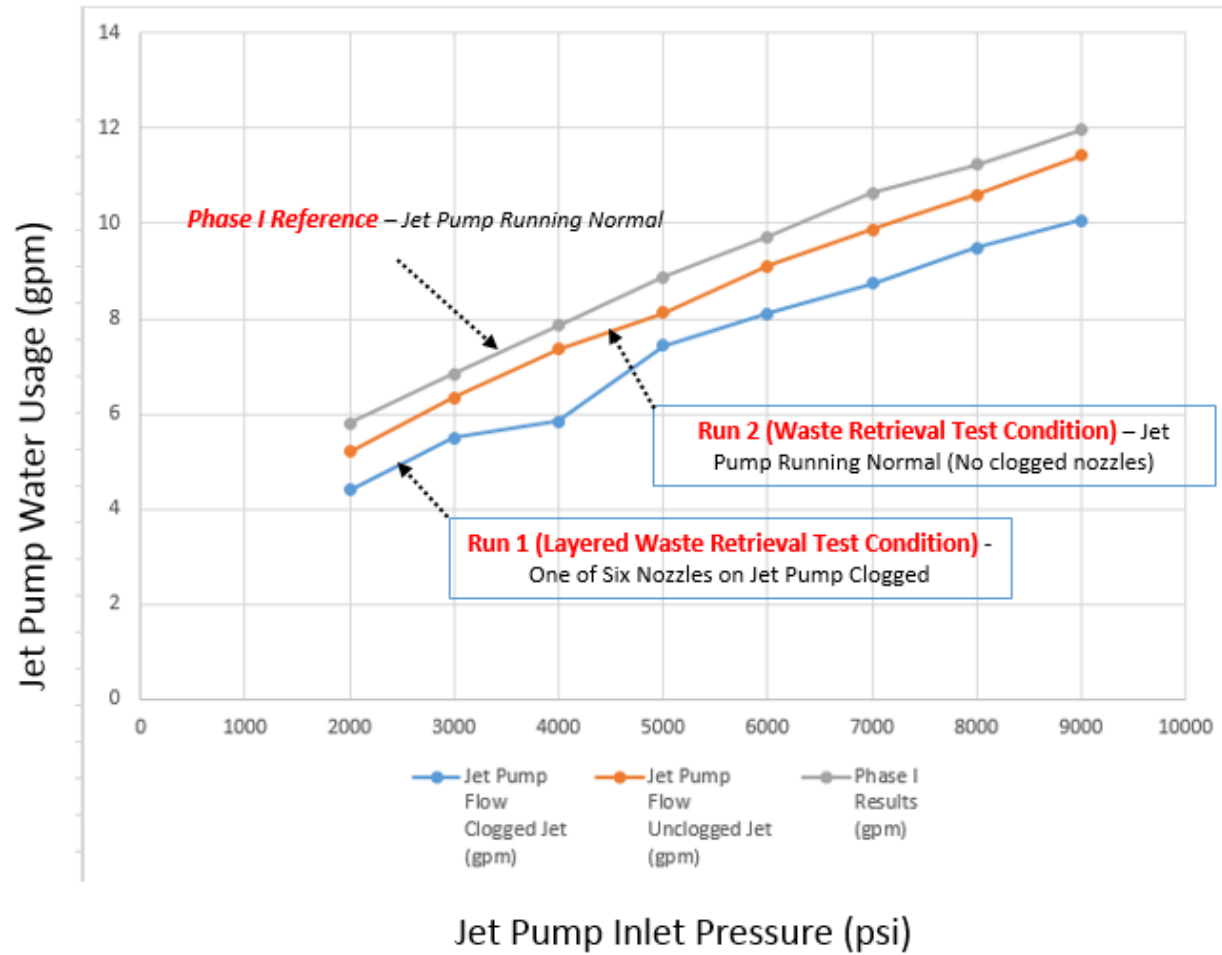


Figure 5.4. Water Usage HWEE Jet Pump and Comparison to Phase I Results.

Table 5.5. Water Usage HWEE Jet Pump and Comparison to Phase I Results

Pressure (psi)	Run 1	Run 2	Phase I
	Jet Pump Flow Clogged Jet (gpm)	Jet Pump Flow Unclogged Jet (gpm)	Jet Pump Flow Results (gpm)
2000	4.41	5.21	5.81
3000	5.5	6.34	6.84
4000	5.84	7.35	7.85
5000	7.44	8.12	8.88
6000	8.11	9.10	9.72
7000	8.73	9.88	10.63

8000	9.49	10.60	11.23
9000	10.06	11.43	11.97

5.1.2 Water Retrieval

Water retrieval by the HWEE jet pump was collected to determine performance when fully submerged in water. Water retrieval was conducted using a catch-and-weigh system to collect and weigh water during steady-state conditions for a collection time, typically at least 1 minute. The equation for water retrieval is:

$$\text{Water Retrieval Rate} = (\text{Water Weight Collected (steady state)} / \text{Collection Time}) - \text{HWEE Jet Pump Water Usage}$$

Data were collected over a range of operating pressures, typically from 1,000 to 10,000 psi in 1,000 psi increments and repeated twice using 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 collection for the HWEE jet pump was in the retrieval tank with the HWEE jet pump operating at 9,600 psi. Water retrieval rate is calculated using the equation in Section 5.1.1 determined by total water collected minus HWEE jet pump water used. 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 rate versus HWEE jet pump pressure 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) as the water level in the simulant tank decreased to keep the HWEE suction flooded.

Water retrieval from the simulant tank using the HWEE jet pump with the HWEE suction flooded is shown in Figure 5.5 and Table 5.6. Multiple runs of different configurations were conducted to fix problems encountered along the way as follows:

Run 1 – Initial component test data taken on May 9, 2018. Result was much lower rate than that measured during HWEE Phase I and was later attributed to a jet pump having one nozzle clogged, HWEE inlet connection was leaking due to lack of sealing tape, and long hose (54 feet) attached between HWEE and jet pump inlet pipe. **NOTE:** This was the HWEE operating condition during the HWEE Phase II layered waste retrieval testing done earlier on May 3, 2018.

Run 2 – Run 1 conditions except changed pressure hose configuration after the foot valve to be all hose directly connected to the jet pump inlet; this eliminated some manual valves and one remote automated

valve in an attempt to boost jet pump nozzle pressure. Results of this testing run showed “no change” in flow rate from Run 1 at 9,000 psi.

Run 3 – Run 1 conditions except changed the HWEE conveyance hose between the HWEE conveyance outlet to jet pump inlet piping from 54-foot hose to 22-foot hose (close to Phase I hose length at this location). Results of this testing run showed significant change in flow rate but still less than Phase I at 9,000 psi.

Run 4 – Run 1 conditions except with jet pump operating with all nozzles functioning and HWEE outlet conveyance hose had been change back to the longer 54-foot hose. Diagnostics prior to this run were to remove and inspect the jet pump nozzles where it was discovered that one of its six nozzles was clogged; this likely occurred during the high-pressure hose connection just before the jet pump as all other upstream hose connections were flushed of debris. Debris was cleared from nozzle and jet pump was reinstalled for this run. Results of this testing run showed some very minor improvement in flow rate at 9,000 psi.

Run 5 – Run 4 conditions except leakage at the HWEE conveyance hose inlet was fixed. Diagnostics prior to this run were the discovery of the HWEE conveyance inlet connection without the tape seal used on Phase I, allowing obvious air leakage through this connection into the conveyance line. As done in Phase 1, tape was wrapped around the HWEE conveyance outlet connection until a tight clearance was achieved and then hose was attached. Results of this testing run showed significant improvement in flow rates at 5,000 and 9,000 psi but still short of Phase I results. **NOTE:** This was the HWEE operating condition existing during the HWEE Phase II waste topography retrieval testing done later on May 16, 2018.

Phase I Results A – These are the flow results for this component measure in Phase I used for comparison. The conveyance hose used during Phase I was shorter (about 22 feet as in Phase II, Run 3) than that used during Phase II retrieval testing (54 feet).

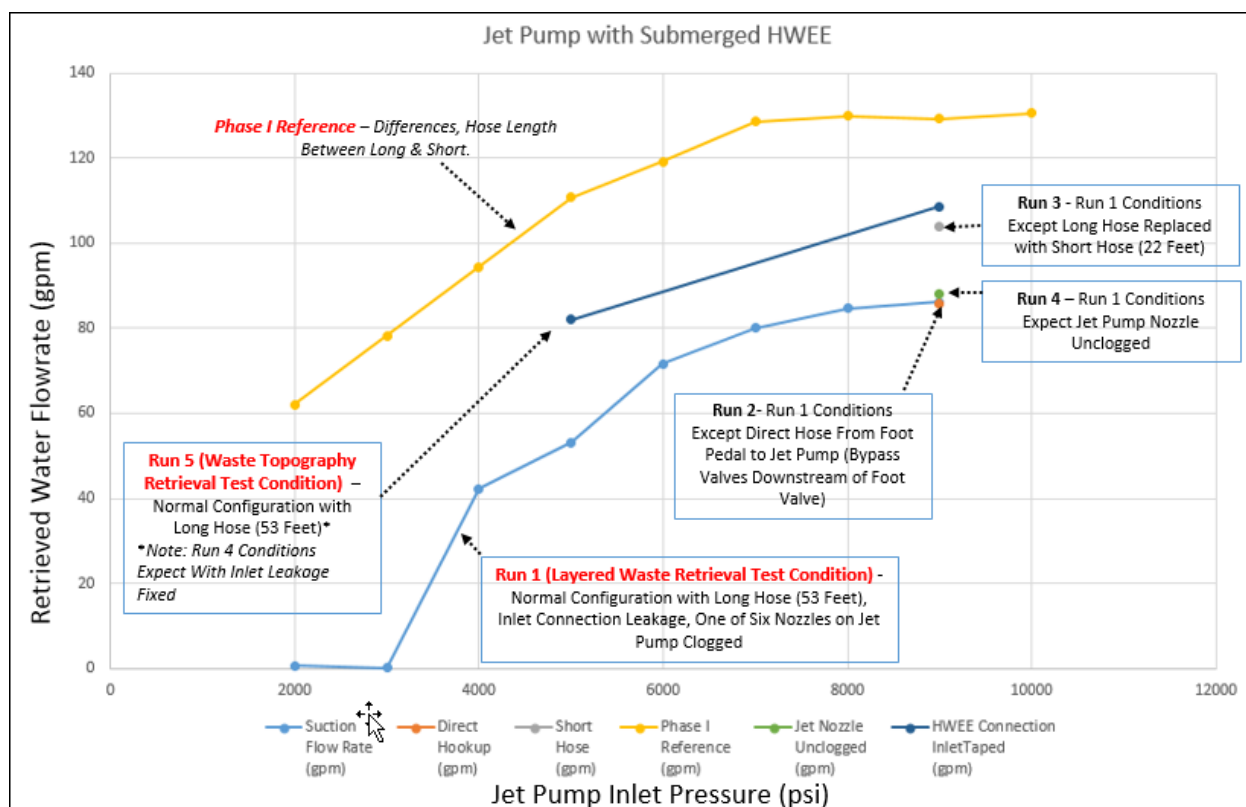


Figure 5.5. Water Retrieval HWEE Flooded Suction with Jet Pump with Repeat Runs Graph

Table 5.6. Water Retrieval Using the HWEE Flooded Suction with Jet Pump with Repeat Runs Data

Phase II Water Suction						Phase I Reference
Jet Pump Inlet Pressure (gpm)	Suction Flow Rate ¹ (gpm)	Direct Hookup (gpm)	Short Hose (gpm)	Jet Nozzle Unclogged (gpm)	HWEE Connection Inlet Sealed w/Tape ² (gpm)	Suction Flow Rate (gpm)
						0.06
2000	0.6					62.01
3000	0.22					78.25
4000	42.28					94.42
5000	53.21				81.98	110.78
6000	71.63					119.15
7000	79.97					128.59
8000	84.59					129.94

Phase II Water Suction						Phase I Reference
Jet Pump Inlet Pressure (gpm)	Suction Flow Rate ¹ (gpm)	Direct Hookup (gpm)	Short Hose (gpm)	Jet Nozzle Unclogged (gpm)	HWEE Connection Inlet Sealed w/Tape ² (gpm)	Suction Flow Rate (gpm)
9000	86.11	85.87	103.84	88.05	108.57	129.19
10000						130.6

¹ Jet Pump Condition for Retrieval Test—Layered Waste

² Jet Pump Condition for Retrieval Test—Waste Topography

At the end of Run 5, a decision was made to use these improved flow conditions for the waste topographic retrieval testing; however, the longer conveyance hose (54 feet) was kept because it had already been used in Phase II layered water retrieval testing. Base on the above testing, it is likely that Run 5 with a shorter conveyance hose like the one used in Phase I (about 22 feet) would have matched Phase I results.

The diagnostic test with the shorter conveyance hose between the HWEE and jet pump producing significant improvement in pumping rate was an interesting observation. Based on this information, using the short hose may have moved the pumping rate numbers closer to the Phase I results. The 54-foot conveyance line used in Phase II testing was longer than the approximate 20.5-foot hose used during Phase I testing and may be the difference seen in pumping performance between these two activities.

5.1.3 Retrieval Tank Fluid Level to Volume Calibration

Phase II testing added a fluid-level gauge to the retrieval tank to improve the level measurements from Phase I. Phase I did not originally have any retrieval tank levels taken as part of the data set, but once testing started, rough, sporadic retrieval tank fluid level measurements were taken using a tape measure to measure the fluid level visible through the opaque tank sidewall from outside of the retrieval tank. The new fluid-level gauge used ultrasonics to measure the fluid surface continually during retrieval tank fluid changes. A field calibration was done with the level gauge to acquire tank volume. The procedure consisted of filling the retrieval tank with water and simultaneously recording the fluid level on the fluid-level gauge, water mass in the retrieval tank, and fluid temperature up to a level of around 33 inches of fill height. The tank fluid volume is calculated from water mass using temperature compensated water density. Field calibrations for retrieval tank fluid level occurred on May 7 and 9, 2018.

The fluid-level gauge successfully continuously monitored fluid level in the retrieval tank, but the turbulent surface generated during all filling operations required data “averaging” to get steady-state results. During initial calibration activities, at periodic level increments, generally three inches, the fluid level in the tank was allowed to “settle” so that a steady-state level could be obtained without averaging. The general “corrected” level-to-volume correlation developed from this field calibration is shown in Figure 5.6 and Table 5.7.

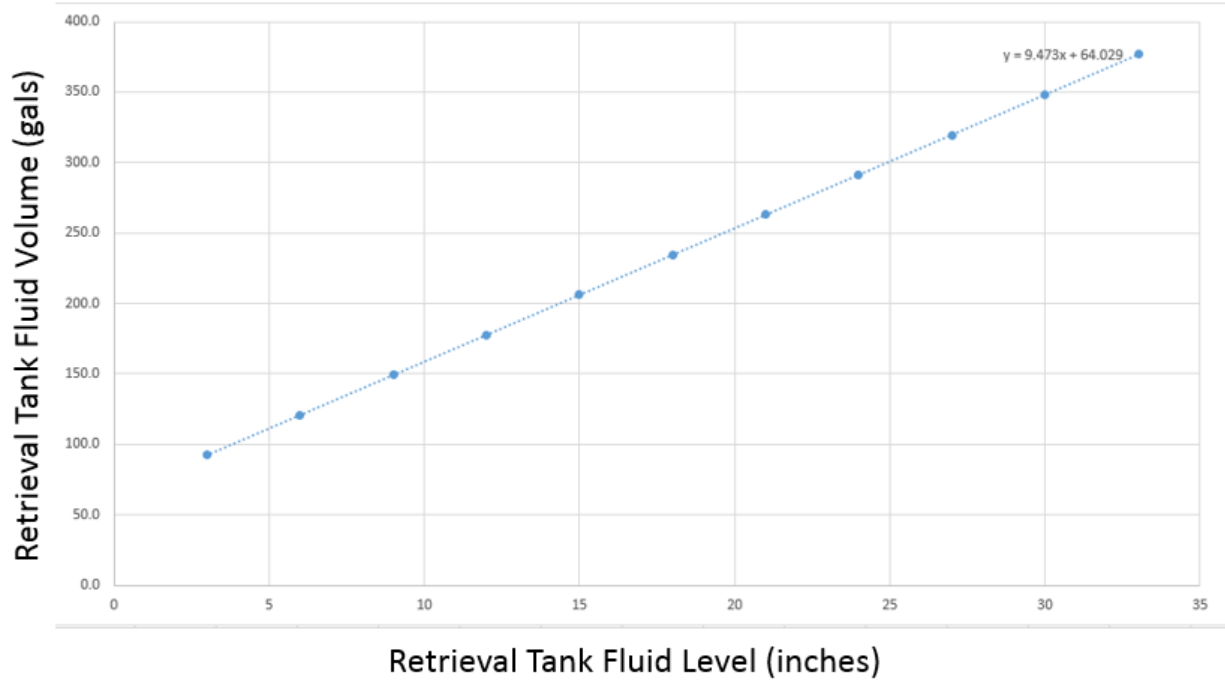


Figure 5.6. Retrieval Tank Fill Level versus Volume

Table 5.7. Retrieval Tank Fill Level versus Volume

Fill Level (inches)	Calculated Volume (gals)	Model Volume (gals)	Difference Model to Calculated (gals)	Error (%)
3	92.6	92.4	-0.12	-0.13
6	120.9	120.9	-0.02	-0.01
9	149.2	149.3	0.09	0.06
12	177.6	177.7	0.08	0.05
15	206.2	206.1	-0.04	-0.02
18	234.6	234.5	-0.05	-0.02
21	262.9	263.0	0.05	0.02
24	291.3	291.4	0.05	0.02
27	319.6	319.8	0.15	0.05
30	348.3	348.2	-0.09	-0.03
33	376.7	376.6	-0.10	-0.03

The data averaging used above was done external to the level instrument. The level instrument could be sent to various modes for data acquisition and the two explored during calibration were “test” mode and “averaging” mode. The test mode produced instantaneous level reading but was much noisier than the averaging mode, which had lag times of several seconds. All measurements were made in test mode because the data could be post-processed for averaging and the first layered retrieval test had level data taken in test mode.

5.2 HWEE Retrieval Demonstrations

The Phase II retrieval demonstrations built on previously completed Phase I retrieval testing done in the summer of 2017 and were performed as outlined in Test Plan section 5.3, HWEE Retrieval Tests. These retrieval demonstrations measured the HWEE performance during simulant mining of Kaolin (sludge) in two configurations that could be expected in a challenging Hanford tank farm waste tank retrieval as follows:

1. Layered waste – Kaolin of two different shear strengths (strong and weak) were layered like a sandwich with the weaker Kaolin in the middle and stronger Kaolin on either side (i.e., top and bottom). Phase I retrieval testing used only a single simulant and single shear strength per retrieval test. The Phase II layering configuration introduced waste retrieval with waste variation in depth along with an increase in total depth of material to be retrieved as would be expected in an actual waste tank.
2. Waste topography – Kaolin of strong shear strength was built in a stepped/profile configuration that would be similar to waste retrievals at the tank bottom corners where waste tends to collect in a bathtub-ring effect.

Both retrieval tests had the following general operating parameters as shown in Table 5.8.

Table 5.8. Retrieval Demonstration Operating Parameters

HWEE	Rotation Speed	300 RPM
	Traverse Speed	300 inches/minute
	Waterjet pressure	1000 psi
	HWEE vertical stepping	1 - 3 inch (variable)
High-pressure System	Pump Pressure	9,000 to 9600 psi

Prior to each retrieval activity, a mining strategy was developed (see Appendix B and C) and dry-run tested. The mining was done in layers with each layer a vertical step downward into the simulant waste bed. Mining of each layer generally consisted of mining using the gantry automated x- and y-axis motions that were restricted by programming design to a serpentine path. For Phase II, the additional option of manually tilting the HWEE head was added, allowing for improved tank wall cleaning and trough mining for water containment. When the HWEE head was tilted at its 35° limit, the HWEE rotating jet cone spray was positioned parallel to an x-axis wall. HWEE head tilting typically required a combination y- and z-axis movement to properly position the HWEE for mining in that layer. The retrieval mining strategy used various combinations of the x-, y-, and z-axis and tilt movements to achieve mining on each layer of the tank. This effort was much more complex than Phase I mining.

A typical mining operational activity starts by setting water pressures to the various HWEE operating devices. The high-pressure water to the HWEE jet pump pressure and inlet to PRM is set using the high-pressure pump pressure regulator and associated pressure gauge. The HWEE in its default condition (pressure off and tilt set at vertical - 0°) is moved over to the capture tank to initiate setting the typically lower pressure to the HWEE rotating jets with only these activated (no flush) using the PRM pressure regulator and associated pressure gauge. The HWEE rotary jets operating independently will run at the pressure set at the PRM, but when both are operating together, a lower pressure will result.

Once all pressures are set, the water to the HWEE rotary jets, flush, and jet pump is turned off and the HWEE is returned to its x- and y-axis “Home” position where automatic positioning control is initiated. Correct vertical positioning is verified and then movement is initiated to the serpentine “start” position. If vertical boring into the waste simulant is required for HWEE layer mining position, then the HWEE rotary jets and jet pump are first turned on and the HWEE is lowered to bore into the waste simulant. Serpentine path is initiated by starting with an x-axis motion (parallel to the long side of the simulant tank) and followed by a y-axis motion (parallel to the short end of the simulant tank). Alternate x- and y-axis motions are done, as applicable, until the full mining path is completed. Multiple mining paths are often required on each layer, and each serpentine path requires a return to the Home position. If any HWEE head tilts are required, this is done at the start and end of x-axis movement. HWEE retrieval operations using the HWEE head tilt was simplified to only include three positions: vertically down (0°) and at maximum tilt positions of $\pm 35^\circ$ around the x-axis. In this document, the x-axis motion may alternately be referred to as a “leg” and the y-axis motions as a “jog.”

During many of the above motions, actual retrieval operations were not being performed, and typically water is shut off. The most common non-mining operations encountered are setting up to start a serpentine path, HWEE head tilting, and returning to Home position after completion of a serpentine path. Serpentine path variations ranged from simple (e.g., single x-axis pass) to complex (e.g., multiple x- and y-axis paths or x-, y-, z-axis movements with HWEE head tilt). In all cases during retrieval, the y-axis moves were generally short and the x-axis moves longer.

At the end of each x-axis move and prior to the start of a y-axis move, normally a two-second flush would be done to clear the HWEE screen of any simulant buildup. Flushing operations were based on HWEE position in the mining, but because path lengths were generally the same, flush times during a layer were periodic. Flushing for these retrieval tests was not optimized but based on previous Phase I testing where flushing kept the screen clear.

In general, retrieval data started once the serpentine path was initiated and until it ended, including all the flushing operations. The retrieval operations were separated into three categories of retrieval (mining operations and flushing), wall cleaning (operations with HWEE head tilted), and cleanup (suction operation to remove liquids without mining).

In conclusion, the Phase II HWEE retrieval operations performed the task required within project schedule and budget restraints. The system design was not the most operationally efficient for mining due to limitations in the gantry automated motions, the various manual operations including z-axis and HWEE head tilt movements, and the small simulant tank area in which to work. The system components were not optimized to reduce water usage, but the remote automatic valves helped use water only during retrieval operations—an improvement from Phase I slow manual valve operation that were mainly used for flushing. A HWEE system designed for in-tank retrieval would likely be much more operationally efficient, and therefore the retrieval results presented here are likely conservative.

Retrieval Water Containment

Water/slurry remaining in the simulant tank after Kaolin retrieval testing was about one inch and likely could have been mostly removed with additional HWEE cleaning that was not specifically pursued for this testing; the remaining water/slurry mix was very liquid and testing has demonstrated HWEE suction capabilities of transporting this type of material out of the slurry tank.

During retrieval, it was demonstrated that water used in mining/flushing could be confined in mining troughs. The benefits of very localized mining and use of a mining strategy to contain water locally in the confines of a mining trough was demonstrated in both Kaolin retrieval tests performed. As these retrieval tests were “one-shot” demonstrations, the progressive development of a mining strategy was not possible. Also, the limitations of the HWEE motions in this test setup did not allow fully variable mining techniques to be demonstrated like slowly swinging (i.e., variable tilting) the HWEE head where material could be mined around the HWEE head with frequent vertical (0 degree) position that was best for removing localized water with the HWEE skirt. During HWEE retrieval/wall cleaning and the HWEE in a fixed tilted position of 35 degrees, very little water was being captured and transported; instead, the water was pooling into the mining trough being built. After Kaolin and Kaolin/plaster retrieval, the water was well confined to the troughs that were cut in the simulant.

Because the Kaolin clay retrieval only required 1,000 psi pressure, the spray and aerosol generation appeared to be small. Some spray mist was noted when the HWEE head was tilted for wall cleaning and exposed to the harder wall surfaces and bottom of the simulant tank.

5.2.1 Retrieval Test – Layered Waste

Retrieval testing with layered waste is detailed in Test Plan Sections 4.2 and 5.3. Testing was successfully conducted on May 3, 2018. The Kaolin simulant was manufactured and put into the simulant tank in the layered configuration (see Figure 4.1 and Figure 5.7) at PNNL’s APEL facility and shipped to CTF to coordinate meeting the Kaolin target shear strength conditions of around 3,375 Pa and 284 Pa for the strong and weak Kaolin respectively; see Test Plan Section 4.4.5 for additional details. Additional details of the simulant targets and preparation can be found in Test Plan Sections 4.4.4.4 and 4.4.4.5.



Figure 5.7. Layered Waste Profile (PNNL Layer Build—Thickness in Sections)

Prior to retrieval, a mining strategy with layer-by-layer operational steps was developed and dry-run tested. The mining strategy was generally as follows:

- Mine out several vertical layers (one-inch drop) of top layer of hard simulant using serpentine path
- After several layers were mined, HWEE was tilted and two sides of the tank were mined in a single path
- Mine out the remaining vertical layers using these same two steps but use a two-inch vertical drop through the middle layer of softer simulant and bottom layer of hard simulant
- Perform final liquid/slurry removal using HWEE suction only from the HWEE jet pump

During retrieval, a few issues were encountered and solved as follows:

- It was found that the larger simulant tank did not allow the HWEE to fully access the bottom of the simulant tank because the car-lift opening of the HWEE gantry system was smaller than the width of the simulant tank. This interference condition was solved by mining into the simulant tank as far as the simulant tank would allow and then cutting the top eleven inches of the simulant tank off to allow the remaining mining to take place.
- Once the HWEE gantry was inside the simulant tank, the y-axis motion was limited by the HWEE support system and force/torque sensor, affecting unmined simulant that HWEE could not sluice. For fully mining the final layers of simulant inside the simulant tank, the un-minable simulant obstruction down to the current retrieval mining area was removed by hand shoveling. The obstructing simulant was easily removed due to the mining that above and below that volume. The y-axis retrieval path inside of tank was then expanded to match the earlier mining path.

- During the last horizontal mining layer, the retrieval process was stopped partway through by the test director because of a concern that the HWEE was not rotating. This mining stop was not necessary because the HWEE was rotating but was not visible to the test director. The mining path was restarted and successfully completed.
- During retrieval testing, at times the HWEE mining path contacted and plowed through some simulant that may have not been fully mined due to test configuration constraints. During the plowing process, it is expected that some higher-than-normal force/torques on the HWEE may have been recorded.
- At the end of testing, it was noted that the HWEE position sensor had become disconnected from its bracket. This was not an issue because all tilt movements during testing went fully to the preset 35-degree stop tilt limits. The bracket was repaired prior to the next retrieval campaign.

Data taken during retrieval testing were recorded and included all instrumentation associated with this testing. Testing was also videotaped. Details of the layered retrieval strategy, mining, and test record can be found in Appendix B.

The partially clogged jet and HWEE conveyance inlet leakage were present during the Phase II layered waste retrieval testing (see Section 5.1.2) as these problem were found after completion of that testing. However, based on visual observations during the first layered retrieval testing, it appears that the jet pump suction was adequately capturing the simulant waste product from mining activities and transporting them through the conveyance line to the retrieval tank. Operation of the HWEE with a clogged nozzle and leaking HWEE conveyance inlet port likely was detrimental to retrieval performance and related dilutions ratio and likely produced conservative calculation for layered retrieval performance.

5.2.2 Retrieval Test—Waste Topography

Retrieval testing with waste topography as detailed in Test Plan Sections 4.2 and 5.3 was successfully conducted on May 16, 2018. The Kaolin simulant was manufactured and put into the simulant tank in the topography configuration (see Figure 4.2 and Figure 5.8) at PNNL's APEL facility and shipped to CTF to coordinate with meeting the Kaolin target shear strength conditions of around 3,375 Pa for the strong Kaolin; see Test Plan Section 4.4.5 for additional details. Additional details of the simulant targets and preparation can be found in Test Plan Sections 4.4.4.4 and 4.4.4.5.



Figure 5.8. Waste Topography Profile (Top: In Form, Bottom: Form Removed)

Prior to retrieval, a mining strategy with layer-by-layer operational steps was developed and dry-run tested. The mining strategy was generally as follows:

- Mine out several vertical layers of the stepped shelf with an emphasis on creating a trough to contain water from mining in the shelf area using narrow passes and HWEE head tilting for wall cleaning

- Once the stepped shelf is removed, continue mining the full simulant bed in a similar fashion as done for the layered bed retrieval
- Perform final liquid/slurry removal using HWEE suction only from the HWEE jet pump

During retrieval, no new issues were encountered; however, some of the same issues solved for layered retrieval were incorporated in this testing, and some pre-retrieval high-pressure water leakage was encountered and solved as follows:

- As discovered during layered retrieval testing, the simulant tank walls interfere with the HWEE vertical motion after some initial simulant layers are removed. In this case, the simulant tank was pre-cut and taped prior to retrieval testing so that the tank top could easily be removed after or during retrieval mining operations.
- As discovered during layered retrieval testing, once the HWEE gantry was inside the simulant tank, the y-axis motion was limited by the HWEE support system and force/torque sensor affecting unmined simulant that the HWEE could not sluice. For fully mining the final layers of simulant inside the simulant tank, the un-minable simulant obstruction down to the current retrieval mining area was removed by hand shoveling. The obstructing simulant was easily removed, and then the y-axis retrieval path inside the tank was expanded to match the earlier mining path.
- Before the start of retrieval operations, pre-test high-pressure leakage checks found leaks at the rotary union joint on the HWEE and one of the new automatic valves on the jet pump. The rotary union joint leakage was fixed by tightening the joint connection, which was found to be loose. The remote valve leakage was solved by removing it from the jet pump high-pressure line string and controlling this line solely with the manual foot pedal valve as was done during Phase I testing.

Data taken during retrieval testing were recorded and included all instrumentation associated with this testing. Testing was also videotaped. Details of the layered retrieval strategy, mining, and test record can be found in Appendix C.

5.3 Retrieval Results

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

5.3.1 Retrieval Rates and Slurry Dilution Ratios

Retrieval rates are calculated for the Phase II HWEE tests using the methodology provided in Berglin et al. (2018). As shown in Appendix G (reproduced from Berglin et al. 2018), the retrieval rate, RR, can be computed from the mass, volume, and temperature measurements of the retrieval tank contents by conservation of mass as

$$RR = \frac{\frac{MSR}{\rho_s}}{t} \quad (5.1)$$

where MSR is the mass of simulant in the retrieval tank, ρ_s is the density of the simulant, and t is the test time. The test data was collected at 500 Hz in order to capture transients in the HWEE reaction forces during the tests. The retrieval rate calculations are based on a 1-second moving average of the data in order to smooth the fluctuations of the level sensor.

Because Equations (5.1) and (5.2) are based on the conservation of mass, the results are physically correct. However, as will be discussed for the retrieval rate, the surface level measurement in the retrieval tank resulted in nonphysical results for some time steps. The dilution ratio computed similarly (see Appendix C) was substantially convoluted. Thus, additional and alternate calculations are used as will be described.

The calculated retrieval rates from Equation (5.1) for the layered test are shown in Figure 5.9 through Figure 5.11. Figure 5.9 provides the calculated retrieval rate for normal retrieval, Figure 5.10 for tilt retrieval, and Figure 5.11 for suction only. These different modes of operation (normal, tilt, and suction) are described in the preceding sections. Three calculated retrieval rates are shown using different simulant densities (see Equation 5.1): 1) simulant density is constant at that of the higher-shear strength top and bottom layers (see Section 4.3), 2) simulant density is that of the lower-shear strength middle layer (see Section 4.3), and 3) volume weighted average density. The three different results, depending on density, span the potential results and are employed as there is no means to discriminate the layers during the retrieval. The layered test retrieval rates are shown to approximately vary from zero to 80 gpm for normal retrieval, zero to 20 gpm for tilt retrieval, and zero to 70 gpm during suction.

The calculated retrieval rates from Equation (5.1) for the topographical test are shown in Figure 5.12, Figure 5.13, and Figure 5.14 for normal, tilt, and suction respectively and approximately vary from zero to 80 gpm for normal retrieval, zero to 30 gpm for tilt retrieval, and zero to 20 gpm during suction. With only one simulant strength, there is no variation in the as-made simulant density, so only one result is shown in contrast to the layered test.

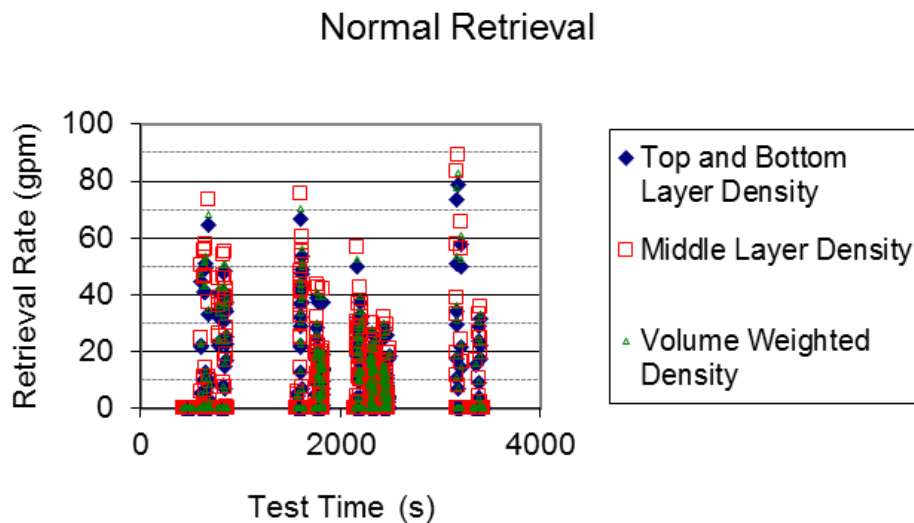


Figure 5.9. Average Retrieval Rates, Layered Test, Normal HWEE Orientation

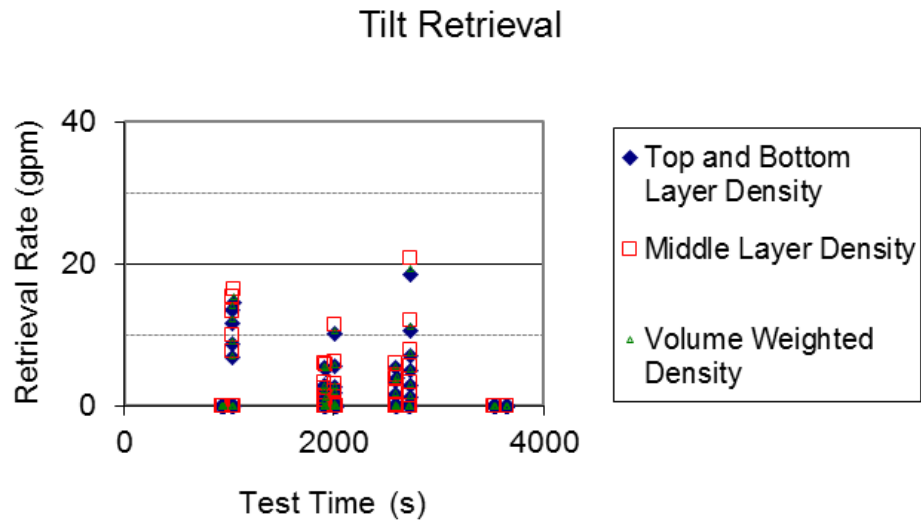


Figure 5.10. Average Retrieval Rates, Layered Test, Tilted HWEE Orientation

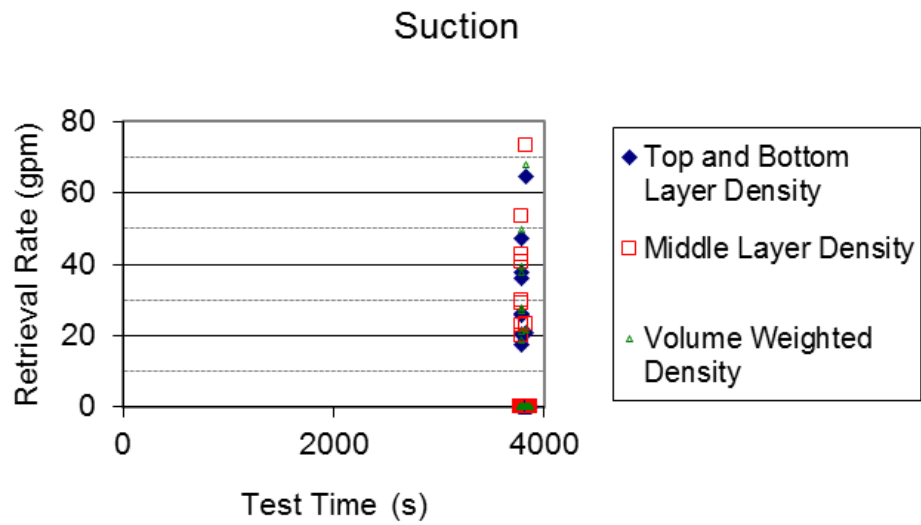


Figure 5.11. Average Suction-only Retrieval Rates, Layered Test, Normal HWEE Orientation

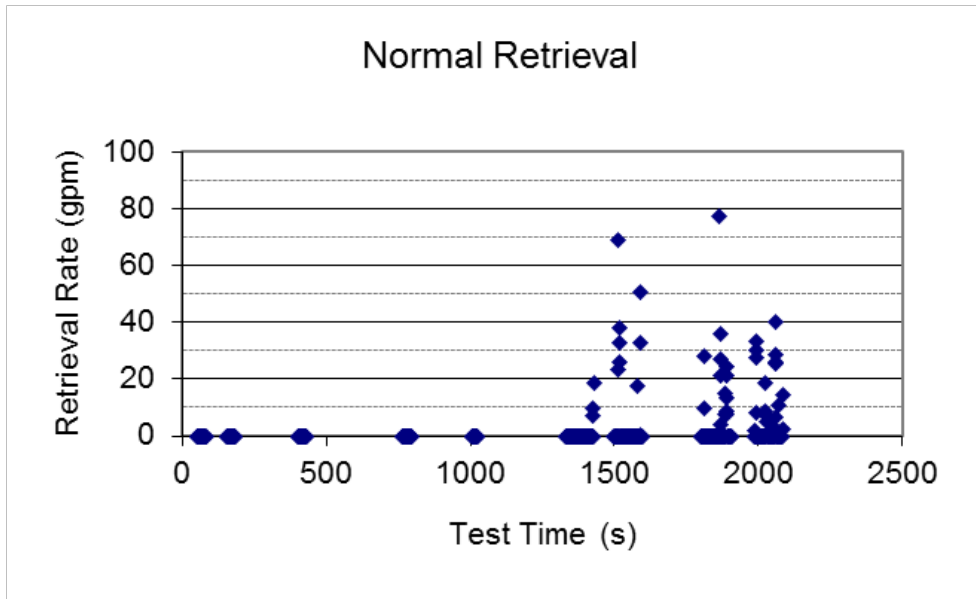


Figure 5.12. Average Retrieval Rates, Topographical Test, Normal HWEE Orientation

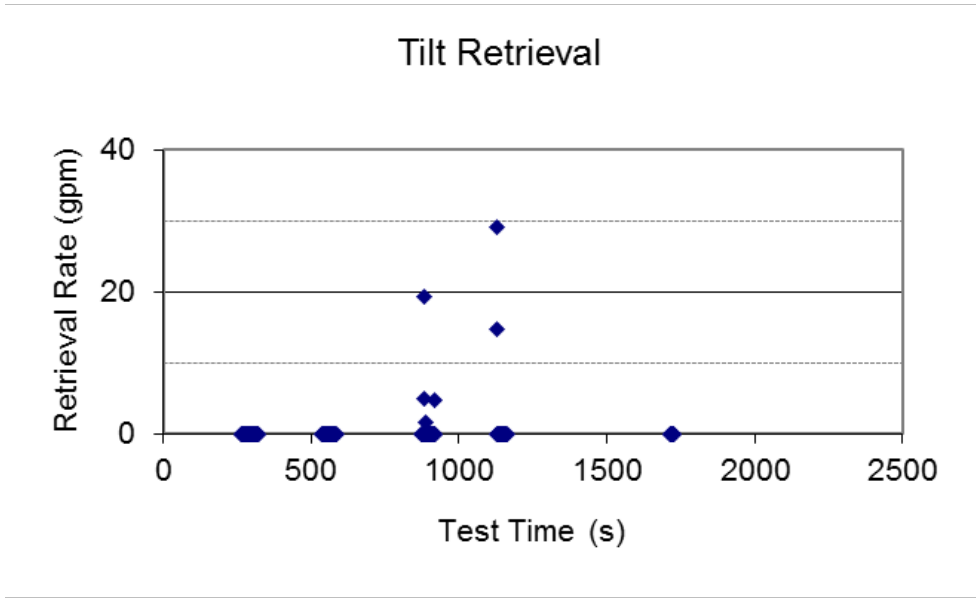


Figure 5.13. Average Retrieval Rates, Topographical Test, Tilted HWEE Orientation

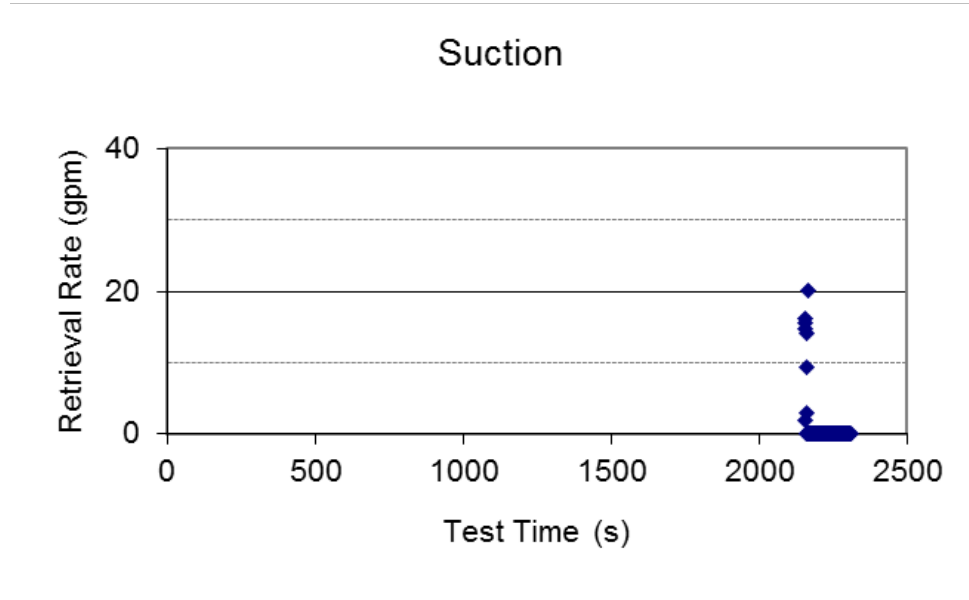


Figure 5.14. Average Suction-only Retrieval Rates, Topographical Test, Normal HWEE Orientation

For both the layered and topographical tests, there are a substantial number of zero gpm calculated results. In limited instances, the zero results are physical. For the majority of the zero results, the rate of increase in volume (i.e., measured level) in the retrieval tank is proportionally more than the mass increase that results in a completely nonphysical indication of the removal of simulant mass in the retrieval tank (via a nonphysically reduced bulk density in the retrieval tank; see Appendix G). It is postulated that this is caused by the pulsing of simulant and water into the retrieval tank and the response of the level sensor. During testing it was observed that slug flow was occurring as evident by the pulsations of the conveyance hose. The nonphysical nature of the substantial periods of zero calculated retrieval rate is simply and easily demonstrated by visual comparison of simulant tank conditions during the topographical test.

Figure 5.15 shows the initial configuration of the topographical test simulant, and Figure 5.16 shows the configuration of the same simulant after 198 seconds of active retrieval time (585 seconds of test time; see Appendix B). It is evident from the images that the top step has been removed from the simulant tank by the HWEE operation. This result can be contrasted with the calculated zero gpm rates shown in Figure 5.13 and Figure 5.14 and clearly demonstrates that these calculated rates are unphysical. To enable the determination of an average retrieval rate, RRa, additional calculations are therefore performed that use the difference in simulant mass in the retrieval tank (MSR) over the active retrieval times as

$$RRa = \frac{\frac{(MSR_1 - MSR_0)}{\rho_S}}{t} \quad (5.2)$$

where the 1 and 0 denote the initial and final mass of the test time of interest t . The dilution ratio is then computed from

$$DRa = \frac{\frac{(MSR1-MSR0)}{\frac{\rho_S}{MH}}}{\rho_H} \quad (5.3)$$

where the water mass MH is computed by difference and ρ_H is the average water density, both computed as shown in Appendix C.



Figure 5.15. Initial Simulant Configuration Just Before Test Start, Topographical Test



Figure 5.16. Simulant Configuration at 198 Seconds Active Retrieval (585 Seconds Total Test Time), Topographical Test

The calculated average retrieval rates and slurry dilution ratios are presented in Table 5.9. As expected from comparison of the normal and tilt retrieval rates in Figure 5.9 through Figure 5.14, the increased usage of tilt retrieval during the retrieval of the top step of the topographical test had the lowest retrieval rate. The topographical test has a reduced retrieval rate and dilution ratio compared to the layered test. It is unclear how much of the reduction is due to the increased tilt retrieval of the topographical test (reducing the retrieval rate) or the lower shear strength layer of the layered test retrieval (with a likely increased retrieval rate).

Table 5.9. HWEE Phase II Average Retrieval Rates and Dilution Ratios

Test	Test Period	Retrieval Rate (gpm)	Dilution Ratio
		RRa	DRa
Layered ¹	Entire Test	7.6	0.24
	Entire Test	3.1	0.11
Topographical	Top Layer	0.9	-
	Bottom Layer	3.7	-

¹ Calculated results reported for volume weighted average simulant density.

- For the Topographical Test, the dilution ratio was calculated for the entire test only

The HWEE Phase II average retrieval rates and dilution ratios compare very favorably to prior work, and the calculated results show quite high retrieval rates regardless of the orientation used in retrieval operation. From Berglin et al. (2017), the HWEE Phase I results for the similar Kaolin simulant during active retrieval were a retrieval rate of 4.9 gpm and dilution ratio of 0.3. The weakest material used for the Mobile Arm Retrieval System-Vacuum (MARS-V) testing, likely an easier to erode simulant than the higher shear strength Kaolin employed herein (see Berglin et al. 2017), had a retrieval rate of 4.3 gpm and dilution ratio of 0.05.

5.3.2 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 5.17, the y-axis of the force-torque sensor was oriented vertically, 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 measured 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. Note that if the HWEE is tilted 35 degrees with respect to vertical, the x and y axis of the force-torque sensor are also tilted.

Reaction forces during retrieval result from waterjet recoil, inertia, manifold rotary motion, hose weight and stiffness, suction, and slurry transport. A summary of the test condition and measured maximum and minimum forces and torques are provided in Table 5.10. The highest recorded value of each column (in absolute value) is shown in bold. The time-varying test results are provided in Appendix A 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 retrieval test 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. Reaction forces from the HWEE were measured during the layered retrieval and the topographical retrieval tests. A subset of this data was analyzed and is summarized in Appendix E, Figures E.1 through E.22.

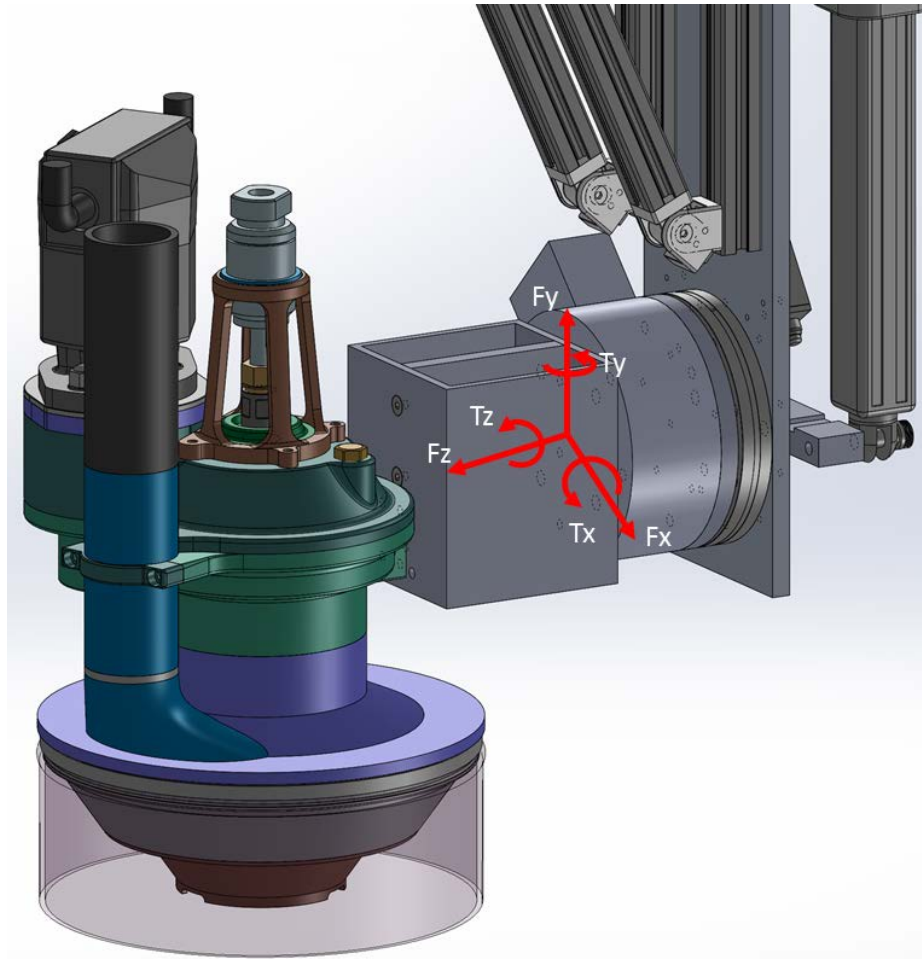


Figure 5.17. Force and Torque Measurement Orientation

For the layered retrieval test, data during retrieval of the top (3,375 Pa), middle (284 Pa), and bottom (3,375 Pa) layers are provided. Forces and torques were higher during retrieval of the top layer due to the higher strength of the simulant material in this layer. Forces and torque were generally higher during retrieval of the bottom layer and during the final suction pass due to intermittent contact with the tank bottom. Note that the gantry used for the test was quite stiff, and interference between the HWEE and the tank bottom resulted in high forces. If a more compliant deployment platform is used to deploy the HWEE, then these tank contact forces will be lower. During the tilt-clean pass, the goal was to clear the material near the tank wall with the waterjets. The reaction forces during the tilt cleaning pass were generally low, but the torque along the z-axis (Figure E.8) increased due to the resistance of the retrieval hose.

For the topographical retrieval test, data collected during five passes are provided to envelop a range of test conditions. During odd-numbered passes (1, 3, and 5), the HWEE was in its normal vertical

orientation, and during even-numbered passes (2 and 4), the HWEE was tilted 35 degrees. The reaction forces during the tilt retrieval pass were somewhat higher because the skirt was dragged through the sludge in this orientation. When the HWEE is tilted, the lower edge of the skirt is presented several inches below the level of the suction port. Dragging the skirt through the sludge generated moderately high forces.

The frequency content of the force and torque values measured during the retrieval tests was highly variable. A pronounced resonance at 40–50 Hz is seen in most plots, however.

Table 5.10. Maximum Forces Measured during Retrieval Tests

Test Type	HWEE Orientation	Extreme	Fx lb	Fy lb	Fz lb	Tx in-lb	Ty in-lb	Tz in-lb
Layered Retrieval Top Layer	Vertical	max	62	60	66	390	635	493
		min	-43	-45	-63	-957	-444	-891
Layered Retrieval Middle Layer	Vertical	max	48	47	55	386	427	287
		min	-40	-39	-55	-627	-315	-599
Layered Retrieval Bottom Layer	Vertical	max	48	65	154	522	409	267
		min	-40	-50	-71	-676	-549	-507
Layered Retrieval Tilt Clean	35°	max	46	33	59	318	467	803
		min	-57	-34	-57	-487	-401	-614
Layered Retrieval Final Suction	Vertical	max	77	156	115	541	606	461
		min	-206	-75	-207	-921	-1030	-2223
Topographical Retrieval Pass 1	Vertical	max	52	51	68	389	534	497
		min	-43	-34	-62	-1000	-365	-651

Test Type	HWEE Orientation	Extreme	Fx lb	Fy lb	Fz lb	Tx in-lb	Ty in-lb	Tz in-lb
Topographical Retrieval Pass 2	35 ³	max	37	65	93	647	350	578
		min	-54	-90	-104	-1219	-467	-567
Topographical Retrieval Pass 3	Vertical	max	49	45	63	586	398	468
		min	-50	-40	-67	-798	-485	-792
Topographical Retrieval Pass 4	35 ³	max	46	75	82	547	438	616
		min	-59	-53	-99	-1102	-369	-547
Topographical Retrieval Pass 5	Vertical	max	61	52	104	550	355	492
		min	-56	-45	-90	-652	-461	-648
Topographical Retrieval Final Suction	Vertical	max	64	57	96	479	478	551
		min	-51	-54	-107	-744	-427	-852

5.3.3 HWEE Flush Inlet Screen Cleaning Demonstration

The HWEE is equipped with a flushing capability to clear the HWEE inlet screen if it gets clogged during retrieval operations. During Phase I testing, the HWEE internal flush jet was noted to use a lot of water. To help minimize water use during retrieval, a smaller flush nozzle was proposed and installed for Phase II testing. Before starting the HWEE flush component testing with new, smaller nozzles, a demonstration of screen clearing was proposed to ensure that the HWEE would be adequately cleaned.

The HWEE screen cleaning test was run on May 2, 2018. The HWEE screen area was hand packed with Kaolin clay, like the screen cleaning demonstrated in Phase I testing, until all the screen inlet hexagonal openings were generously filled with Kaolin. The inlet pressure at the PRM was set at 1000 psi with only the HWEE rotary jets operating (i.e., no flush operating). With the HWEE rotary jets spinning at 300 rpm, the HWEE flush was remotely activated for approximately 2 seconds, which gave the spinning inlet screen approximately 10 rotations through the flush spray. At flush activation, it was noted that the PRM inlet pressure dropped to 500 psi with both the HWEE rotating jet and flush operating together; therefore, the flush pressure for this screen cleaning was 500 psi. Inspection of the HWEE screen after flushing found that the hexagonal holes in the screen had been cleared and the flush performed its function of screen clearing (see Figure 5.18), allowing HWEE Phase II retrieval tests to proceed with this flush nozzle.



Figure 5.18. HWEE Screen Cleaning Demonstration of Kaolin Clay with 500 psi Internal Flush

5.4 Jet Pump Vertical Lift Tests

Jet pump vertical lift tests as detailed in Test Plan Sections 4.3 and 5.4 was successfully conducted on May 22, 2018. Test setup details are describe in Section 2.3.7. Some of the Kaolin simulant retrieved during waste topography testing as a diluted slurry in the retrieval tank was transferred to an interim metal stock tank for using in vertical lift testing with simulant. As most of the Kaolin slurry would settle to the bottom of a tank in less than one minute, the simulant was actively suspended in the tank within several seconds using a submersible pump that discharged contents back into the tank in a circulating flow prior to transfer to the simulant tank for testing. Dip samples of the simulant were taken using water bottles that were dipped into the slurry mix that was suspended by circulation and transfer. These simulant dip

samples were measured for density in two samples (one from the mixing tank and the other from the simulant tank) after the test at PNNL's APEL simulant lab with measured density of 1.0777 g/cm³.

The general test strategy was to observe the change in weight of the simulant and retrieval tanks as contents were being conveyed. In all cases, the retrieval tank should continually see a constant weight gain if fluids are being positively transported. Except for air testing, the simulant tank should see constant weight loss if fluids are being transported. A positive weight gain in the simulant tank indicates a lack of fluid transport that may also include jet pump water that is flowing back down the vertical pipe. Because test durations for all these tests were short, the long-term vertical transport of jet pump water to the retrieval tank could not be fully accessed. Fluid hold up in the conveyance line cannot be accounted for because there was no instrumentation to perform this function. There is some lag time for fluid transfers between the simulant tank and retrieval tank due to the length of the conveyance hose and piping. A video of operations at the simulant tank was recorded and shows the position(s) of the jet pump hose with the HWEE inlet attached during the test duration. Jet pump vertical lift tests focused on demonstrating the vertical conveyance abilities of the AquaDyne jet pump configured the same way for both HWEE Phase I and II retrieval test operations up to pressures of 10,000 psi. The minimum lift height of at least 35 feet, including both suction lift and discharge lift of the jet pump, was achieved with the total measured lift in the "as-built" test setup just over 39 feet, including 6.5 feet of suction and the remainder discharge. The jet pump was oriented in a vertical configuration; suction lift of 6.5 feet was close to Phase I and II retrieval conditions; and the old HWEE screen from Phase I was used to mimic HWEE inlet restrictions; see Appendix D for additional details of test setup. The jet pump vertical testing was separated into four tests (A, B, C, and D) which proceeded in steps with increasing complexity of fluid flow and materials transported. These tests are detailed in the following subsections.

In the results below, Test A with air only is all jet pump motivation fluid. For all other tests, the jet pump motivation fluid is mixed with other fluids and therefore the "apparent" jet pump flow rate is calculated by taking the difference between simulant and retrieval tank weights. This "apparent" jet flow calculation is not exact because there is some lag and holdup in the conveyance line that cannot be measured or accounted for with this test setup.

5.4.1 Test A—Air Only

For this test, the inlet hose with the HWEE screen attached was suspended in air above the simulant tank while the jet pump was run at various pressures. Jet pump water transport into the retrieval tank was monitored and measured. The simulant tank should not have seen any weight change, and any weight change was attributed to not all jet pump water being transported to the retrieval tank or suspended in the conveyance line.

During air testing, nothing was drawn from simulant tank. Ideally, the retrieval tank flow rate should be equal to the jet pump flow rate (11.5 gpm) if all jet pump motivation water is being deposited in the retrieval tank and not dropping back to the simulant tank. Results from this testing are shown in Figure 5.19 and are close to the jet pump flow rate.

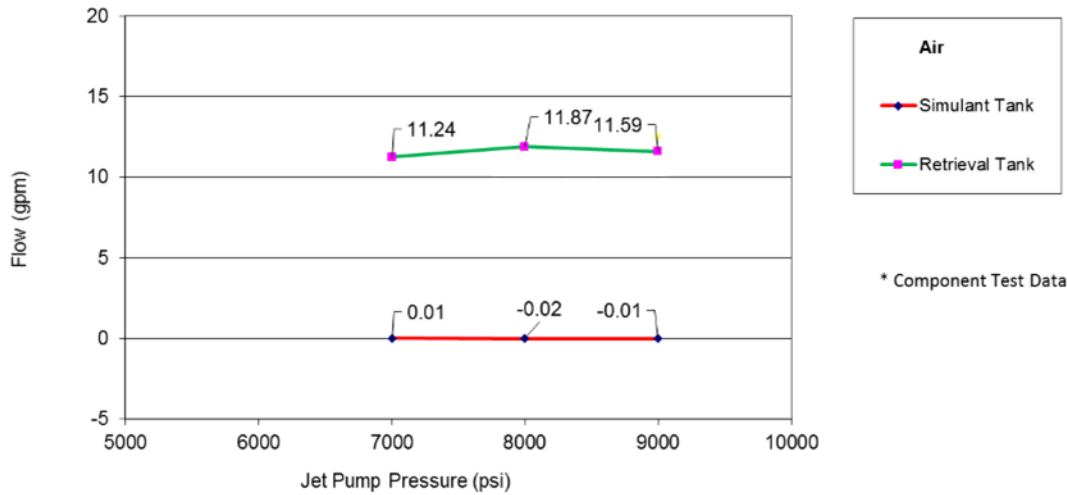


Figure 5.19. Jet Pump Lift—Air Only

This test demonstrated that when operating in air, all water flow out of the jet pump was conveyed to the retrieval tank and did not drop back to the simulant tank for 7,000 psi and above.

5.4.2 Test B—Water Submerged Suction

The testing sequence consisted of starting with the tank filled with water just under the jet pump inlet in the raised position. When jet pump airflow was established, the jet pump inlet with HWEE screen attached was dropped into the water at the lower position with the flange inlet face (i.e., top of 4-inch deep inlet screen cone) approximately 7 inches off the bottom of the simulant tank. Pumping continued until the jet pump inlet was exposed and started sucking air at the lower position. Initial testing was done with the jet pump operating at high pressure, but later testing lowered the pressure to attempt to define the transition pressure where no conveyance occurred.

During water submerged suction, the simulated HWEE inlet (operating at set jet pressure) above the water level was quickly fully submerged in water to about 2 feet and allowed to pump. Results from this testing are shown in Figure 5.20.

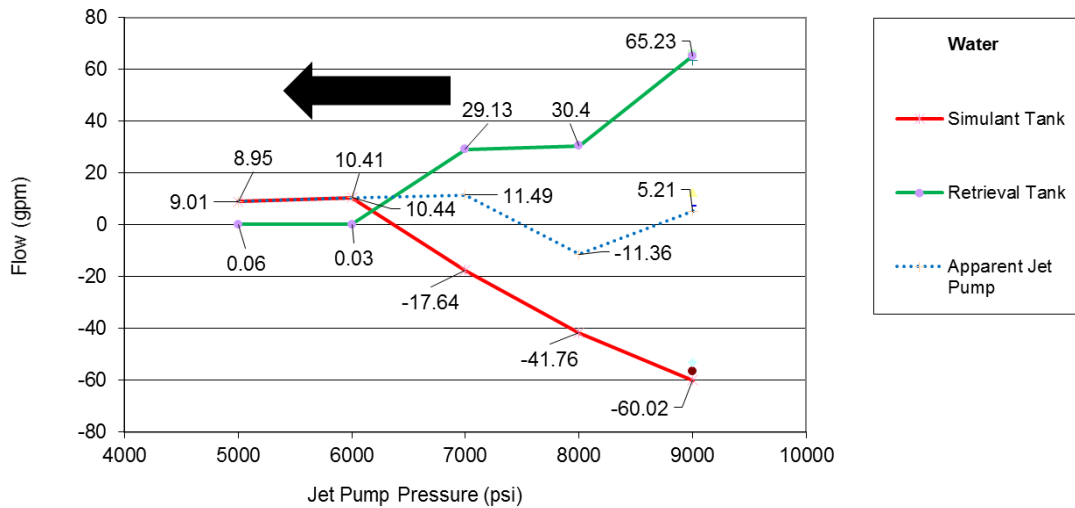


Figure 5.20. Jet Pump Lift—Water Submerged Suction

This testing demonstrated that the jet pump submerged in water with flooded suction can pump water the vertical distance when operating at 7,000 psi and above; higher operating pressures are better. Below 7,000 psi, as indicated by the black arrow in Figure 5.20, the flow drops off significantly and pumping is not efficient. The source of the non-linearity of the retrieval tank plot above 7,000 psi cannot be determined.

5.4.3 Test C – Water/Air with Intermittent Submerged Suction

A combination of the two previous tests where the jet pump hose inlet with HWEE screen attached is moved in and out of the simulant tank fluid randomly as might be expected during an actual HWEE retrieval operation. Actual random motion of air and water suction oscillations is recorded in the video record.

During water/air submerged suction, the simulated HWEE inlet (operating at set jet pressure) above the water level is alternately submerged in and out of the water to various depths to mimic a “more typical” retrieval operation. Jet pump only operated at 9,000 psi pressure for this test. Results of this testing are shown in Figure 5.21.

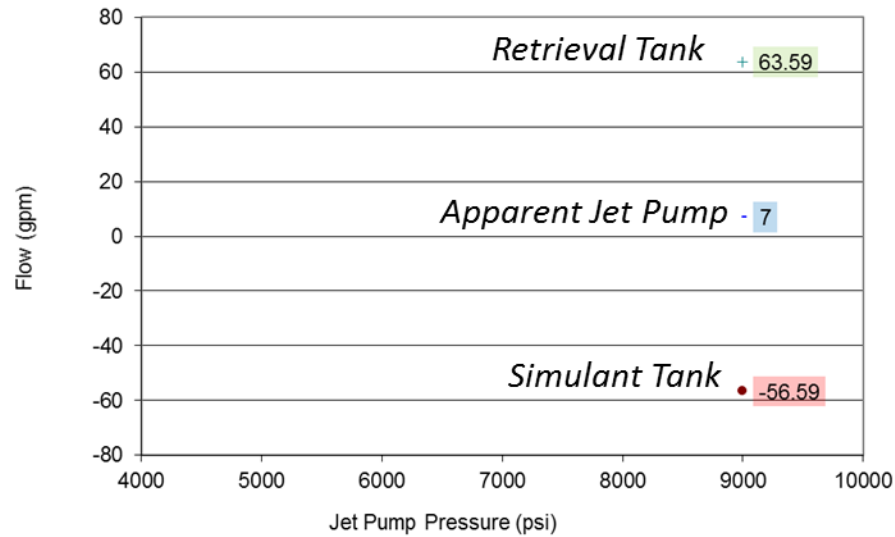


Figure 5.21. Jet Pump Lift—Air\Water—Alternating

This testing demonstrated that the jet pump may effectively work in a mixed fluid-phase environment at 9,000 psi with water. There is not enough data to evaluate if it could maintain effectiveness for a long period of time.

5.4.4 Test D—Simulant Submerged Suction

This is the same test as Test B except water with simulant was used instead of only water.

Due to limited simulant, HWEE project management (WRPS) decided, and PNNL agreed, that only a flooded suction test (like Test B) and not a random suction inlet test (like Test C) would be done. Simulant consisting of Kaolin and water left over from HWEE Phase II retrieval testing was premixed in the metal holding tank before transfer to the simulant tank using a submersible pump in the mixing tank and outlet providing circulating flow in the mixing tank. Before transfer to the simulant tank, a sample of mixed simulant was taken (Sample A). Simulant from the mixing tank was transferred to the simulant tank using a diaphragm pump and hose. Once simulant was transferred to the simulant tank, a sample of simulant was taken (Sample B). Jet pump vertical testing immediately followed. At the end of testing, these simulants were transferred to PNNL's simulant lab and analyzed for density only. During simulant submerged suction, the simulated HWEE inlet (operating at set jet pressure) above the water level was quickly fully submerged in water to about 2 feet and allowed to pump. The jet pump only operated at 9,000 psi pressure for this test. Results of this testing are shown in Figure 5.22.

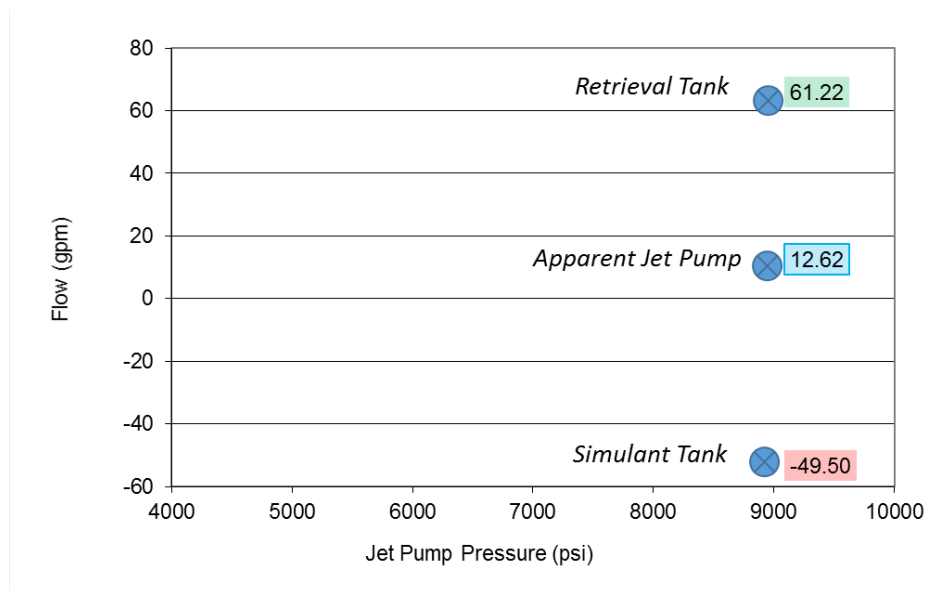


Figure 5.22. Jet Pump Lift—Simulant Submerged Suction

5.4.5 Vertical Testing Result Summary

The jet pump vertical testing demonstrated that the HWEE jet pump operating in its current configuration (0.031-inch diameter jets installed at 9,000 psi pump pressure) can transport simulant (at density 1.0777 g/cm^3) beyond 35 feet total vertical lift (39 feet actual lift) that included 6.5 feet of suction lift. The test setup did not allow evaluation of lift beyond the 39 feet of maximum lift demonstrated because test setup was configured to a set vertical height; however, it is likely that the maximum lift possible was beyond 39 feet. Water lift testing showed that 39 feet of lift could be achieved when the jet pump inlet pressure was reduced to 7,000 psi but then fell off rapidly at inlet pressures below 7,000 psi (5,000 and 6,000 psi tests). Operational testing of the jet pump in mixed flow (air/water) showed an apparent slight decrease in performance over fully submerged flooded suction flow, but some of these flow difference may have to do with fluid transport lag time as actual testing time was limited to available fluid volume in the simulant tank. A summary of the vertical test data is presented in Table 5.11 below.

The “apparent” jet pump flow rate is calculated using the weight change between the simulant tank and retrieval tank and assumes: 1) constant flow in the conveyance line and 2) the build-up of fluid in the transport line has reached steady-state conditions. Therefore, the jet pump “apparent” flow could be calculated to be negative, as is the case for water retrieval at 8000 psi. Because this is a nonphysical result, it indicates that flow had not reached steady-state conditions. Because the vertical lift test setup had a limited simulant and retrieval tank capacity, the test durations were short: usually less than 100 seconds. Longer test times would have allowed more data to be collected at steady-state conditions but would have required larger tanks to be used.

Table 5.11. Jet Pump Vertical Lift Test Summary

PNNL Data File	Collection Time (secs)	Media	Jet Pump Pressure (psi)	Simulant Tank Flow (gpm)	Retrieval Tank Flow (gpm)	Apparent Jet Pump Flow (gpm)
8	250	Air	9000	No Flow* (-0.01)	11.59	11.58
21	80	Air	8000	No Flow* (-0.02)	11.87	11.85
16	90	Air	7000	No Flow* (0.01)	11.24	11.25
11	100	Air/water	9000	-56.59	63.59	7
13	80	Simulant	9000	-49.5 **	61.22 **	11.72 **
10	100	Water	9000	-60.02	65.23	5.21
19	70	Water	8000	-41.76	30.4	-11.36
15	100	Water	7000	-17.64	29.13	11.49
18	100	Water	6000	10.41	0.03	10.44
17	60	Water	5000	8.95	0.06	9.01

* For air media, "No Flow" indicates all jet pump fluid is being motivated vertically upstream to the Retrieval Tank with no water drop out back into the Simulant Tank. Water drop would be indicated by a positive flow into the Simulant Tank.

** Density adjusted for slurry (approximately 1.0777 g/cm³ at ambient temperature).

The jet pump conveyance maximum transport and vertical lift capabilities beyond those tested are largely unknown. Discussions with the AquaDyne jet pump manufacturer engineering team revealed that past operational and test data collected on these pumps has been lost and new testing is not planned. In industrial mining applications where these jet pumps are used to move and lift mining slurries, the jet pumps are used in series (i.e., daisy chained) to get the needed lift, which may be hundreds of feet. In these applications, water usage is not a concern as it is in the HWEE application. Past testing with another jet pump (Butterworth Model 70-8500, which is no longer manufactured) indicated that vertical lifts above 70 feet are possible (Summers 1994) in a single lift, but that finding may be specific for that particular jet pump.

The current AquaDyne jet pump may have enhanced lift performance capabilities beyond those demonstrated in these tests as two parameter can be varied: jet pump nozzle size and jet pump inlet pressure. The effects of increasing either of these parameters are unknown, but it is hypothesized that increased nozzle size and increased pressure would enhance the jet pump performance. The current jet pump pressure is limited to a maximum working pressure of 15,000 psi, but other AquaDyne jet pumps can be operated as high as 40,000 psi per the manufacturer. The only method to determine additional jet pump operational parameters is by testing.

No problems were encountered during the jet pump vertical testing. Prior to testing, a 90° elbow installed at the jet pump pressure inlet leaked and was removed and hose was attached directly.

Data taken during retrieval testing were recorded and included all instrumentation associated with this testing (see Appendix A). Only the simulant tank retrieval testing was videotaped. Additional details of the jet pump vertical lift test record can be found in Appendix D.

6.0 Summary of Major Test Results

6.1 Retrieval Performance Summary

The calculated average retrieval rates and slurry dilution ratios are presented in Table 6.1. The increased usage of tilt retrieval during the retrieval of the top step of the topographical reduced the retrieval rate and the dilution ratio during the topographical test.

Table 6.1. HWEE Phase II Average Retrieval Rates and Dilution Ratios

Test	Retrieval Rate (gpm)	Dilution Ratio
Layered	7.6	0.24
Topographical	3.1	0.11

The HWEE Phase II tests demonstrated a retrieval rate of 7.6 gpm during the layered simulant retrieval test. From Berglin et al. (2017), the HWEE Phase I results for the similar Kaolin simulant during active retrieval were a retrieval rate of 4.9 gpm and dilution ratio of 0.3. The weakest material used for the MARS-V system testing, likely an easier to erode simulant than the higher shear strength Kaolin employed herein (see Berglin et al. 2017), had a retrieval rate of 4.3 gpm and dilution ratio of 0.05.

6.2 Retrieval Test – Layered Waste

The HWEE successfully retrieved the layered simulant without the need to modify the HWEE operating parameters. The retrieval rate calculated for Phase II was significantly higher than Phase I results (7.6 gpm versus 4.9 gpm), and the dilution ratio was slightly lower (0.24 versus 0.3). As layers of simulant were retrieved, higher strength material at a raised elevation would slump slightly into the lower strength material, but the effect was not significant and did not impact the performance of the HWEE.

6.3 Retrieval Test – Waste Topography

The HWEE successfully retrieved the simulant with topographical features using the predetermined mining strategy. The water was well contained during the feature removal, but it was noted that the skirt was dragged across the simulant bed, which created a small pathway for liquid to drain into the lower level of simulant. The retrieval rate calculated for Phase II during the topographical retrieval test was somewhat lower than Phase I results (3.1 gpm versus 4.9 gpm), and the dilution ratio was significantly lower (0.11 versus 0.3). It was noted that when performing retrieval with a tilted HWEE, the suction inlet was inclined with respect to the level of the simulant. This resulted in a loss of suction. The overall complexity of the test was significant, due to the need to operate the tilt stage and cleaning valves at redefined points. This test required significant concentration of the test operator, and points to the need to automate the HWEE functions, such as screen cleaning.

6.4 Retrieval Operational Summary

The capability to tilt the HWEE enhance tank wall cleaning significantly. During Phase I testing a ledge was left behind and mining proceeded downward. During Phase II, the simulant left along the edge of the tank could be sluiced and mobilized. However, the retrieval rate that was calculated with the HWEE tilted was significantly lower.

Deeper simulant depth caused interference between the HWEE support bracket and the simulant. Phase I tests used a simulant depth of 6 inches, whereas the Phase II tests used a simulant depth of 14 inches. The increase in depth caused an interference between the HWEE mounting bracket which required manual excavation. This effect will need to be considered with respect to the Extended Reach Sluicing System (ERSS) to insure the HWEE creates clearance.

The fast acting pneumatic control valves were essential to implementing the periodic flushing operations. They were also useful for turning off the HWEE during tilting or repositioning operations.

For the layered retrieval test, force/torque data during retrieval of the top (3,375 Pa), middle (284 Pa), and bottom (3,375 Pa) layers were analyzed. Forces and torques were higher during retrieval of the top layer due to the higher strength of the simulant material in this layer. Forces and torque were generally higher during retrieval of the bottom layer and during the final suction pass due to intermittent contact with the tank bottom. Note that the gantry used for the test was quite stiff, and interference between the HWEE and the tank bottom resulted in high forces. If a more compliant deployment platform is used to deploy the HWEE, then these tank contact forces will be lower. During the tilt-clean pass, the goal was to clear the material near the tank wall with the waterjets. The reaction forces during the tilt cleaning pass were generally low, but the torque along the z-axis increased due to the resistance of the retrieval hose.

For the topographical retrieval test, data collected during five passes were analyzed to envelop a range of test conditions. The reaction forces during the tilt retrieval pass were somewhat higher because the skirt was dragged through the sludge in this orientation. When the HWEE is tilted, the lower edge of the skirt is presented several inches below the level of the suction port. Dragging the skirt through the sludge generated moderately high forces.

6.5 Jet Pump Vertical Lift Tests

The jet pump vertical testing demonstrated that the HWEE jet pump operating in its current configuration (0.031-inch diameter jets installed at 9,000 psi pump pressure) can transport simulant (at density 1.0777 g/cm³) at least 39 feet including 6.5 feet of suction lift. The test setup did not allow evaluation of lift beyond the 39 feet because test setup was configured to a set vertical height; however, it is likely that the maximum lift possible was beyond 39 feet. Water lift testing showed that 39 feet of lift could be achieved when the jet pump inlet pressure was reduced to 7,000 psi. These tests demonstrated the ability of the system to retrieve material from a Hanford 500,000-gallon single-shell tank (35 ft); further testing and potentially system enhancement would be needed to demonstrate lifting material the required 60 feet for a 1,000,000-gallon tank.

6.6 Lessons Learned

The following lessons can be applied to future similar testing campaigns.

- The new simulant tank limited downward vertical motions of the HWEE by physical interference and required the top 11 inches of the tank to be removed during retrieval testing.
- The new HWEE tilt was somewhat cumbersome inside the simulant tank; space was very limited and tilting the HWEE required extra gantry motions to avoid colliding with the tank or tank simulant. For future deployment, articulating the motion between the tilt and other stages would be beneficial.
- The limitations of gantry motions to a serpentine path only required significant extra non-retrieval motions of gantry to operate during testing.
- Some minor high-pressure leaks that developed during pre-test and test operations required testing to be stopped to fix leakage. Leakage that developed in one of the HWEE remote activated valves during testing resulted in the HWEE jet pump only being controlled by the NLB foot pedal for the second retrieval test sequence (i.e., topographic retrieval).
- Partway through the first retrieval testing (i.e., layer retrieval), the HWEE tilt motion linear position sensor bracket broke due to impact with simulant by HWEE over-positioning into movement into an unmined volume and resulted in loss of tilt position recording; this was repaired before and operable through the second retrieval test sequence (i.e., topographic retrieval).
- Measurement of the fluid levels in the retrieval tank would have been beneficial if a more applicable level measurement device had been available for use, such as a Drexelbrook® Guided Wave Radar device, that works well with turbulent surface conditions. The device used may have also benefitted from a tank baffle to reduce the sloshing and turbulent surface conditions during this retrieval testing.
- A diagnostic test with a shorter conveyance hose between the HWEE and jet pump produced a significant improvement in pumping rate. For fielded retrieval systems, efforts should be made to minimize the hose/pipe length and number of elbows between the HWEE and the jet pump.
- Vertical lift testing, if conducted in the future, can explore jet pump optimization. Parameters of the jet pump that can be varied include the jet pump pressure (up to 40,000 psi) and the length of the suction lift. It is also recommended that longer-term pumping be done to assess transient conditions like fluid buildup in the conveyance line. In addition, multiple jet pumps can be used to achieve very high lift capabilities.

6.7 Recommended for Future Work

Future phases of work will demonstrate full-scale integrated Alternate Retrieval Technology system effectiveness in a cold simulated waste environment. Integration of the jet pump and conveyance hoses will need to occur, with special consideration of hose bending radius, reaction forces, and pressure drops. The reliability of the HWEE and associated components will need to be determined in the presence of tank environments (radiation, chemical, heat). Future work will identify and develop systems to convey mobilized waste to the full height of a Hanford SST or DST waste tank plus margin using a single jet pump with modified operating parameters and/or multiple jet pumps.

7.0 References

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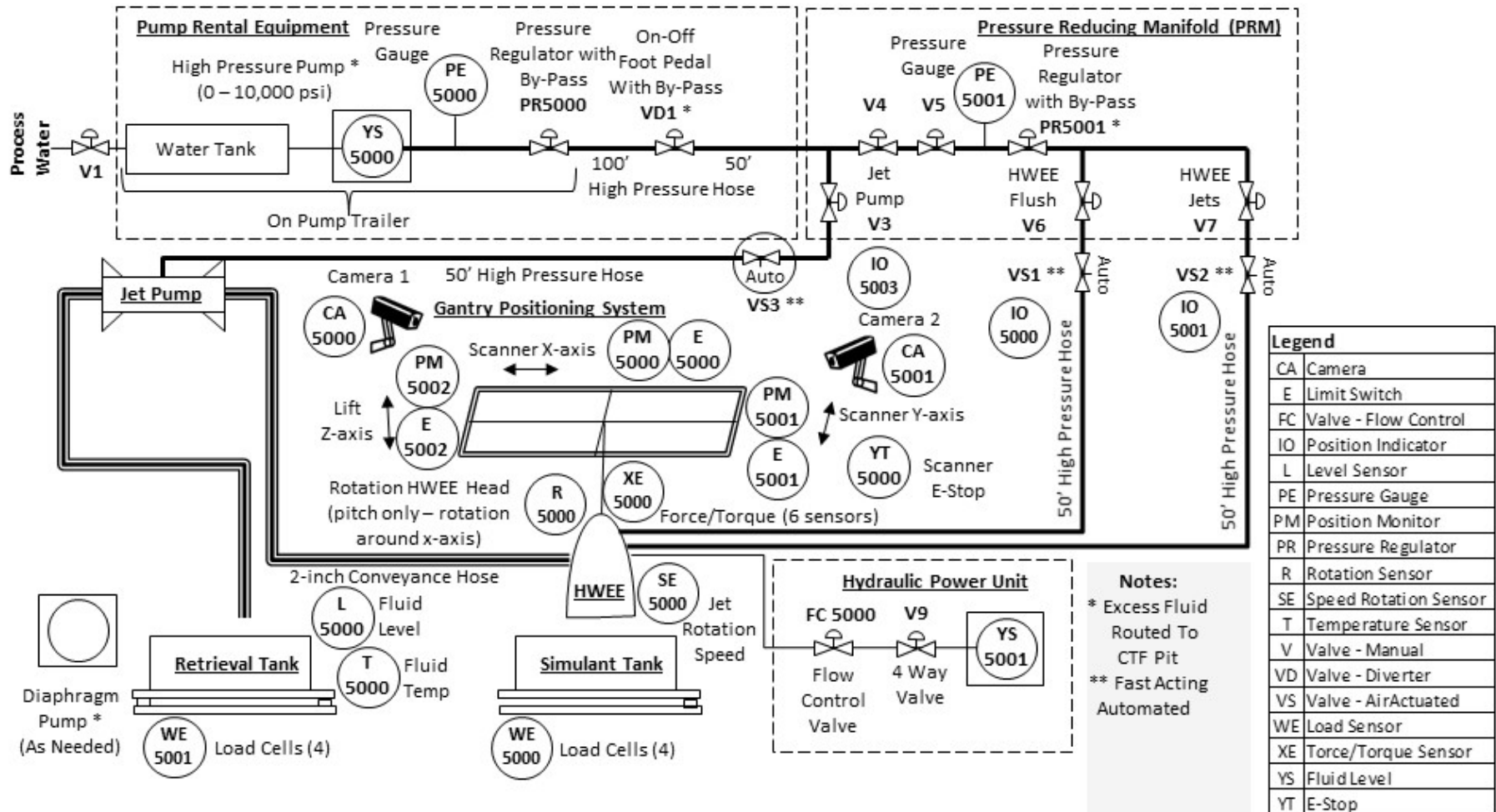
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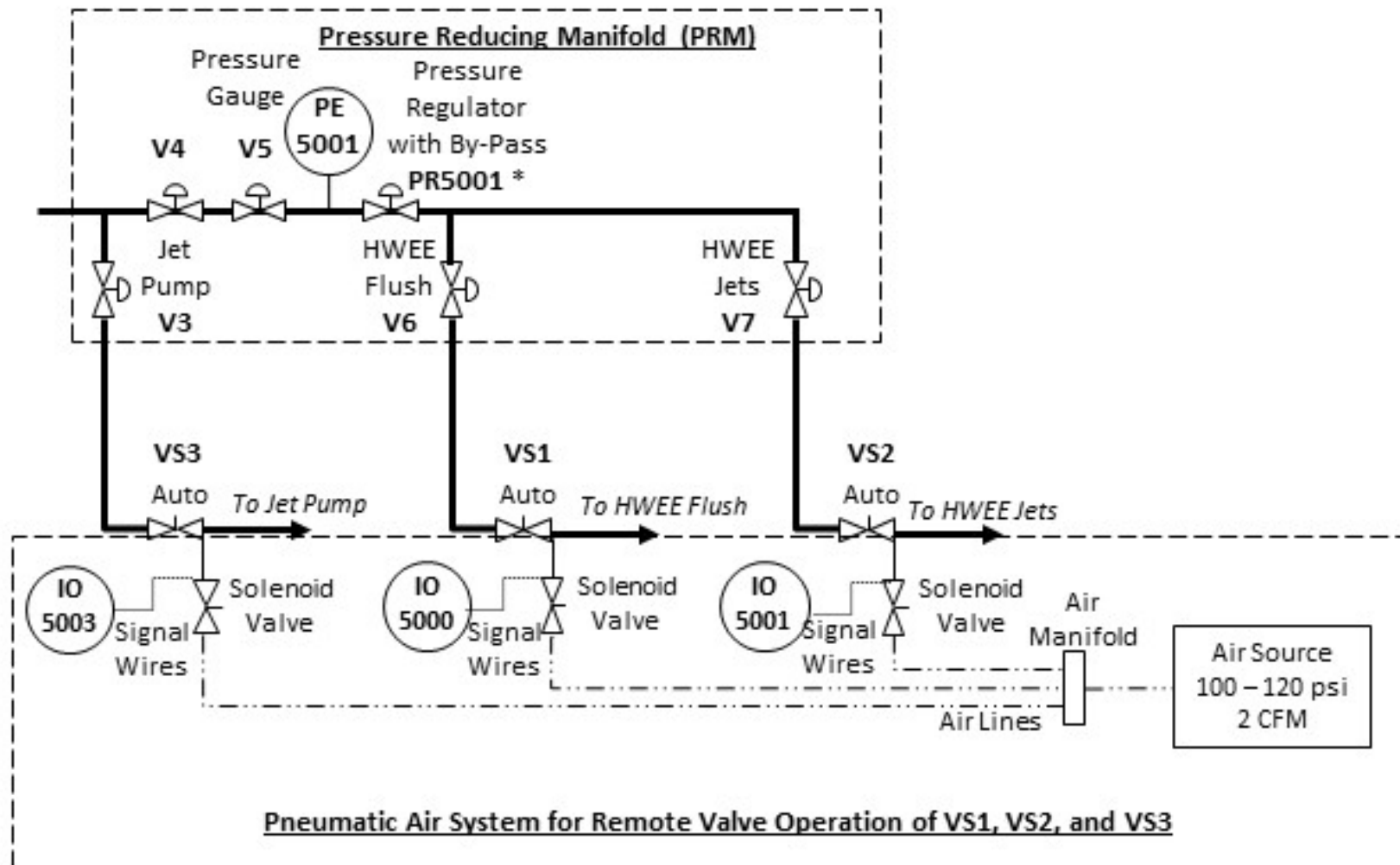
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Appendix A: Piping and Instrument Diagrams

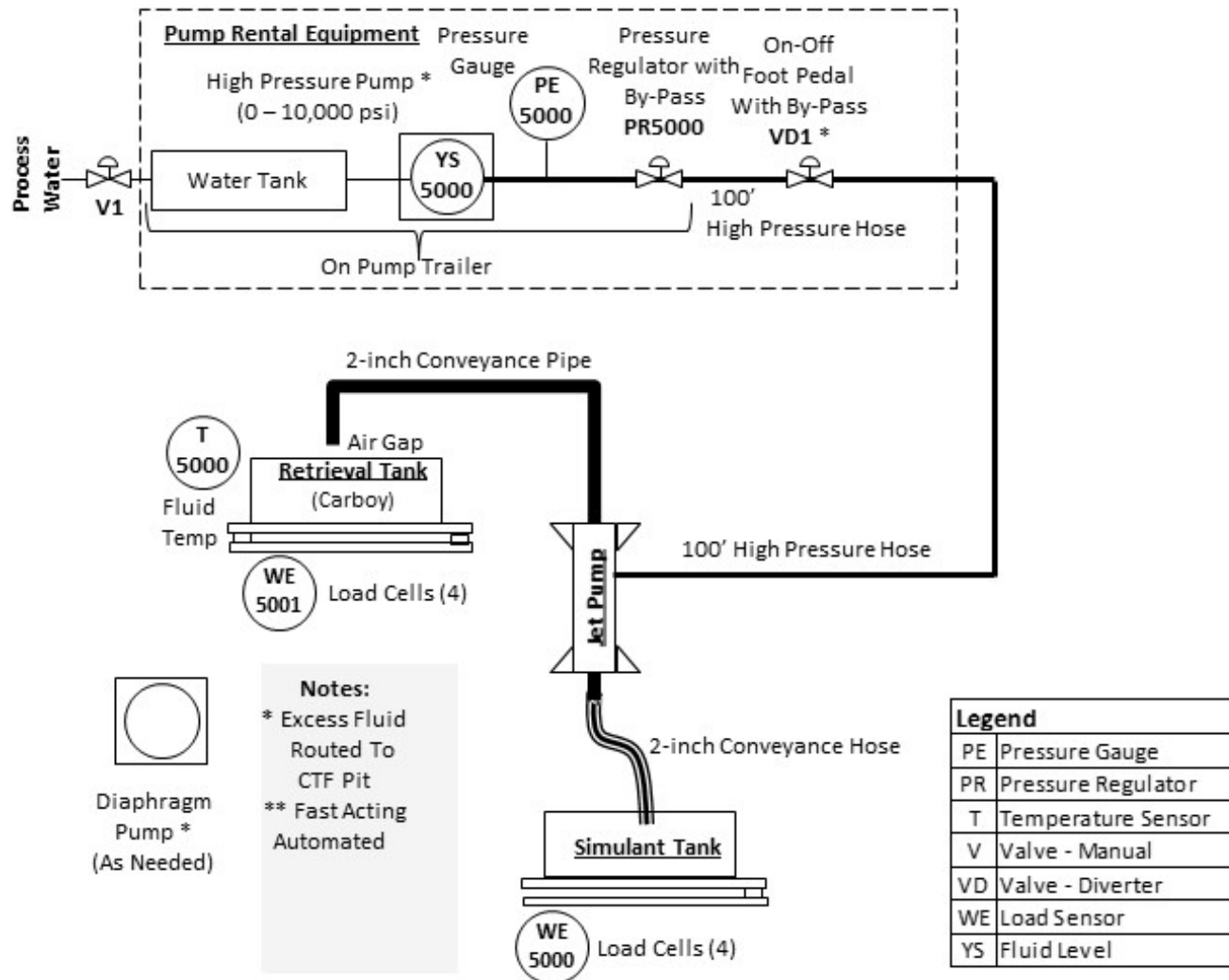
A.1 HWEE Phase II – Retrieval Test Schematic - General



A.2 HWEE Phase II – Retrieval Test Schematic – Remote Pneumatic Valve Operation



A.3 HWEE HWEE Phase II – Jet Pump Vertical Lift Test Schematic - General



Appendix B: Retrieval Layered Test Summaries

Layered Simulant Mining Paths

Thickness/Type Dark = Hard Light = Soft	Pass	Depth, inch	Measuring Tape (in)	Reduce Traverse During Retrieval Pass	Tilt Clean Pass After Retrieval Pass	Stop Test After Step	Pump out Retrieval Tank after Step
	1	¼ inch above	61.25				
1	2	-1	60				
2	3	-2	59		yes	yes, remove tank top	
3							
4	4	-4	57				
5							
6	5	-6	55		yes	yes	yes
7							
8	6	-8	53	Yes			
9							
10	7	-10	51	Yes			
11							
12	8	-12	49		yes	yes	yes
13							
14	9	-13.5	47.5	*			

* Simulant was removed under HWEE bracket so that traverse reduction was not necessary

HWEE Phase II Retrieval Test - Layered Simulant - Video Record Summary - May 3, 2018**Cam1 - Layered Test - Summary of Camera Videos**

	Date	Day	Start Time	Stop Time	EIapse Time	Comments
00000000363000000.mp4	5/3/2018	Thu	15:16:35	15:44:49	0:28:14	
00000000365000000.mp4	5/3/2018	Thu	15:44:50	16:13:06	0:28:16	
00000000367000000.mp4	5/3/2018	Thu	16:13:07	16:41:23	0:28:16	
00000000369000000.mp4	5/3/2018	Thu	16:41:24	17:09:41	0:28:17	
00000000371000000.mp4	5/3/2018	Thu	17:09:42	17:37:59	0:28:17	

NOTE: Yellow Highlighted Sections Below Are Where Actual HWEE Retrieval Operations Are Being Performed**Retrieval Operations Include Mining, Flushing, Wall Cleaning, and Final Suction Clean Up at End****00000000363000000.mp4**

Setting Initial Pressure - In Capture Tank

Setting Pressure in Capture Tank

Voice out of Capture Tank

5/3/2018	Thu	15:16:35	15:44:49	0:28:14
		15:16:35	15:21:33	0:04:58
		15:20:40	15:21:00	0:00:20
		15:21:14	15:21:33	0:00:19

Pass 1

Moving to Vertical Position Depth

Turn on jet pump

Mining + X-axis .eg 1

Flush + Y-axis .eg 1

Mining - X-axis .eg 2

Flush + Y-axis .eg 2

Mining + X-axis .eg 3

Flush + Y-axis .eg 3

Mining - X-axis .eg 4

Flush + Y-axis .eg 4

Mining + X-axis .eg 5

Flush + Y-axis .eg 5

Mining - X-axis .eg 6

Flush + Y-axis .eg 6

Move back to home position

5/3/2018	Thu	15:22:35	15:22:52	0:00:17
		15:24:07	15:24:14	0:00:07
		15:24:14	15:24:24	0:00:10
		15:24:24	15:24:32	0:00:08
		15:24:32	15:24:45	0:00:13
		15:24:45	15:24:49	0:00:04
		15:24:49	15:25:01	0:00:12
		15:25:01	15:25:05	0:00:04
		15:25:05	15:25:17	0:00:12
		15:25:17	15:25:21	0:00:04
		15:25:21	15:25:32	0:00:11
		15:25:32	15:25:37	0:00:05
		15:25:37	15:25:48	0:00:11
		15:25:48	15:25:52	0:00:04
		15:25:52	15:25:59	0:00:07

Pass 2

Moving to Vertical Position Depth

Getting ready to start horizontal run

Mining + X-axis .eg 1

Flush + Y-axis .eg 1

Mining - X-axis .eg 2

Flush + Y-axis .eg 2

Mining + X-axis .eg 3

Flush + Y-axis .eg 3

Mining - X-axis .eg 4

Flush + Y-axis .eg 4

Mining + X-axis .eg 5

Flush + Y-axis .eg 5

Mining - X-axis .eg 6

Flush at end of run

Move back to home position

5/3/2018	Thu	15:26:07	15:26:45	0:00:38
		15:26:45	15:26:58	0:00:13
		15:26:58	15:27:08	0:00:10
		15:27:08	15:27:21	0:00:13
		15:27:21	15:27:33	0:00:12
		15:27:33	15:27:40	0:00:07
		15:27:40	15:27:51	0:00:11
		15:27:51	15:27:59	0:00:08
		15:27:59	15:28:10	0:00:11
		15:28:10	15:28:14	0:00:04
		15:28:14	15:28:26	0:00:12
		15:28:26	15:28:31	0:00:05
		15:28:31	15:28:44	0:00:13
		15:28:44	15:28:46	0:00:02
		15:28:46	15:28:55	0:00:09

Pass 3

Moving to Vertical Position Depth

Getting ready to start horizontal run

Mining + X-axis .eg 1

Flush + Y-axis .eg 1

Mining - X-axis .eg 2

Flush + Y-axis .eg 2

Mining + X-axis .eg 3

Flush + Y-axis .eg 3

Mining - X-axis .eg 4

Flush + Y-axis .eg 4

Mining + X-axis .eg 5

Flush + Y-axis .eg 5

Mining - X-axis .eg 6

Flush at end of run

Move back to home position

5/3/2018	Thu	15:29:08	15:29:24	0:00:16
		15:29:24	15:30:02	0:00:38
		15:30:02	15:30:12	0:00:10
		15:30:12	15:30:16	0:00:04
		15:30:16	15:30:29	0:00:13
		15:30:29	15:30:33	0:00:04
		15:30:33	15:30:44	0:00:11
		15:30:44	15:30:48	0:00:04
		15:30:48	15:31:00	0:00:12
		15:31:00	15:31:04	0:00:04
		15:31:04	15:31:16	0:00:12
		15:31:16	15:31:19	0:00:03
		15:31:19	15:31:32	0:00:13
		15:31:32	15:31:37	0:00:05
		15:31:37	15:31:43	0:00:06

Pass 3 - Wall Cleaning After Mining

Moving to Vertical Position Depth

Getting ready to start horizontal run

Move to + X-axis Position for Tilt - No Mining

Move to + Y-axis Position for Tilt

Tilt head for wall clean pass - No Mining

Getting ready for wall clean pass

Clean wall - X-axis - One Pass Only

Flush after pass

Tilt head back to horizontal position

move back to home position

Getting ready for opposite wall clean pass

Move in + X-axis Leg 1 - No mining

Move in + Y-axis Leg 1 - No mining

5/3/2018	Thu	15:31:46	15:31:55	0:00:09
		15:31:55	15:32:06	0:00:11
		15:32:06	15:32:17	0:00:11
		15:32:17	15:32:19	0:00:02
		15:32:19	15:32:26	0:00:07
		15:32:26	15:32:40	0:00:14
		15:32:40	15:32:53	0:00:13
		15:32:53	15:32:58	0:00:05
		15:32:58	15:33:09	0:00:11
		15:33:09	15:33:34	0:00:25
		15:33:34	15:33:43	0:00:09
		15:33:43	15:33:54	0:00:11
		15:33:54	15:33:59	0:00:05

HWEE Phase II Retrieval Test - Layered Simulant - Video Record Summary - May 3, 2018

	Date	Day	Start Time	Stop Time	Elapsed Time	Comments
Tilt head for opposite wall cleaning			15:33:59	15:34:07	0:00:08	
Clean wall - X-axis, One Pass Only			15:34:07	15:34:29	0:00:22	
Tilt head back to horizontal position			15:34:29	15:34:43	0:00:14	
Return to home position			15:34:43	15:35:15	0:00:32	
In hold position - personnel observe tank			15:35:15	15:44:49	0:09:34	

00000000365000000.mp4

	5/3/2018	Thu	15:44:50	16:13:06	0:28:16	
In hold position - personnel observe tank			15:44:50	16:13:06	0:28:16	
Removing water from Capture tank			15:47:17	15:48:18	0:01:01	
Looking at cutting down tank top for clearance			15:51:08	15:51:22	0:00:14	
Marking simulant tank for cutting			15:51:22	16:02:02	0:10:40	
Putting in plastic to capture particles during tank cutting			16:02:02	16:04:38	0:02:36	
Cutting simulant tank top off 11 inches			16:08:25	16:12:59	0:04:34	
Removing cut simulant tank top			16:12:59	16:13:06	0:00:07	

00000000367000000.mp4

	5/3/2018	Thu	16:13:07	16:41:23	0:28:16	
In hold position			16:13:07	16:15:37	0:02:30	
Removing cut simulant tank top			16:13:07	16:13:27	0:00:20	
Removing plastic after cut			16:14:01	16:14:43	0:00:42	
Looking and probing simulant condition			16:15:21	16:15:37	0:00:16	
Moving to Capture Tank to set pressures			16:20:25	16:25:49	0:05:24	
Setting pressure in Capture Tank			16:25:49	16:26:40	0:00:51	
Moving HWEE out of Capture Tank to home position			16:27:09	16:27:54	0:00:45	
Moving into vertical position			16:28:17	16:28:48	0:00:31	

Pass 4

	5/3/2018	Thu				
Moving to Vertical Position Depth			16:28:48	16:29:29	0:00:41	
Turn on jet pump & HWEE			16:29:29	16:29:34	0:00:05	
Mining + X-axis .eg 1			16:29:34	16:29:44	0:00:10	
Flush + Y-axis .eg 1			16:29:44	16:29:49	0:00:05	
Mining - X-axis .eg 2			16:29:49	16:30:01	0:00:12	
Flush + Y-axis .eg 2			16:30:01	16:30:06	0:00:05	
Mining + X-axis .eg 3			16:30:06	16:30:19	0:00:13	
Flush + Y-axis .eg 3			16:30:19	16:30:23	0:00:04	
Mining - X-axis .eg 4			16:30:23	16:30:39	0:00:16	
Flush + Y-axis .eg 4			16:30:39	16:30:43	0:00:04	
Mining + X-axis .eg 5			16:30:43	16:30:56	0:00:13	
Flush + Y-axis .eg 5			16:30:56	16:31:05	0:00:09	
Mining - X-axis .eg 5			16:31:05	16:31:12	0:00:07	
Flush at end of run			16:31:12	16:31:17	0:00:05	
Move back to home position			16:31:17	16:31:24	0:00:07	

Pass 5

	5/3/2018	Thu				
Moving to Vertical Position Depth			16:31:24	16:32:41	0:01:17	
Getting ready to start horizontal run			16:31:24	16:32:41	0:01:17	
Mining + X-axis .eg 1			16:32:41	16:32:50	0:00:09	
Flush + Y-axis .eg 1			16:32:50	16:32:56	0:00:06	
Mining - X-axis .eg 2			16:32:56	16:33:09	0:00:13	
Flush + Y-axis .eg 2			16:33:09	16:33:13	0:00:04	
Mining + X-axis .eg 3			16:33:13	16:33:25	0:00:12	
Flush + Y-axis .eg 3			16:33:25	16:33:28	0:00:03	
Mining - X-axis .eg 4			16:33:28	16:33:41	0:00:13	
Flush + Y-axis .eg 4			16:33:41	16:33:44	0:00:03	
Mining + X-axis .eg 5			16:33:44	16:33:56	0:00:12	
Flush + Y-axis .eg 5			16:33:56	16:34:00	0:00:04	
Mining - X-axis .eg 5			16:34:00	16:34:13	0:00:13	
Flush at end of run			16:34:13	16:34:17	0:00:04	
Move back to home position			16:34:17	16:34:25	0:00:08	

Pass 5 - Wall Cleaning After Mining

	5/3/2018	Thu				
Moving to Vertical Position Depth			16:34:25	16:34:32	0:00:07	
Getting ready to start horizontal run			16:34:32	16:34:51	0:00:19	
Move in + X-axis Position for Tilt - No Mining			16:34:51	16:35:03	0:00:12	
Move in + Y-axis Position for Tilt - No Mining			16:35:03	16:35:04	0:00:01	
Tilt head for wall clean pass			16:35:04	16:35:14	0:00:10	
Getting ready for opposite wall clean pass			16:35:14	16:35:27	0:00:13	
Clean wall - X-axis, One Pass Only			16:35:27	16:35:41	0:00:14	
Flush after pass			16:35:41	16:35:44	0:00:03	
Tilt head back to horizontal position			16:35:44	16:35:54	0:00:10	
move back to home position			16:35:54	16:36:23	0:00:29	
Getting ready for opposite wall clean pass			16:36:23	16:36:34	0:00:11	
Move in + X-axis .eg 1 - No mining			16:36:34	16:36:44	0:00:10	
Move in + Y-axis .eg 1 - No mining			16:36:44	16:36:49	0:00:05	
Tilt head for opposite wall cleaning			16:36:49	16:36:59	0:00:10	
Clean wall - X-axis, One Pass Only			16:36:59	16:37:23	0:00:24	
Move in - Y-axis then + Y-axis			16:37:23	16:37:53	0:00:30	
Move for tilt			16:37:53	16:37:55	0:00:02	
Tilt head back to horizontal position			16:37:55	16:38:02	0:00:07	

HWEE Phase II Retrieval Test - Layered Simulant - Video Record Summary - May 3, 2018

	Date	Day	Start Time	Stop Time	Elapsed Time	Comments
Return to home position			16:38:02	16:38:04	0:00:02	
In hold position - personnel observe tank			16:38:04	16:38:46	0:00:42	

Pass 6

	5/3/2018	Thu			
Moving to Vertical Position Depth			16:38:46	16:38:51	0:00:05
Getting ready to start horizontal run			16:38:51	16:39:25	0:00:34
Mining + X-axis .seg 1			16:39:25	16:39:31	0:00:06
Flush + Y-axis .seg 1			16:39:31	16:39:37	0:00:06
Mining - X-axis .seg 2			16:39:37	16:39:47	0:00:10
Flush + Y-axis .seg 2			16:39:47	16:39:53	0:00:06
Mining + X-axis .seg 3			16:39:53	16:40:04	0:00:11
Flush + Y-axis .seg 3			16:40:04	16:40:08	0:00:04
Mining - X-axis .seg 4			16:40:08	16:40:16	0:00:08
Flush + Y-axis .seg 4			16:40:16	16:40:22	0:00:06
Mining + X-axis .seg 5			16:40:22	16:40:31	0:00:09
Flush + Y-axis .seg 5			16:40:31	16:40:35	0:00:04
Mining - X-axis .seg 6			16:40:35	16:40:43	0:00:08
Flush at end of run			16:40:43	16:40:46	0:00:03
Move back to home position			16:40:46	16:40:56	0:00:10
Return to home position			16:40:56	16:41:02	0:00:06
In hold position			16:41:02	16:41:23	0:00:21

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Pass 7

	5/3/2018	Thu			
Moving to Vertical Position Depth			16:41:24	16:41:50	0:00:26
Getting ready to start horizontal run			16:41:50	16:41:50	0:00:00
Mining + X-axis .seg 1			16:41:50	16:41:56	0:00:06
Flush + Y-axis .seg 1			16:41:56	16:42:02	0:00:06
Mining - X-axis .seg 2			16:42:02	16:42:11	0:00:09
Flush + Y-axis .seg 2			16:42:11	16:42:14	0:00:03
Mining + X-axis .seg 3			16:42:14	16:42:22	0:00:08
Flush + Y-axis .seg 3			16:42:22	16:42:27	0:00:05
Mining - X-axis .seg 4			16:42:27	16:42:35	0:00:08
Flush + Y-axis .seg 4			16:42:35	16:42:39	0:00:04
Mining + X-axis .seg 5			16:42:39	16:42:48	0:00:09
Flush + Y-axis .seg 5			16:42:48	16:42:52	0:00:04
Mining - X-axis .seg 6			16:42:52	16:43:01	0:00:09
Flush at end of run			16:43:01	16:43:03	0:00:02
Move back to home position			16:43:03	16:43:10	0:00:07

Pass 8

	5/3/2018	Thu			
Moving to Vertical Position Depth			16:43:22	16:43:29	0:00:07
Getting ready to start horizontal run			16:43:29	16:43:47	0:00:18
Mining + X-axis .seg 1			16:43:47	16:44:04	0:00:17
Flush + Y-axis .seg 1			16:44:04	16:44:07	0:00:03
Mining - X-axis .seg 2			16:44:07	16:44:17	0:00:10
Flush + Y-axis .seg 2			16:44:17	16:44:21	0:00:04
Mining + X-axis .seg 3			16:44:21	16:44:29	0:00:08
Flush + Y-axis .seg 3			16:44:29	16:44:34	0:00:05
Mining - X-axis .seg 4			16:44:34	16:44:42	0:00:08
Flush + Y-axis .seg 4			16:44:42	16:44:46	0:00:04
Mining + X-axis .seg 5			16:44:46	16:44:55	0:00:09
Flush + Y-axis .seg 5			16:44:55	16:44:58	0:00:03
Mining - X-axis .seg 6			16:44:58	16:45:07	0:00:09
Flush at end of run			16:45:07	16:45:12	0:00:05
Move back to home position			16:45:12	16:45:19	0:00:07

Pass 8 - Wall Cleaning After Mining

	5/3/2018	Thu			
Moving to Vertical Position Depth			16:45:19	16:46:27	0:01:08
Getting ready to start horizontal run			16:45:19	16:46:27	0:01:08
Move to + X-axis Position for Tilt - No Mining			16:46:27	16:46:34	0:00:07
Move to + Y-axis Position for Tilt - No Mining			16:46:34	16:46:36	0:00:02
Tilt head for wall clean pass			16:46:36	16:46:43	0:00:07
Getting ready for wall clean pass			16:46:43	16:46:46	0:00:03
Clean wall - X-axis One Pass Only			16:46:46	16:46:56	0:00:10
Flush after pass			16:46:56	16:47:00	0:00:04
Tilt head back to horizontal position			16:47:00	16:47:10	0:00:10
move back to home position			16:47:10	16:47:40	0:00:30
Getting ready for opposite wall clean pass			16:47:40	16:48:27	0:00:47
Move in + X-axis Leg 1 - No mining			16:48:27	16:48:33	0:00:06
Move in + Y-axis Leg 1 - No mining			16:48:33	16:48:38	0:00:05
Tilt head for opposite wall cleaning			16:48:38	16:48:48	0:00:10
Clean wall - X-axis One Pass Only			16:48:48	16:49:08	0:00:20
Tilt head back to horizontal position			16:49:08	16:49:17	0:00:09
Move towards tank center; X & Y axis move			16:49:17	16:49:39	0:00:22
Remove standing water in simulant trough area			16:49:39	16:50:29	0:00:50
In hold position after suction			16:50:29	16:51:59	0:01:30
Move HWEE vertically up to highest position			16:51:59	16:52:59	0:01:00

HWEE Phase II Retrieval Test - Layered Simulant - Video Record Summary - May 3, 2018

Observation of simulant condition and simulant shelf	Date	Day	Start Time	Stop Time	Elapsed Time	Comments
Prepare for removal of simulant shelf in simulant tank			16:52:59	16:59:01	0:06:02	
Remove simulant manually from simulant tank - Load 1			16:59:01	17:00:38	0:01:37	
Remove simulant manually from simulant tank - Load 2			17:00:38	17:01:20	0:00:42	
Hold prior to continue mining			17:01:20	17:02:55	0:01:35	
Ted Wooley takes some pictures of tank after simulant removal			17:02:55	17:06:15	0:03:20	
Move HWEE vertically down			17:06:15	17:06:19	0:00:04	
On hold			17:06:19	17:07:13	0:00:54	
			17:07:13	17:09:41	0:02:28	

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Date	Day	Start Time	Stop Time	Elapsed Time	Comments
5/3/2018	Thu	17:09:42	17:09:42	0:00:00	
		17:09:42	17:10:12	0:00:30	
		17:10:12	17:18:53	0:08:41	
		17:18:53	17:19:40	0:00:47	
		17:19:40	17:21:15	0:01:35	

Pass 9 (Original Run - Truncated and Rerun)

Date	Day	Start Time	Stop Time	Elapsed Time	Comments
5/3/2018	Thu	17:21:15	17:21:58	0:00:43	Moving to Vertical Postion Depth
		17:21:58	17:22:16	0:00:18	Getting ready to start horizontal run
		17:22:16	17:22:26	0:00:04	Small move prior to start
		17:22:26	17:22:30	0:00:10	Start HWEE
		17:22:30	17:23:23	0:00:53	Mining + X-axis .eg 1
		17:23:23	17:23:23	0:00:00	Stopped at end of run in heavy simulant sludge (tank moved)
		17:23:23	17:23:25	0:00:02	Flush + Y-axis .eg 1
		17:23:25	17:23:37	0:00:12	Mining + X-axis .eg 2
		17:23:37	17:23:41	0:00:04	Flush + Y-axis .eg 2
		17:23:41	17:23:54	0:00:13	Mining + X-axis .eg 3
		17:23:54	17:23:58	0:00:04	Flush + Y-axis .eg 3
		17:23:58	17:24:13	0:00:15	Mining + X-axis .eg 4
		17:24:13	17:24:17	0:00:04	Flush + Y-axis .eg 4
		17:24:17	17:24:23	0:00:06	Mining + X-axis .eg 5 (Manually stopped about 1/4 of the way)
		17:24:23	17:25:34	0:01:11	Return to home position to rerun Pass 9

Pass 9 (Rerun)

Date	Day	Start Time	Stop Time	Elapsed Time	Comments
5/3/2018	Thu	17:25:34	17:26:14	0:00:40	Getting ready to start horizontal run
		17:26:14	17:26:15	0:00:01	Moving into position
		17:26:15	17:26:36	0:00:21	Mining + X-axis .eg 1
		17:26:36	17:26:43	0:00:07	Flush + Y-axis .eg 1
		17:26:43	17:26:59	0:00:16	Mining + X-axis .eg 2
		17:26:59	17:27:07	0:00:08	Flush + Y-axis .eg 2
		17:27:07	17:27:19	0:00:12	Mining + X-axis .eg 3
		17:27:19	17:27:23	0:00:04	Flush + Y-axis .eg 3
		17:27:23	17:27:35	0:00:12	Mining + X-axis .eg 4
		17:27:35	17:27:39	0:00:04	Flush + Y-axis .eg 4
		17:27:39	17:27:51	0:00:12	Mining + X-axis .eg 5
		17:27:51	17:27:56	0:00:05	Flush + Y-axis .eg 5
		17:27:56	17:28:09	0:00:13	Mining + X-axis .eg 6
		17:28:09	17:28:12	0:00:03	Flush at end of run
		17:28:12	17:28:19	0:00:07	Move back to home position

Pass 9 - Wall Cleaning After Mining

Date	Day	Start Time	Stop Time	Elapsed Time	Comments
5/3/2018	Thu	17:28:19	17:29:17	0:00:58	Getting ready to start horizontal run
		17:29:17	17:29:28	0:00:11	Move to + X-axis position for Tilt - No Mining
		17:29:28	17:29:30	0:00:02	Move to + Y-axis position for Tilt
		17:29:30	17:29:36	0:00:06	Tilt head for wall clean pass - No Mining
		17:29:36	17:29:59	0:00:23	Clean well - X-axis- One Pass Only
		17:29:59	17:30:01	0:00:02	Flush after pass
		17:30:01	17:30:14	0:00:13	Tilt head back to horizontal position
		17:30:14	17:30:41	0:00:27	move back to home position
		17:30:41	17:31:05	0:00:24	Getting ready for opposite wall clean pass
		17:31:05	17:31:16	0:00:11	Move in + X-axis Leg 1 - No mining
		17:31:16	17:31:21	0:00:05	Move in + Y-axis Leg 1 - No mining
		17:31:21	17:31:27	0:00:06	Tilt head for opposite wall cleaning
		17:31:27	17:31:50	0:00:23	Clean well - X-axis- One Pass Only
		17:31:50	17:32:08	0:00:18	Tilt head back to horizontal position
		17:32:08	17:32:52	0:00:44	Return to home position
					In hold position

Pass 9 (Suction Clean - No Flushing Over Entire Run)

Date	Day	Start Time	Stop Time	Elapsed Time	Comments
5/3/2018	Thu	17:32:52	17:32:52	0:00:00	Getting ready to start horizontal run
		17:32:52	17:33:47	0:00:55	Moving into position
		17:33:47	17:33:57	0:00:10	Suction clean + X-axis Leg 1
		17:33:57	17:34:01	0:00:04	No Flush + Y-axis Leg 1
		17:34:01	17:34:13	0:00:12	Suction clean + X-axis Leg 2
		17:34:13	17:34:16	0:00:03	No Flush + Y-axis Leg 2
		17:34:16	17:34:29	0:00:13	Suction clean + X-axis Leg 3
		17:34:29	17:34:35	0:00:06	No Flush + Y-axis Leg 3
		17:34:35	17:34:50	0:00:15	Suction clean + X-axis Leg 4
		17:34:50	17:34:53	0:00:03	No Flush + Y-axis Leg 4
		17:34:53	17:35:04	0:00:11	Suction clean + X-axis Leg 5

I WTC dragging on bottom of tank

HWEE dragging on bottom of tank

HWEE Phase II Retrieval Test - Layered Simulant - Video Record Summary - May 3, 2018

	Date	Day	Start Time	Stop Time	Elapsed Time	Comments
No Flush - Y axis, deg 5			17:35:04	17:35:09	0:00:05	
Suction clean - X axis, deg 5			17:35:09	17:35:20	0:00:11	
In holding position			17:35:20	17:36:27	0:01:07	
Lift HWEE vertically			17:36:27	17:37:41	0:01:14	
Observe result: 0° end of layered simulant retrieval			17:37:41	17:37:59	0:00:18	

HWEE Phase II Retrieval Test - Layered Simulant

Video Snapshots - May 3, 2018

VIDEO SNAPSHOTS

(See associated Video Summary Record for Written Details)

Note: The video record below only used CAM 1 video data. CAM 2 video would show the same video sequences but looking back at the simulant tank from the opposing end (i.e. end by capture tank)

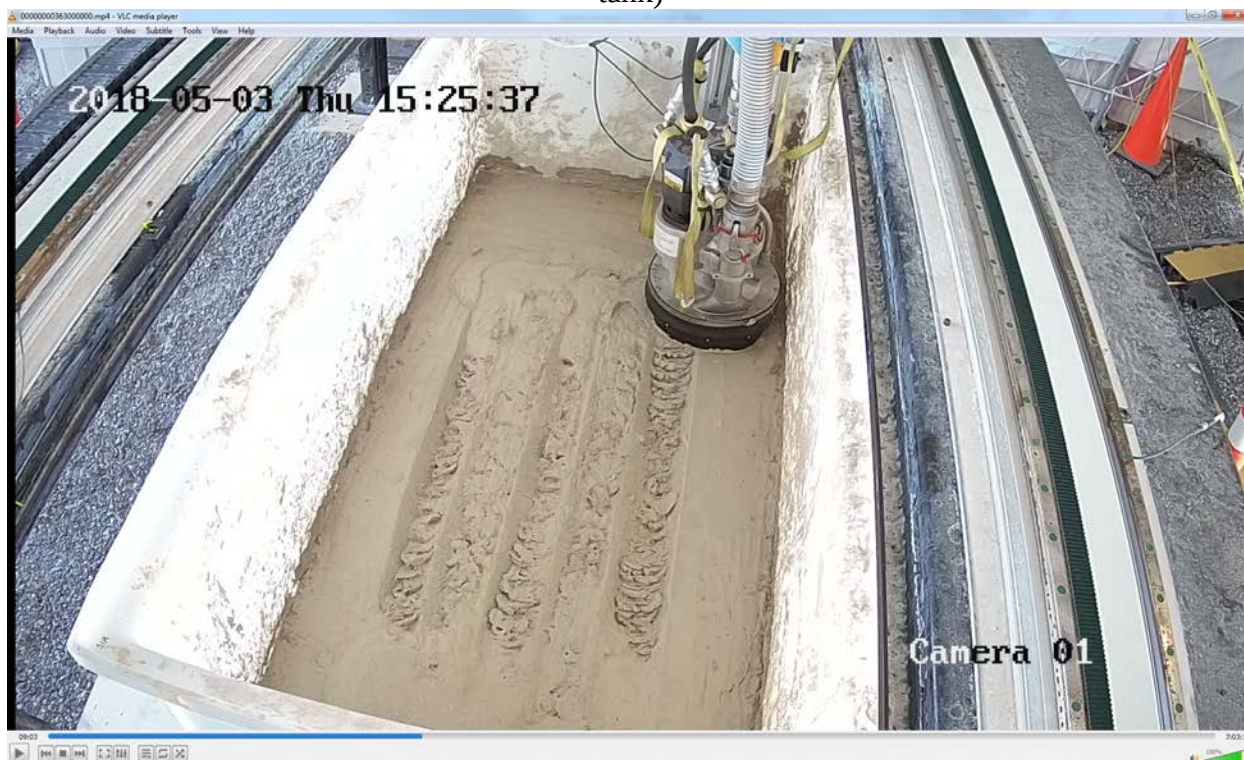


Figure LS1 - Pass 1 – Leg 6 -Start



Figure LS2 - Pass 2 – Leg 6 - Start

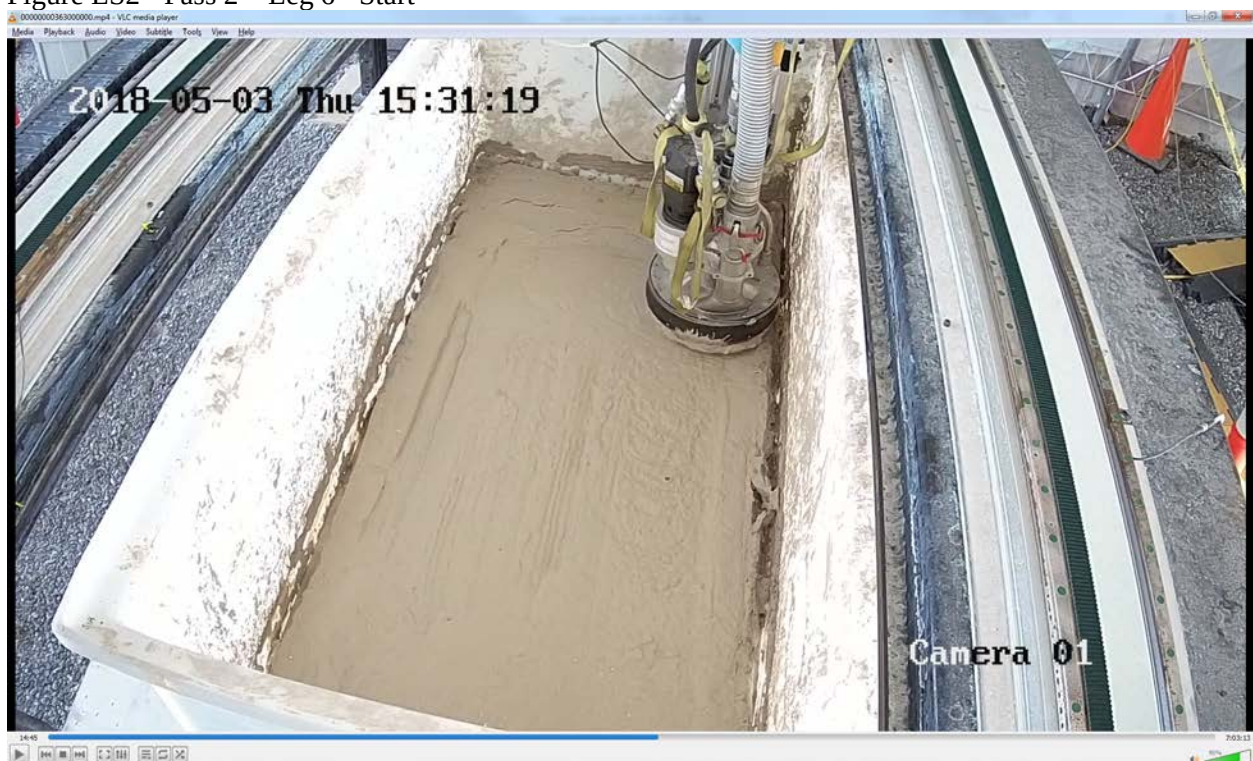


Figure LS3 - Pass 3 – Leg 6 - Start



Figure LS4 - Pass 3 – Wall Cleaning - Near Side - Start



Figure LS5 - Pass 3 – Wall Cleaning - Far side – Start



Figure LS6 - Simulant Tank Top Removal – Cut off 11 inches – Required to reduce interference from gantry/scanner moving down vertically to continue retrieval mining.



Figure LS7 - Pass 4 – Leg 6 - Start



Figure LS8 - Pass 5 – Leg 6 - Start



Figure LS9 - Pass 5 – Wall Cleaning - Near Side - Start



Figure LS10 - Pass 5 - Wall Cleaning - Far Side - Start



Figure LS11 - Pass 6 – Leg 6 - Start



Figure LS12 - Pass 7 – Leg 6 - Start



Figure LS13 - Pass 8 – Leg 1 - End



Figure LS14 - Pass 8 – Leg 5 - End



Figure LS15 - Pass 8 – Leg 6 - Start



Figure LS16 - Pass 8 – Wall Cleaning - Near Side - Start

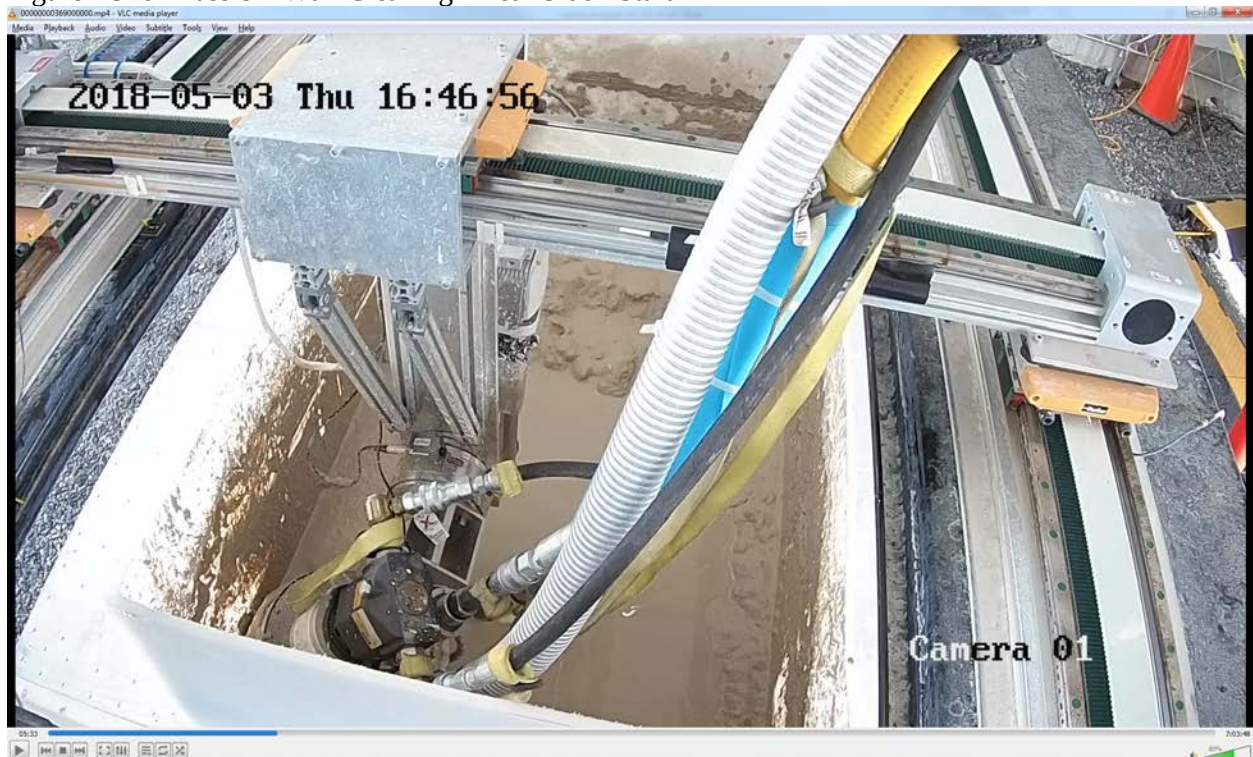


Figure LS17 - Pass 8 – Wall Cleaning - Near Side - End



Figure LS18 - Pass 8 – Wall Cleaning - Far Side - Start



Figure LS19 - After Pass 8 – Water in simulant clean up using HWEE suction – Prior to start of suction



Figure LS20 - After Pass 8 – Water in simulant clean up using HWEE suction – End of suction

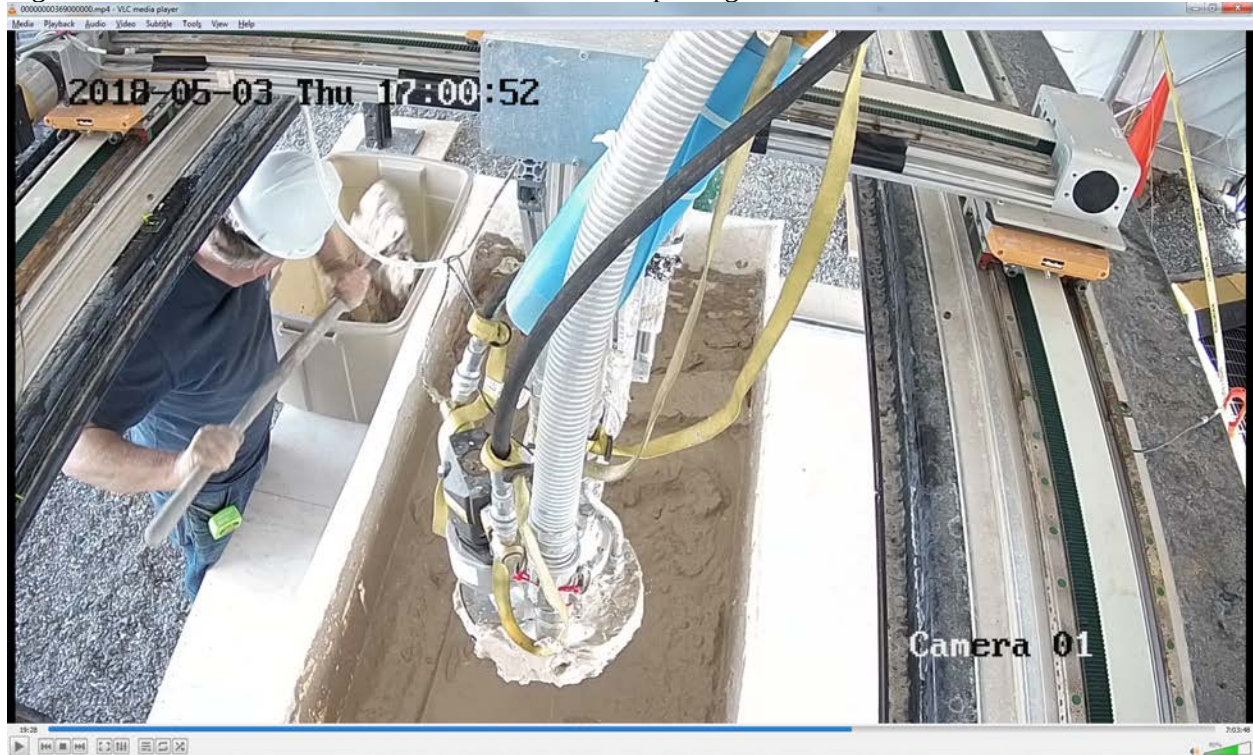


Figure LS21 - After Pass 8 & Water Removal – Simulant shelf removal – Load 1. Removed to allow HWEE support bracket clear simulant shelf in tank and give a larger mining area.

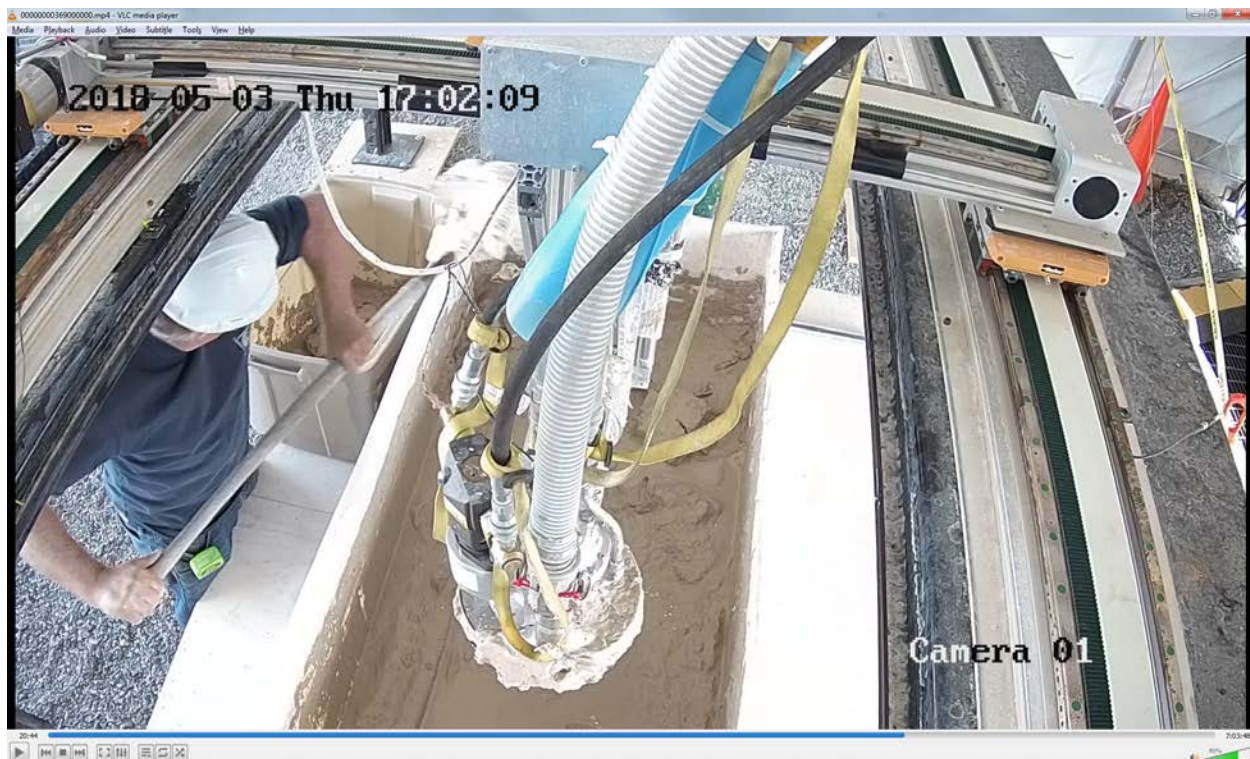


Figure LS22 - After Pass 8 & Water Removal – Simulant shelf removal – Load 2



Figure LS23 - Setting HWEE pressure in Capture Tank prior to Pass 9. This operation is required whenever the high pressure pump has been shut down to set pressure of the HWEE rotating jet to 1,000 psi operating pressure (set with pressure reducing station gauge) for this kaolin simulant retrieval operation. Flush pressure is not set, only HWEE rotating jets with the HWEE jet pump operating

(nominally 9,000 psi at high pressure pump). When HWEE jet and HWEE flush is operated together, indicated pressure at pressure reducing station gauge was around 500 psi.



Figure LS24 - Pass 9 – Leg 1 - Start - in previously mined simulant – HWEE moving well is this previously mined simulant.



Figure LS25 - Pass 9 – Leg 1 - End – HWEE in simulant removed to level of other simulant. This simulant is not mined like simulant in foreground. Major slow down and pushing lots of sludge. Tank actually moved up slightly on foreground end with HWEE pushed sludge into wall at other end of tank. HWEE tilt string pot broke around this moment when harder unmined sludge was impacted.



Figure LS26 - Pass 9 – Leg 2 - Midway Through – Pushing quite a bit of sludge and sludge piling up on HWEE.



Figure LS27 - Pass 9 – Leg 3 - End – HWEE is impacting simulant sludge at far end and tank is being lifted on foreground end slightly when the far end is reached.



Figure LS28 - Pass 9 – Leg 5 - Stopped at this point (about ¼ into run length) - Test stopped because test personnel thought the HWEE was not rotating in error. After looking at data, HWEE rotation was operating properly and test did not need to be stopped. After test was stopped at this point, it was decided to rerun this Pass 9.



Figure LS29 - Pass 9 (Rerun) – Leg 1 – End - Tank lifting slightly again when simulant sludge at far end is impacted by HWEE.



Figure LS30 - Pass 9 (rerun) – Leg 5 - End



Figure LS31 - Pass 9 - Wall Cleaning - Near Side - Start



Figure LS32 - Pass 9 - Wall Cleaning - Far Side - Start



Figure LS33 - Pass 9 - Suction Clean – No flushing - Leg 3 – HWEE dragging along bottom of tank. See exposed tank bottom where scrapping occurred.



Appendix C: Retrieval Waste Topography Test Summaries

HWEE Topographic Testing 5/16/2018

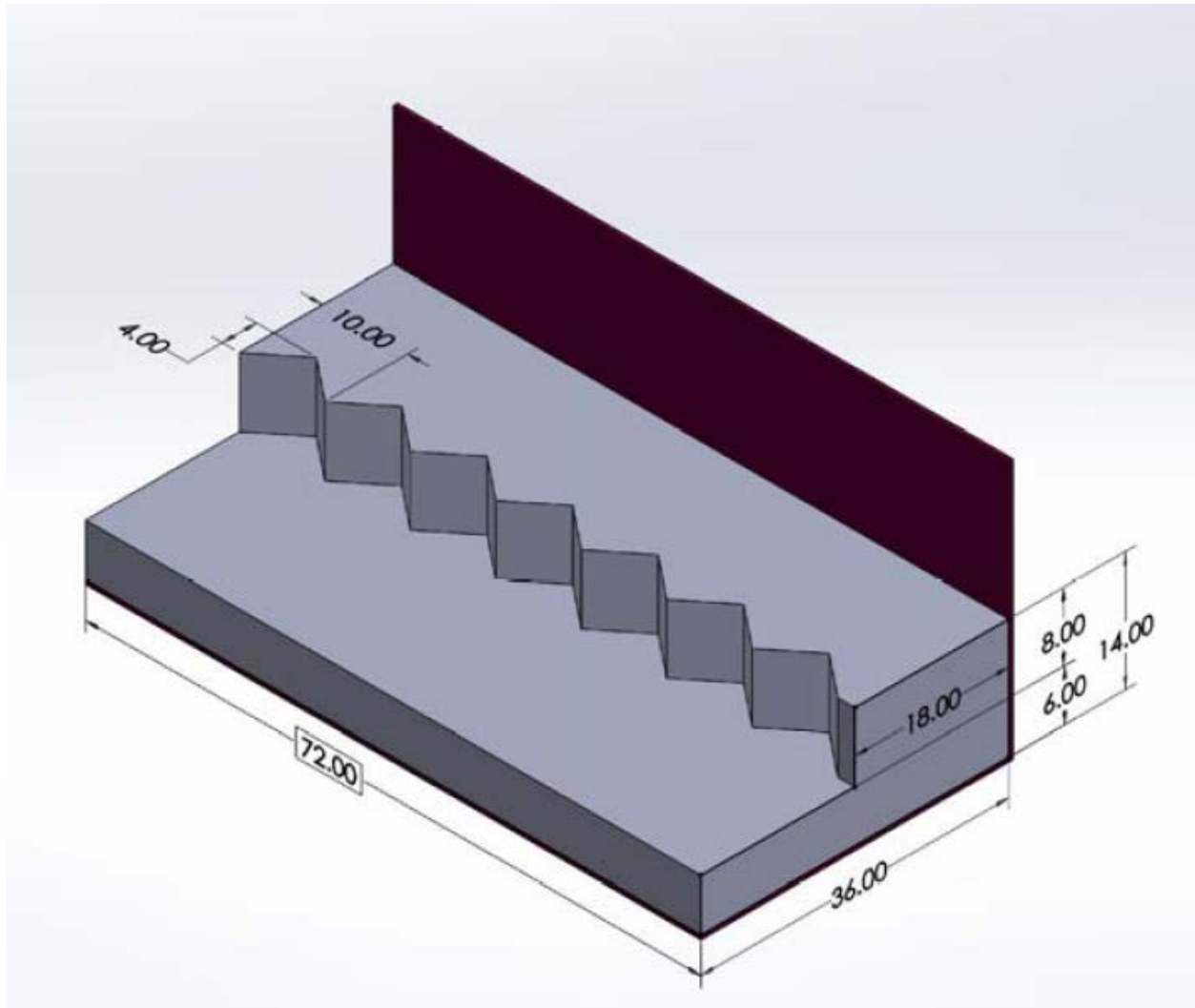
Basic Parameters

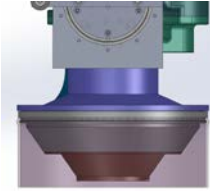
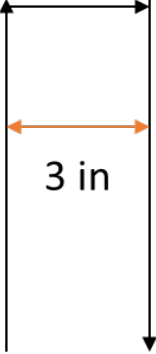
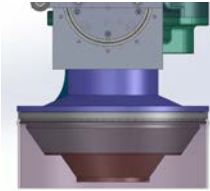
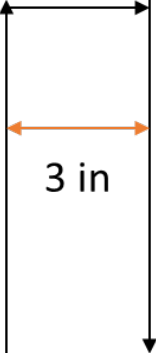
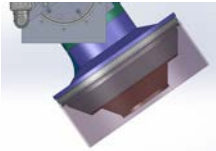
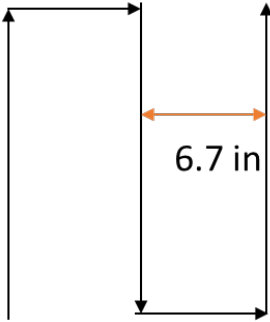
Kaolin: Rotation Speed 300 RPM

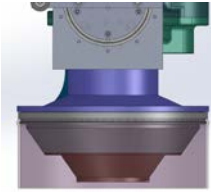
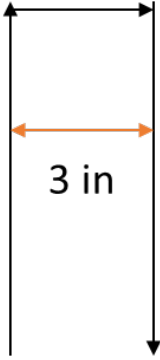
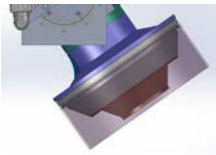
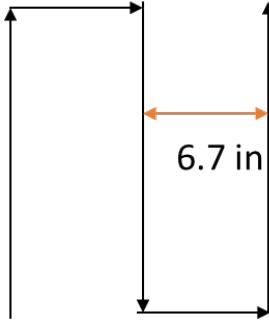
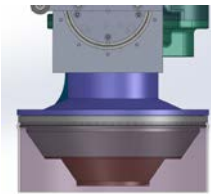
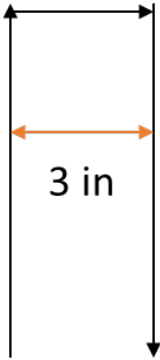
(Sludge) Traverse Speed 300 inches/minute

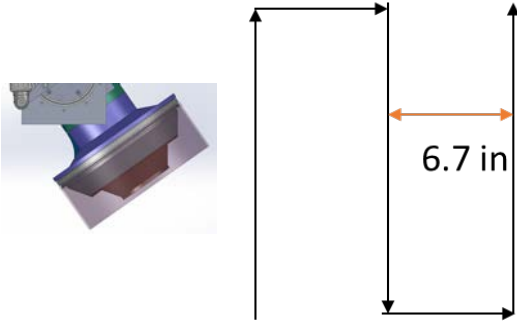
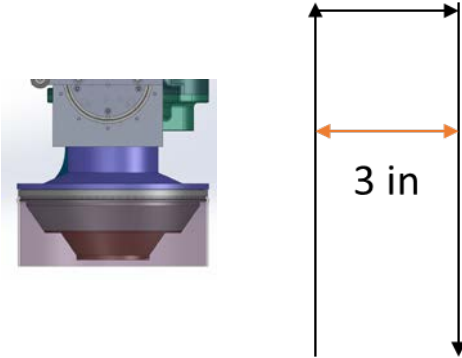
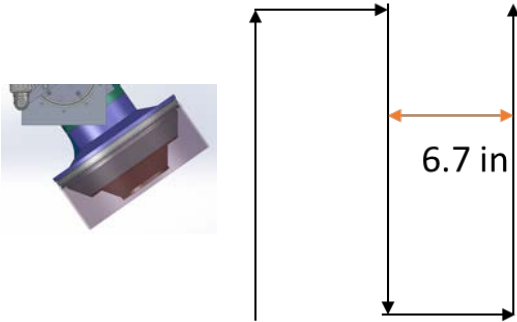
Waterjet pressure 1000 psi

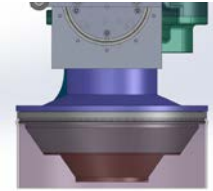
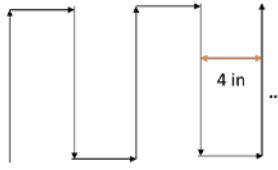
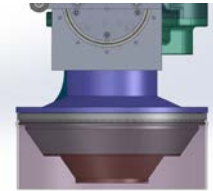
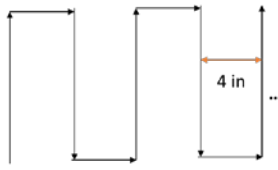
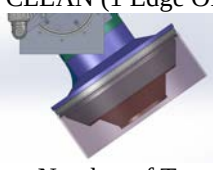
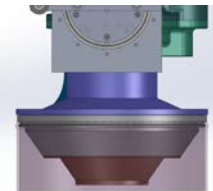
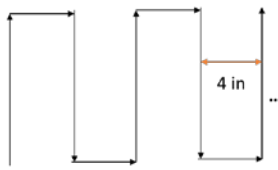
Flush Every Y Move

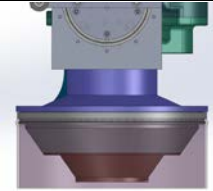
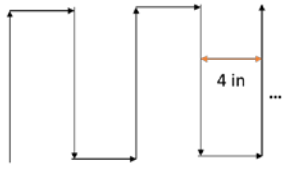


Step	Description	Offset Wall	Tilt Angle	Depth Change (Cumulative)	Mining Pattern	Start X/Y	Length	File
1	Starting Point	0	0	+1/4" from surface TAPE 61	Close to usual starting tank corner as possible	0.5 0.25		01
2	Mining Pass 1						43	02
3	Starting Point	0	0	- 1 inch (-1 inch) TAPE 60		0.5 0.25		01
4	Mining Pass 2						43	02
5	Starting Point	STE P 1: 3 inch	STE P 2: 35	STEP 3: -3 inch (-4 inch) TAPE 57		0.5 3		03
6	Mining Pass 3						43	04
7	Raise HWEE			+ 1 inch (-3 inch) TAPE 58				
8	Starting Point	0	0			3 .25		05

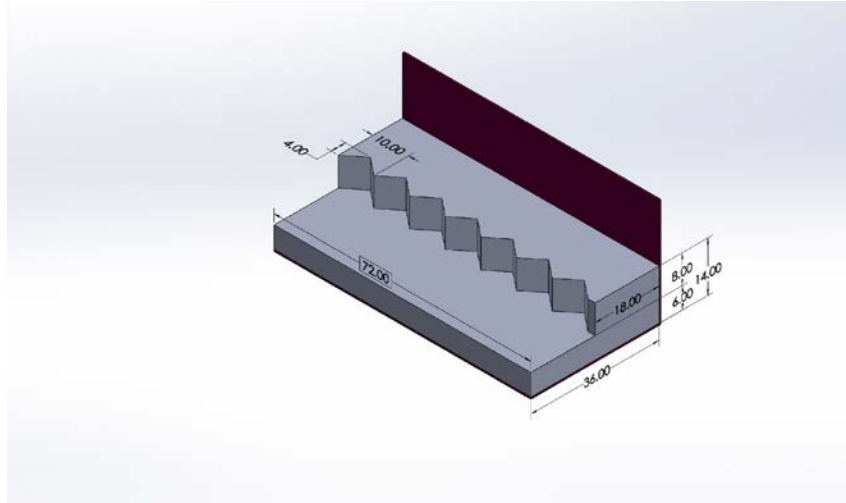
Step	Description	Offset Wall	Tilt Angle	Depth Change (Cumulative)	Mining Pattern	Start X/Y	Length	File
9	Mining Pass 4						40	06
10	Starting Point	STE P 1: 3 inch	STE P 2: 35	STEP 3: -3 inch (-6 inch) TAPE 55		3 3		07
11	Mining Pass 5						40	08
12	Raise HWEE			+ 1 inch (-5 inch) TAPE 56				
12a				STOP TEST STOP NLB PUMP PUMP OUT THE RETREIVAL TANK REMOVE TANK TOP				
13	Starting Point	0	0	+ 1 inch (-5 inch) TAPE 56		3 .25		09
14	Mining Pass 6						40	10
15	Starting Point	STE P 1:	STE P 2:	STEP 3: -3 inch		3 3		11

Step	Description	Offset Wall	Tilt Angle	Depth Change (Cumulative)	Mining Pattern	Start X/Y	Length	File
		3 inch	35	(-8 inch) TAPE 53				
16	Mining Pass 7						40	12
17				(deleted)				
18	Raise HWEE			+ 1 inch (-7 inch) TAPE 54				
19	Starting Point	0	0			6 0.25		13
20	Mining Pass 8						21	14
21	Starting Point	STE P 1 3 inch	STE P 2 35	STEP 3 -3 inch (-10 inch) TAPE 51		6 3		15
22	Mining Pass 9						21	16
23	STOP TEST STOP NLB PUMP PUMP OUT THE RETREIVAL TANK DIG MATERIAL OUT (OVERHANG) Begin Normal Mining							

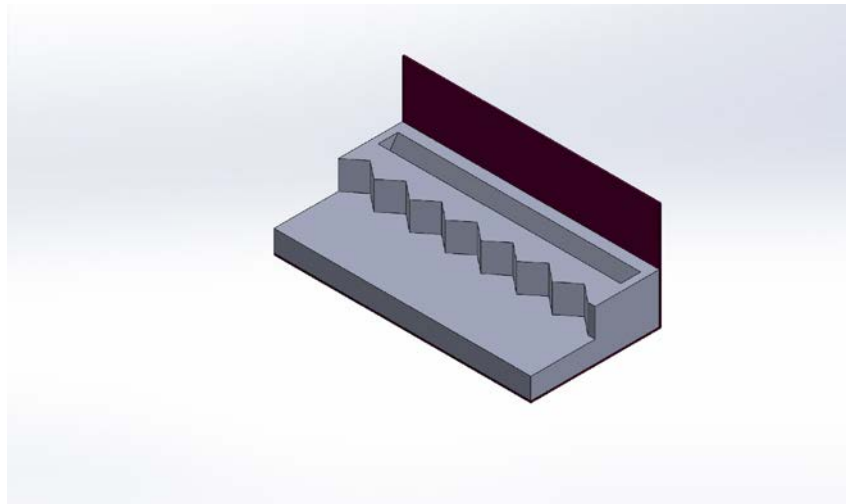
Step	Description	Offset Wall	Tilt Angle	Depth Change (Cumulative)	Mining Pattern	Start X/Y	Length	File
24	Raise HWEE			+ 1 inch (-9 inch) TAPE 52				
25	Starting Point	0	0			6 0.25		17
26	Mining Pass 10						21	18
27	Starting Point	0	0	- 1 inch (-10 inch) TAPE 51		6 0.25		17
28	Mining Pass 11						21	18
29	Starting Point	STEP 1 P 1 3 inch	STEP 2 P 2 35	STEP 3 NO CHANGE TILT CLEAN (1 Edge ONLY) 				
30				Reduce Number of Traverses		3	21	man
31	Starting Point	0	0	- 2 inch (-12 inch) TAPE 49		6 0.25		17
32	Mining Pass 12						21	18
33				(deleted)				
34	Starting Point	0	0	- 2 inch (-14 inch) TAPE 47		6 0.25		17

Step	Description	Offset Wall	Tilt Angle	Depth Change (Cumulative)	Mining Pattern	Start X/Y	Lengt h	File
35	Mining Pass 13						21	18
36	MOVE HWEE TO BOTTOM OF THE TANK JETPUMP RESIDUAL LIQUID END OF TEST							

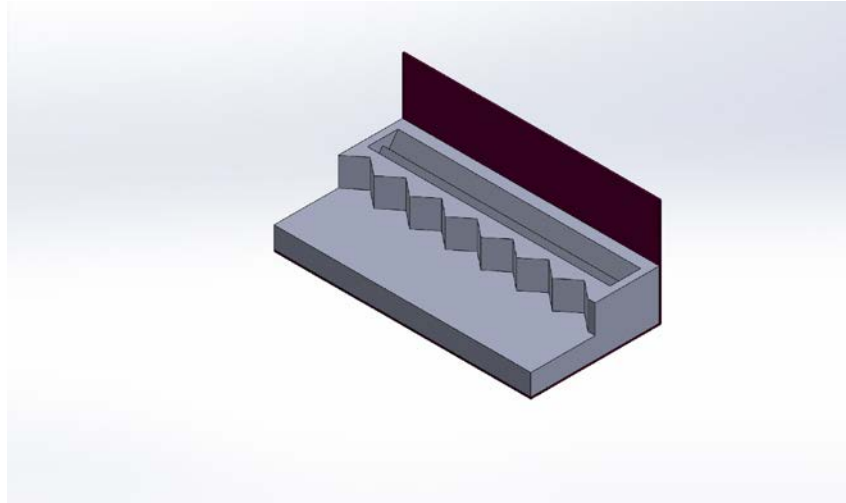
Simulant Configuration for Waste Topography Retrieval Test



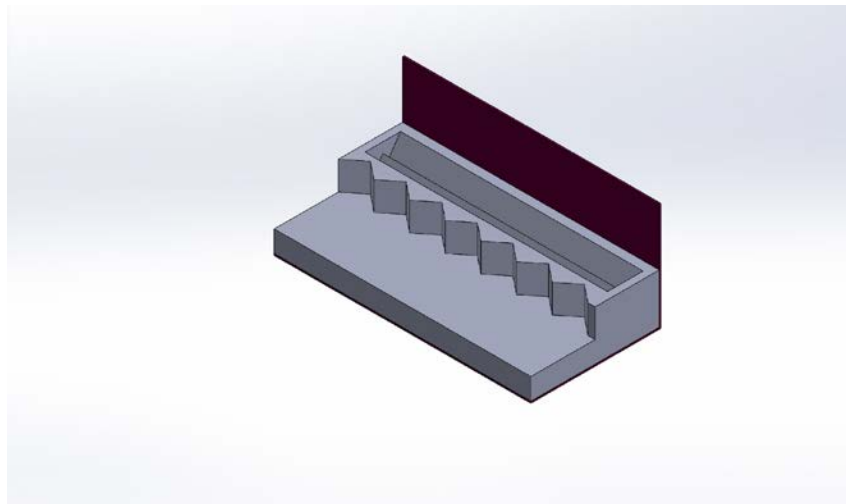
Simulant Bed After Pass 1 (Leg 1) HWEE in Vertical Orientation



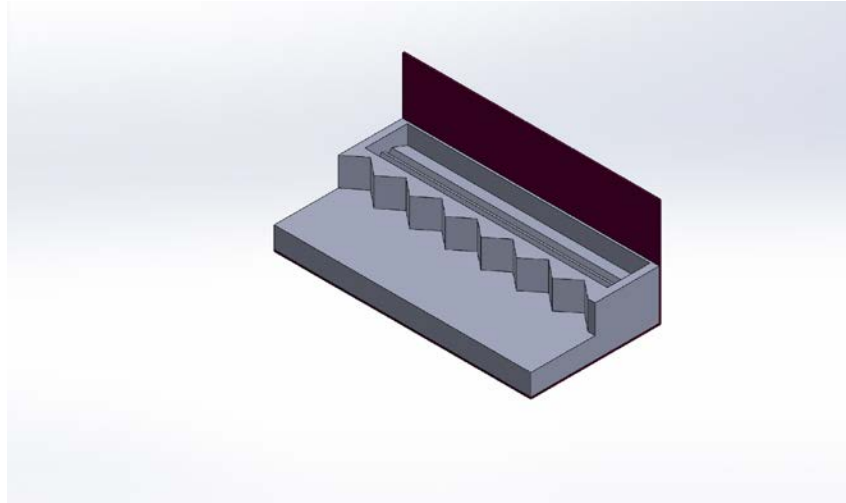
Simulant Bed After Pass 2 (Leg 2) HWEE in Vertical Orientation



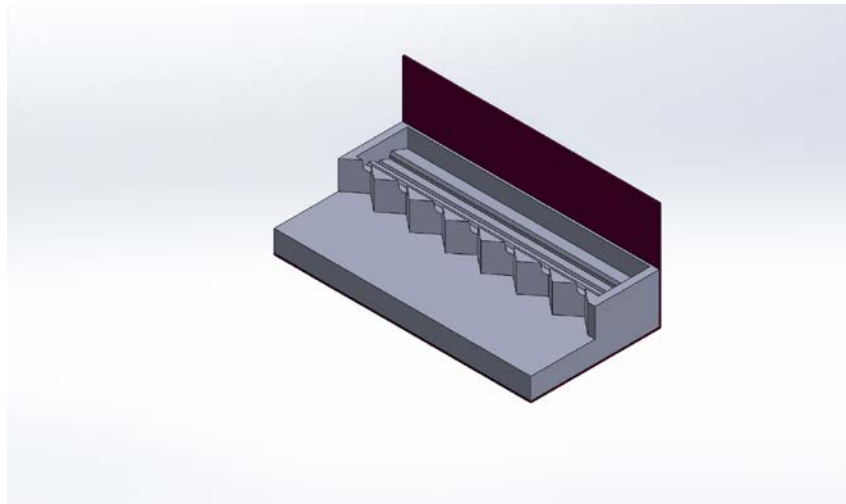
Simulant Bed After Pass 2 HWEE in Vertical Orientation



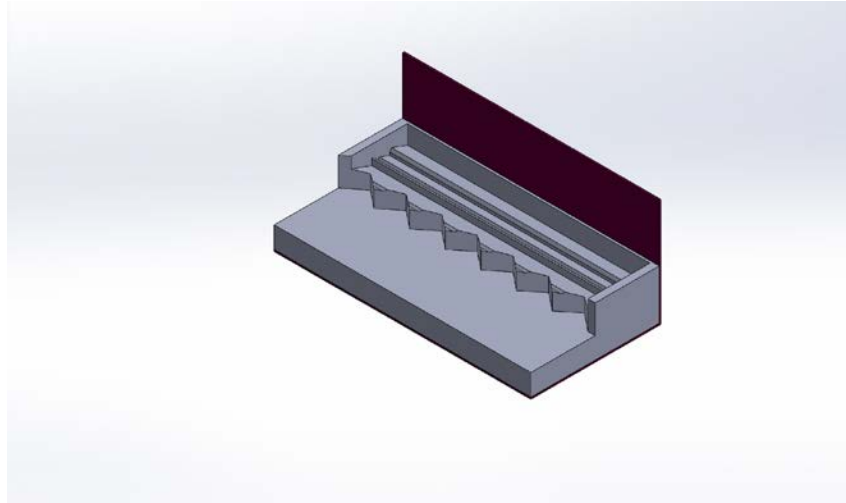
Simulant Bed After Pass 3 (Leg 1) HWEE in Tilted Orientation



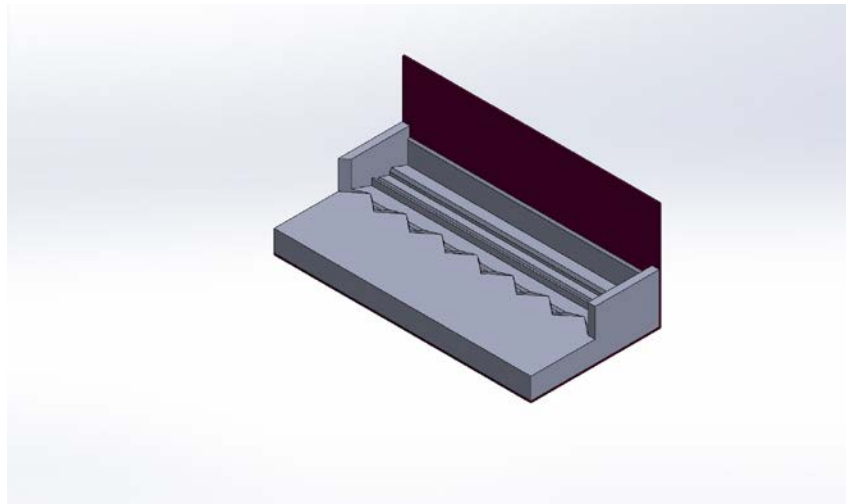
Simulant Bed After Pass 3 (Leg 2) HWEE in Tilted Orientation



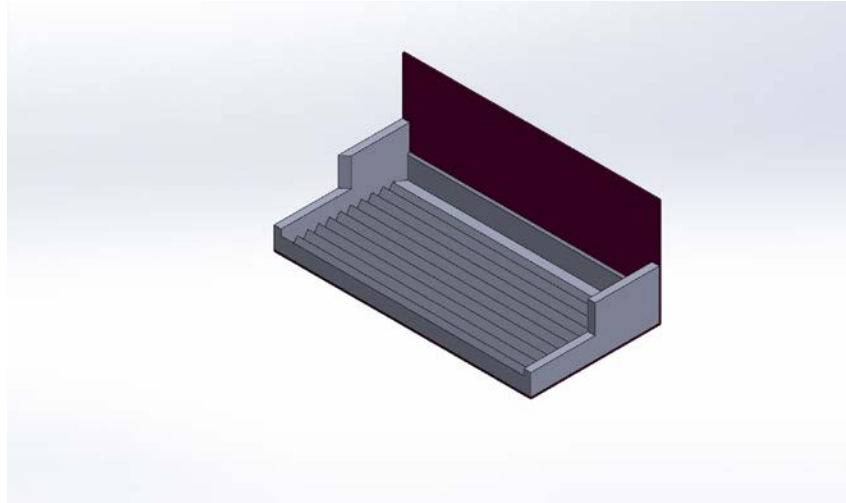
Simulant Bed After Pass 3 (Leg 3) HWEE in Tilted Orientation



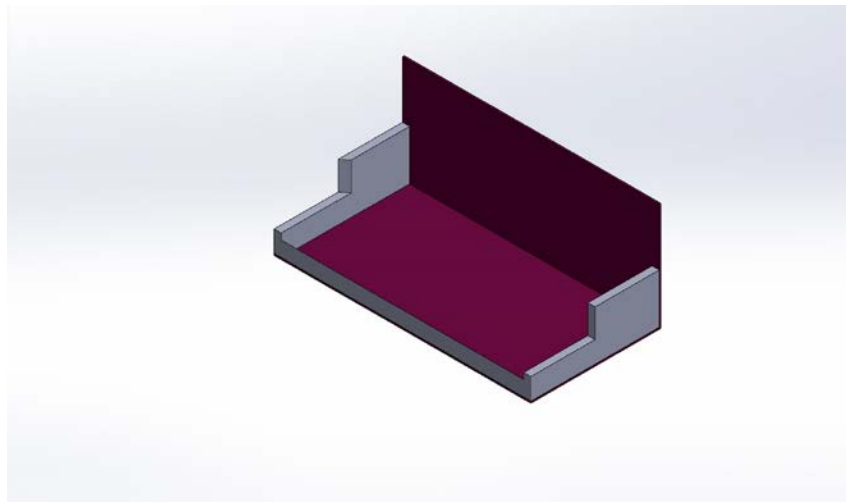
Simulant Bed After Pass 4 and 5 (same as Pass 2 and 3)



Simulant Bed After Passes 10-13



Simulant Bed After Final Surface Cleaning HWEE in Vertical Orientation



HWEE Phase II Retrieval Test - Topographic Simulant - Video Record Summary - May 16, 2018**Cam1 - Layered Test - Summary of Camera Videos**

	Date	Day	Start Time	Stop Time	Elapse Time
0000000435000000.mp4	5/16/2018	Wed	13:33:53	14:02:07	0:28:14
0000000437000000.mp4	5/16/2018	Wed	14:02:08	14:30:24	0:28:16
0000000439000000.mp4	5/16/2018	Wed	14:30:25	14:58:40	0:28:15
0000000441000000.mp4	5/16/2018	Wed	14:58:40	15:19:20	0:20:40

NOTE: Yellow Highlighted Sections Below Are Where Actual HWEE Retrieval Operations Are Being Performed
Retrieval Operations Include Mining, Flushing, Wall Cleaning, and Final Suction Clean Up at End

0000000435000000.mp4

Setting Initial Pressure - In Capture Tank	5/16/2018	Wed			
Setting Pressure in Capture Tank			NA	NA	
Move vertically up out of Capture Tank			13:39:19	13:39:45	0:00:26
Move horizontally to home position			13:39:45	13:40:05	0:00:21
Move horizontally to start position x-y axis			13:40:06	13:40:30	0:00:24

Mining Pass 1 (2 Legs, No Tilt)

Moving to start position	5/16/2018	Wed			
Getting ready to start horizontal run			13:40:30	13:41:20	0:00:50
Mining + X-axis Leg 1			13:41:20	13:41:35	0:00:15
Mining + Y-axis Leg 1			13:41:35	13:41:45	0:00:11
Mining + X-axis Leg 2			13:41:46	13:41:50	0:00:04
Flush at end of run			13:41:50	13:42:02	0:00:12
Move back to home position			13:42:02	13:42:05	0:00:04
			13:42:06	13:42:19	0:00:13

Well defined mining and contained.

Mining Pass 2 (2 Legs, No Tilt)

Getting ready to start horizontal run	5/16/2018	Wed			
Mining + X-axis Leg 1			13:42:19	13:43:19	0:01:00
Mining + Y-axis Leg 1			13:43:19	13:43:29	0:00:10
Mining + X-axis Leg 2			13:43:29	13:43:33	0:00:04
Flush at end of run			13:43:33	13:43:46	0:00:13
Move back to home position			13:43:46	13:43:49	0:00:03
			13:43:49	13:44:11	0:00:22

Well defined mining and contained.

Mining Pass 3 (3 Legs, Tilt 35°)

Moving to start position	5/16/2018	Wed			
Tilt HWEE head 35°			13:44:11	13:44:32	0:00:21
Getting ready to start horizontal run			13:44:32	13:44:41	0:00:11
Mining + X-axis Leg 1			13:44:43	13:45:08	0:00:25
Mining + Y-axis Leg 1			13:45:08	13:45:30	0:00:22
Mining + X-axis Leg 2			13:45:30	13:45:25	0:00:15
Mining + Y-axis Leg 2			13:45:25	13:45:40	0:00:15
Mining + X-axis Leg 3			13:45:40	13:45:50	0:00:10
Flush at end of run			13:45:50	13:46:03	0:00:13
Move up vertically			13:46:03	13:46:13	0:00:10
Tilt HWEE head back to 0°			13:46:13	13:46:38	0:00:25
Move back to home position			13:46:38	13:46:22	0:00:16

Well defined mining and contained.
On Leg 2, HWEE support push down on simulant face.**Mining Pass 4 (2 Legs, No Tilt)**

Moving to start position	5/16/2018	Wed			
Moving to vertical depth position			13:46:37	13:46:53	0:00:16
Mining + X-axis Leg 1			13:46:56	13:47:23	0:00:27
Mining + Y-axis Leg 1			13:47:23	13:47:35	0:00:12
Mining + X-axis Leg 2			13:47:35	13:47:40	0:00:05
Flush at end of run			13:47:40	13:47:52	0:00:12
Move back to home position			13:47:52	13:47:58	0:00:06
			13:47:58	13:48:18	0:00:20

Well defined mining and mostly contained.

Mining Pass 5 (3 Legs, Tilt 35°)

Moving to start position	5/16/2018	Wed			
Tilt HWEE head 35°			13:48:18	13:48:34	0:00:16
Getting ready to start horizontal run			13:48:34	13:48:40	0:00:06
Move HWEE vertically downward			13:48:40	13:48:57	0:00:17
Mining + X-axis Leg 1			13:48:57	13:49:42	0:00:45
Mining + Y-axis Leg 1			13:49:42	13:49:51	0:00:09
Mining + X-axis Leg 2			13:49:51	13:49:56	0:00:05
Mining + Y-axis Leg 2			13:49:56	13:50:08	0:00:12
Mining + X-axis Leg 3			13:50:08	13:50:13	0:00:05
Flush at end of run			13:50:13	13:50:25	0:00:12
Move up vertically			13:50:25	13:50:34	0:00:09
Tilt HWEE head back to 0°			13:50:34	13:50:48	0:00:14
Move HWEE vertically upward			13:50:48	13:50:53	0:00:05
In hold position			13:50:53	13:51:48	0:00:55
In hold position			13:51:48	13:52:49	0:01:01
Simulant Tank top removed (13 inches)			13:52:49	13:53:18	0:00:29
In hold position - Observing test, taking pictures			13:53:18	14:02:07	0:08:49

Less defined mining. Some spillage occurring off shelf.

0000000437000000.mp4

In hold position - personnel observe tank	5/16/2018	Wed			
Moving to home position			14:02:08	14:02:50	0:00:42
Moving HWEE horizontally to Capture Tank			14:02:50	14:03:02	0:00:12
Moving HWEE vertically down into Capture Tank			14:03:02	14:04:15	0:01:13
Hold HWEE in Capture Tank			14:04:15	14:04:34	0:00:19
Set HWEE pressure in Capture Tank			14:04:34	14:06:42	0:02:08
Moving HWEE vertically up out of Capture Tank			14:06:42	14:06:57	0:00:15
Moving HWEE horizontally and vertically to home position			14:06:57	14:07:17	0:00:20
			14:07:17	14:07:49	0:00:32

HWEE Phase II Retrieval Test - Topographic Simulant - Video Record Summary - May 16, 2018

	Date	Day	Start Time	Stop Time	Elapse Time
Mining Pass 6 (2 Legs, No Tilt)					
Moving to start position	5/16/2018	Wed			
Getting ready to start; horizontal run			14:07:49	14:07:58	0:00:09
Moving down to vertical start position			14:07:58	14:08:20	0:01:22
Mining - X-axis Leg 1			14:08:20	14:08:30	0:00:10
Mining - Y-axis Leg 1			14:08:30	14:08:39	0:00:09
Mining - X-axis Leg 2			14:08:39	14:08:45	0:00:06
Flush at end of run			14:09:45	14:09:58	0:00:13
Move back to home position			14:09:58	14:10:08	0:00:08
			14:10:08	14:10:16	0:00:10
Mining Pass 7 (3 Legs, Tilt 35°)					
Moving to start position	5/16/2018	Wed			
Tilt HWFF head 35°			14:10:16	14:10:35	0:00:19
Getting ready to start; horizontal run			14:10:35	14:10:43	0:00:08
Move HWFF vertically downward			14:10:43	14:11:00	0:00:27
Mining - X-axis Leg 1			14:11:00	14:11:15	0:00:05
Mining - Y-axis Leg 1			14:11:15	14:11:28	0:00:12
Mining - X-axis Leg 2			14:11:28	14:11:33	0:00:05
Mining - Y-axis Leg 2			14:11:33	14:11:45	0:00:12
Mining - X-axis Leg 3			14:11:45	14:11:50	0:00:05
Flush at end of run			14:11:50	14:12:01	0:00:11
Move up vertically			14:12:01	14:12:08	0:00:07
Tilt HWFF head back to 0°			14:12:08	14:12:15	0:00:07
Move back to home position			14:12:15	14:12:19	0:00:04
			14:12:19	14:12:32	0:00:13
Mining Pass 8 (2 Legs, No Tilt)					
Moving to start position	5/16/2018	Wed			
Getting ready to start; horizontal run			14:12:32	14:12:53	0:00:21
Move HWFF vertically downward			14:12:53	14:13:11	0:00:18
Mining - X-axis Leg 1			14:13:11	14:13:29	0:00:18
Mining - Y-axis Leg 1			14:13:29	14:13:35	0:00:06
Mining - X-axis Leg 2			14:13:35	14:13:38	0:00:04
Flush at end of run			14:13:38	14:13:47	0:00:08
Move back to home position			14:13:47	14:14:02	0:00:15
			14:14:02	14:14:15	0:00:13
000000003690000000.mp4					
Mining Pass 9 (3 Legs, Tilt 35°)					
Moving to start position	5/16/2018	Wed			
Tilt HWFF head 35°			14:14:15	14:14:52	0:00:37
Getting ready to start; horizontal run			14:14:52	14:14:54	0:00:02
Move HWFF vertically downward			14:14:54	14:15:42	0:00:50
Mining - X-axis Leg 1			14:15:42	14:15:52	0:00:10
Mining - Y-axis Leg 1			14:15:52	14:15:58	0:00:06
Mining - X-axis Leg 2			14:15:58	14:15:59	0:00:01
Mining - Y-axis Leg 2			14:15:59	14:15:59	0:00:00
Mining - X-axis Leg 3			14:15:59	14:15:59	0:00:00
Flush at end of run			14:15:59	14:16:04	0:00:05
Tilt HWFF head back to 0°			14:16:04	14:16:11	0:00:07
Move up vertically			14:16:11	14:16:21	0:00:10
Move back to home position			14:16:21	14:17:26	0:01:05
Move horizontally to Capture Tank			14:17:26	14:17:38	0:00:12
On hold - Test conditions observations			14:17:38	14:18:09	0:00:31
			14:18:09	14:19:21	0:01:12
Remove Simulant Shelf, Set Pressure					
Remove simulant shelf in Simulant tank - Load 1			14:19:21	14:21:07	0:01:46
Remove simulant shelf in Simulant tank - Load 2			14:21:07	14:23:21	0:02:14
Remove simulant shelf in Simulant tank - Load 3			14:23:21	14:25:50	0:02:29
Remove simulant shelf in Simulant tank - Load 4			14:25:50	14:28:43	0:02:53
Remove simulant shelf in Simulant tank - Load 5			14:28:43	14:30:24	0:01:41
000000004390000000.mp4 (Start)					
Remove simulant shelf in Simulant tank - Load 5 (cont.)	5/16/2018	Wed			
Test personnel probing simulant in tank			14:30:25	14:33:12	0:02:47
On hold			14:33:12	14:32:44	0:00:43
Move vertically downward into Capture Tank			14:32:44	14:37:29	0:04:45
On hold in Capture Tank			14:37:29	14:37:50	0:00:21
Set pressure in Capture Tank			14:37:50	14:40:03	0:02:13
Move vertically upward out of Capture Tank			14:40:03	14:40:19	0:00:16
On hold			14:40:19	14:40:35	0:00:17
Move horizontally to home position			14:40:35	14:41:15	0:00:40
Move vertically down to home position			14:41:15	14:41:39	0:00:23
			14:41:39	14:42:14	0:00:35
Mining Pass 10 (6 Legs, No Tilt)					
Moving to start position	5/16/2018	Wed			
Getting ready to start; horizontal run			14:42:14	14:42:31	0:00:17
Mining down into simulant			14:42:31	14:43:01	0:00:30
Mining - X-axis Leg 1			14:43:01	14:43:09	0:00:08
Mining - Y-axis Leg 1			14:43:09	14:43:20	0:00:11
Mining - X-axis Leg 2			14:43:20	14:43:24	0:00:04
Mining - Y-axis Leg 2			14:43:24	14:43:37	0:00:13
Mining - X-axis Leg 3			14:43:37	14:43:41	0:00:04
Mining - Y-axis Leg 3			14:43:41	14:43:53	0:00:12
			14:43:53	14:43:57	0:00:04

HWEE Phase II Retrieval Test - Topographic Simulant - Video Record Summary - May 16, 2018

	Date	Day	Start Time	Stop Time	Elapse Time
Mining - X-axis Leg 4			14:43:57	14:44:10	0:00:13
Mining - Y-axis Jog 4			14:44:10	14:44:13	0:00:03
Mining - X-axis Leg 5			14:44:13	14:44:25	0:00:11
Mining - Y-axis Jog 5			14:44:26	14:44:29	0:00:03
Mining - X-axis Leg 6			14:44:29	14:44:45	0:00:16
Flush at end of run			14:44:45	14:44:57	0:00:12
Move back to home position			14:44:57	14:45:15	0:00:19

Good mining in simulant slurries.

Mining Pass 11 (6 Legs, No Tilt)

	5/16/2018	Wed			
Moving to start position			14:45:16	14:45:33	0:00:17
Getting ready to start, horizontal run			14:45:33	14:45:50	0:00:17
Mining down into simulant			14:45:50	14:45:58	0:00:08
Mining - X-axis Leg 1			14:45:58	14:46:08	0:00:10
Mining - Y-axis Jog 1			14:46:08	14:46:11	0:00:03
Mining - X-axis Leg 2			14:46:11	14:46:24	0:00:13
Mining - Y-axis Jog 2			14:46:24	14:46:28	0:00:04
Mining - X-axis Leg 3			14:46:28	14:46:41	0:00:13
Mining - Y-axis Jog 3			14:46:41	14:46:44	0:00:03
Mining - X-axis Leg 4			14:46:44	14:46:58	0:00:14
Mining - Y-axis Jog 4			14:46:58	14:47:02	0:00:04
Mining - X-axis Leg 5			14:47:02	14:47:14	0:00:12
Mining - Y-axis Jog 5			14:47:14	14:47:28	0:00:04
Mining - X-axis Leg 6			14:47:18	14:47:37	0:00:14
Flush at end of run			14:47:32	14:47:39	0:00:07
Move back to home position			14:47:39	14:47:55	0:00:16

Good mining in simulant slurries.

Mining Pass 11 (1 Leg, Tilt 35°)

	5/16/2018	Wed			
Moving in - X-axis - No Mining			14:47:55	14:48:20	0:00:25
Moving in - X-axis - No Mining			14:48:20	14:48:33	0:00:13
Moving to start position			14:48:33	14:48:51	0:00:18
Tilt HWEE head 35°			14:48:53	14:49:00	0:00:07
Getting ready to start, horizontal run			14:49:00	14:49:29	0:00:29
Mining - X-axis Leg 1			14:49:29	14:49:40	0:00:11
Flush at end of run			14:49:40	14:49:44	0:00:04
Move up vertically and tilt HWEE head back to 0°			14:49:44	14:50:07	0:00:18
Move to home position			14:50:02	14:50:13	0:00:11
On hold			14:50:13	14:50:30	0:00:17

Good liquification of simulant along wall. Less capture.

Mining Pass 12 (6 Legs, No Tilt)

	5/16/2018	Wed			
Moving to start position			14:50:30	14:50:32	0:00:02
On hold			14:50:32	14:50:51	0:00:19
Mining down into simulant			14:50:53	14:50:57	0:00:04
Mining - X-axis Leg 1			14:50:57	14:51:07	0:00:10
Mining - Y-axis Jog 1			14:51:07	14:51:12	0:00:05
Mining - X-axis Leg 2			14:51:12	14:51:24	0:00:12
Mining - Y-axis Jog 2			14:51:24	14:51:28	0:00:04
Mining - X-axis Leg 3			14:51:28	14:51:40	0:00:12
Mining - Y-axis Jog 3			14:51:40	14:51:45	0:00:05
Mining - X-axis Leg 4			14:51:45	14:51:57	0:00:12
Mining - Y-axis Jog 4			14:51:57	14:52:02	0:00:05
Mining - X-axis Leg 5			14:52:02	14:52:15	0:00:13
Mining - Y-axis Jog 5			14:52:15	14:52:28	0:00:14
Mining - X-axis Leg 6			14:52:29	14:52:42	0:00:13
Flush at end of run			14:52:42	14:52:47	0:00:05
Move back to home position			14:52:47	14:53:05	0:00:18

Some delay and extra flushing between Legs 5 & 6.
Ineffective mining as HWEE is spaced above simulant surface.

Mining Pass 13 (6 Legs, No Tilt)

	5/16/2018	Wed			
Moving to start position			14:53:06	14:53:22	0:00:16
On hold			14:53:22	14:53:35	0:00:13
Mining down into simulant			14:53:35	14:54:02	0:00:27
Mining - X-axis Leg 1			14:54:02	14:54:17	0:00:10
Mining - Y-axis Jog 1			14:54:12	14:54:15	0:00:04
Mining - X-axis Leg 2			14:54:16	14:54:29	0:00:11
Mining - Y-axis Jog 2			14:54:29	14:54:34	0:00:05
Mining - X-axis Leg 3			14:54:34	14:54:47	0:00:13
Mining - Y-axis Jog 3			14:54:47	14:54:50	0:00:03
Mining - X-axis Leg 4			14:54:50	14:55:03	0:00:13
Mining - Y-axis Jog 4			14:55:03	14:55:07	0:00:04
Mining - X-axis Leg 5			14:55:07	14:55:19	0:00:12
Mining - Y-axis Jog 5			14:55:19	14:55:21	0:00:04
Mining - X-axis Leg 6			14:55:23	14:55:35	0:00:13
Flush at end of run			14:55:36	14:55:38	0:00:02
Move back to home position			14:55:38	14:56:05	0:00:28

Ineffective mining as HWEE is spaced above simulant surface.

Cleaning Pass 13 (6 Legs, No Tilt)

	5/16/2018	Wed			
Moving to start position			14:56:06	14:56:23	0:00:20
On hold			14:56:26	14:56:51	0:00:25
Mining - X-axis Leg 1			14:56:51	14:57:00	0:00:09
Mining - Y-axis Jog 1			14:57:00	14:57:18	0:00:18
Mining - X-axis Leg 2			14:57:18	14:57:30	0:00:12
Mining - Y-axis Jog 2			14:57:30	14:57:40	0:00:10
Mining - X-axis Leg 3			14:57:40	14:57:53	0:00:13
Mining - Y-axis Jog 3			14:57:53	14:58:07	0:00:14

HWEE Phase II Retrieval Test - Topographic Simulant - Video Record Summary - May 16, 2018

	Date	Day	Start Time	Stop Time	Elapsed Time
Mining - X-axis Jog 4			14:58:07	14:58:19	0:00:12
Mining - Y-axis Jog 4			14:58:19	14:58:27	0:00:08
Mining - X-axis Jog 5			14:58:27	14:58:40	0:00:13
0000000441000000.mp4					
Mining - Y-axis Jog 5			14:58:40	14:59:00	0:00:20
Mining - X-axis Jog 6			14:59:00	14:59:14	0:00:14
Flush at end of run			14:59:14	14:59:21	0:00:07
On hold			14:59:21	14:59:47	0:00:26
Moving up vertically			14:59:47	15:01:05	0:01:18
Move back to home position			15:01:05	15:01:17	0:00:07

Ineffective clearing as HWEE is spaced above simulant surface.

End of Test Observation	5/16/2018	Wed			
On hold			15:01:12	15:01:21	0:00:09
Moved to Capture Tank horizontally			15:01:21	15:01:43	0:00:22
Observe retrieval results by test personnel			15:01:43	15:04:48	0:03:05
On hold			15:04:48	15:07:37	0:02:49
Moving HWEE horizontally			15:07:37	15:08:00	0:00:23
Moving HWEE down vertically			15:08:00	15:08:52	0:00:52
On hold - Nothing happening			15:08:52	15:19:00	0:10:08

HWEE Phase II Retrieval Test - Topographic Simulant

Video Snapshots - May 16, 2018

VIDEO SNAPSHOTS

(See associated Video Summary Record for Written Details)

Note: The video record below only used CAM 1 video data. CAM 2 video would show the same video sequences but looking back at the simulant tank from the opposing end (i.e. end by capture tank)



Figure TS1 – Initial conditions. HWEE in Capture Tank to set pressure.



Figure TS2 – Pass 1 – Leg 1 – Start



Figure TS3 – Pass 1 – Leg 1 – End



Figure TS4 – Pass 1 – Leg 2 – End



Figure TS5 – Pass 2 – Leg 1 – End



Figure TS6 – Pass 2 – Leg 2 – End



Figure TS7 – Pass 3 – Leg 1 – End

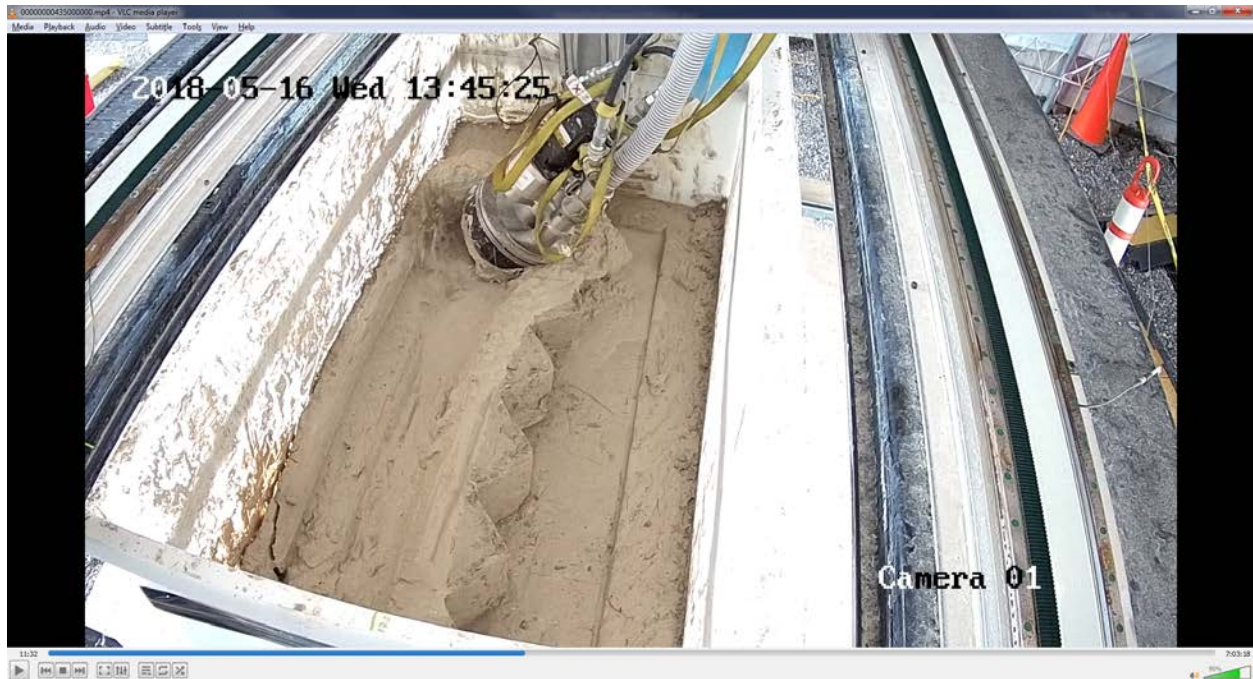


Figure TS8 – Pass 3 – Jog 1 – End

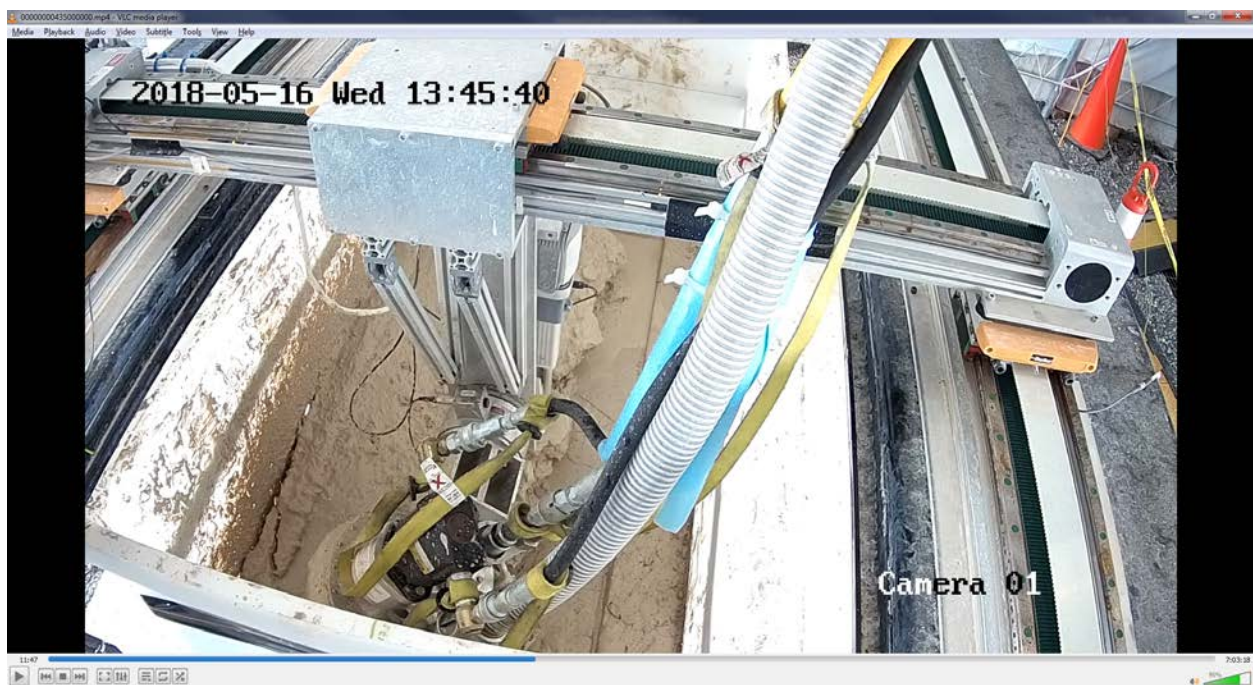


Figure TS9 – Pass 3 – Leg 2 – End



Figure TS10 – Pass 3 – Jog 2 – End



Figure TS11 – Pass 3 – Leg 3 – End

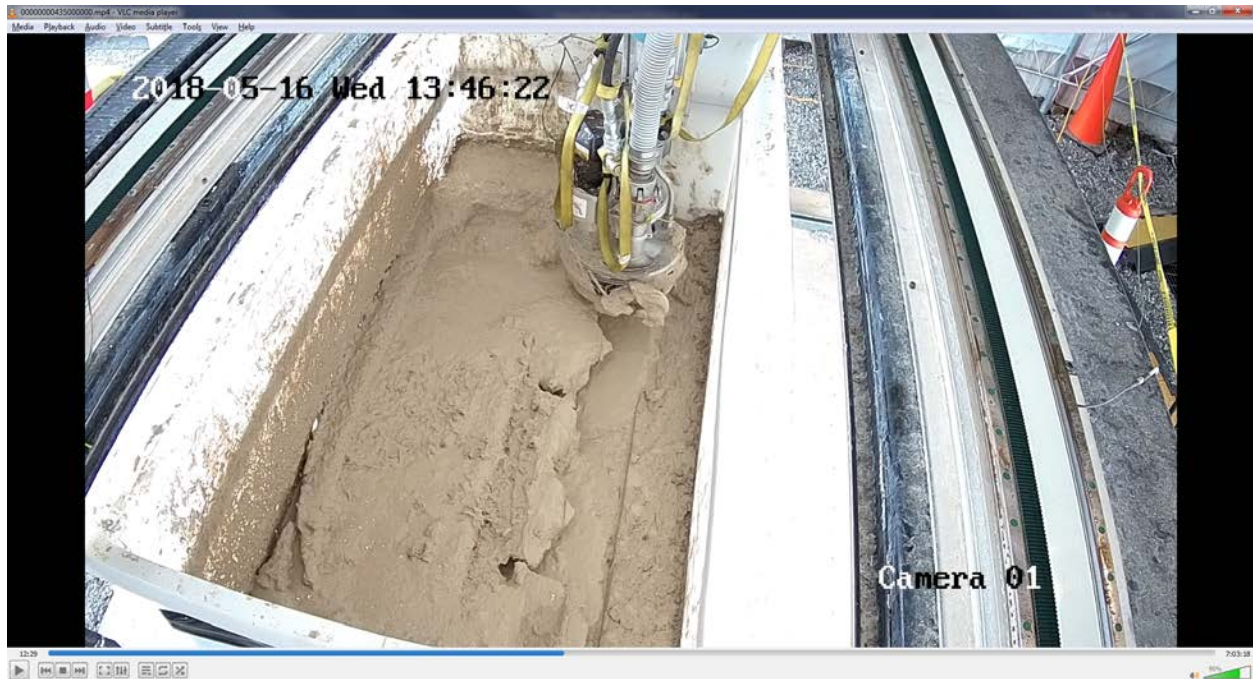


Figure TS11 – Pass 3 – Leg 3 – End (HWEE Moved)



Figure TS12 – Pass 3 – Leg 3 – End (HWEE Moved to Start)



Figure TS13 – Pass 4 – Leg 1 – End



Figure TS14 – Pass 4 – Leg 2 – End

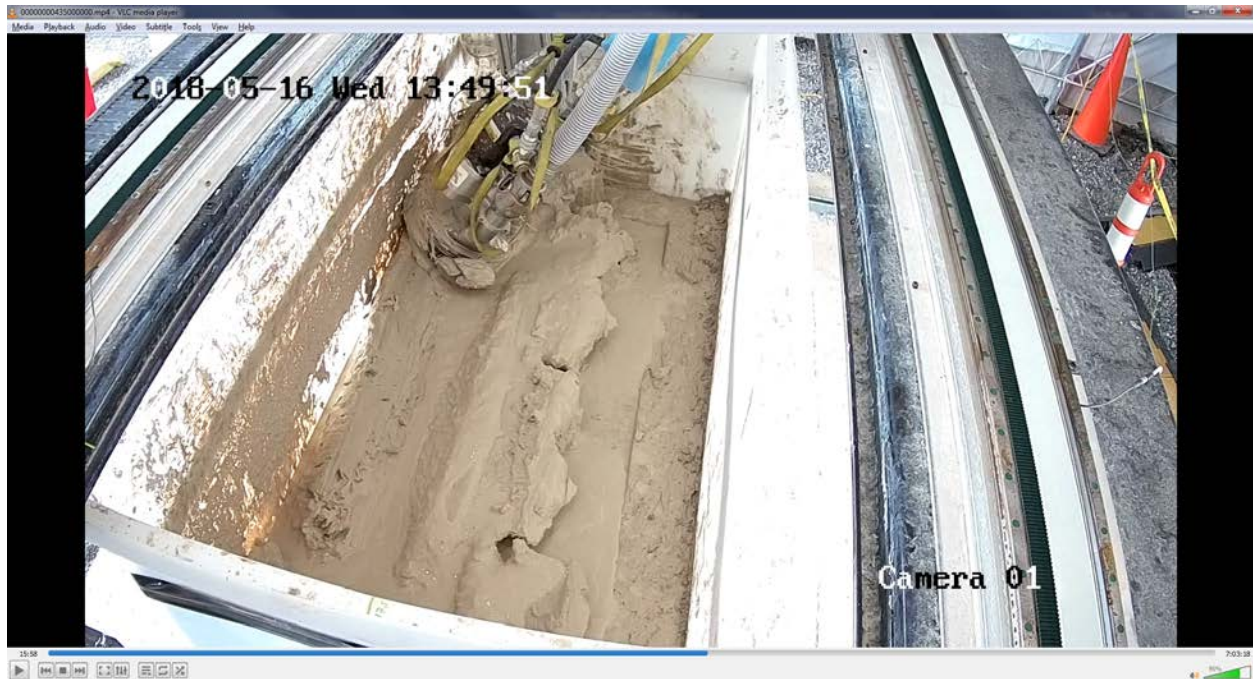


Figure TS15 – Pass 5 – Leg 1 – End

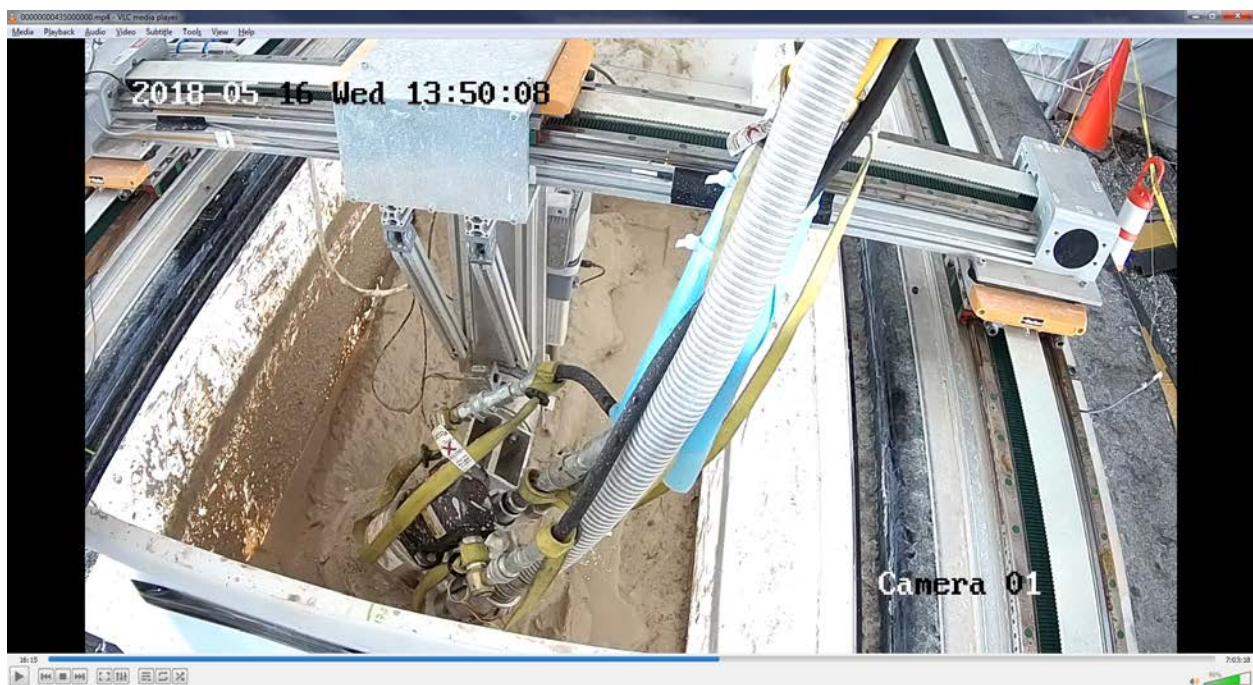


Figure TS16 – Pass 5 – Leg 2 – End

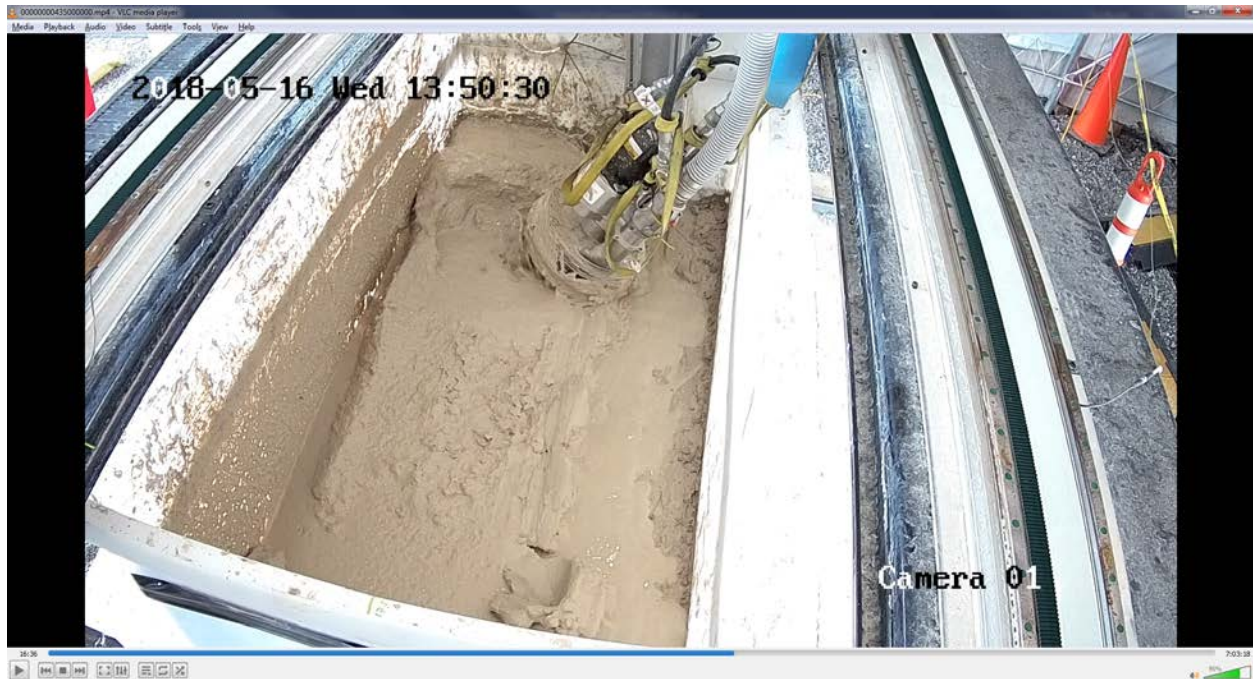


Figure TS17 – Pass 5 – Leg 3 – End



Figure TS18 – Pass 5 – Leg 3 – End (HWEE Moved – Small Vertical Position)



Figure TS19 – Pass 5 – Leg 3 – End (HWEE Moved – High Vertical Position)



Figure TS20 – Simulant Tank top removed (11 inches)



Figure TS21 – Setting HWEE pressure (1000 psi) in Capture Tank



Figure TS22 – Pass 6 – Leg 1 – End



Figure TS23 – Pass 6 – Leg 2 – End

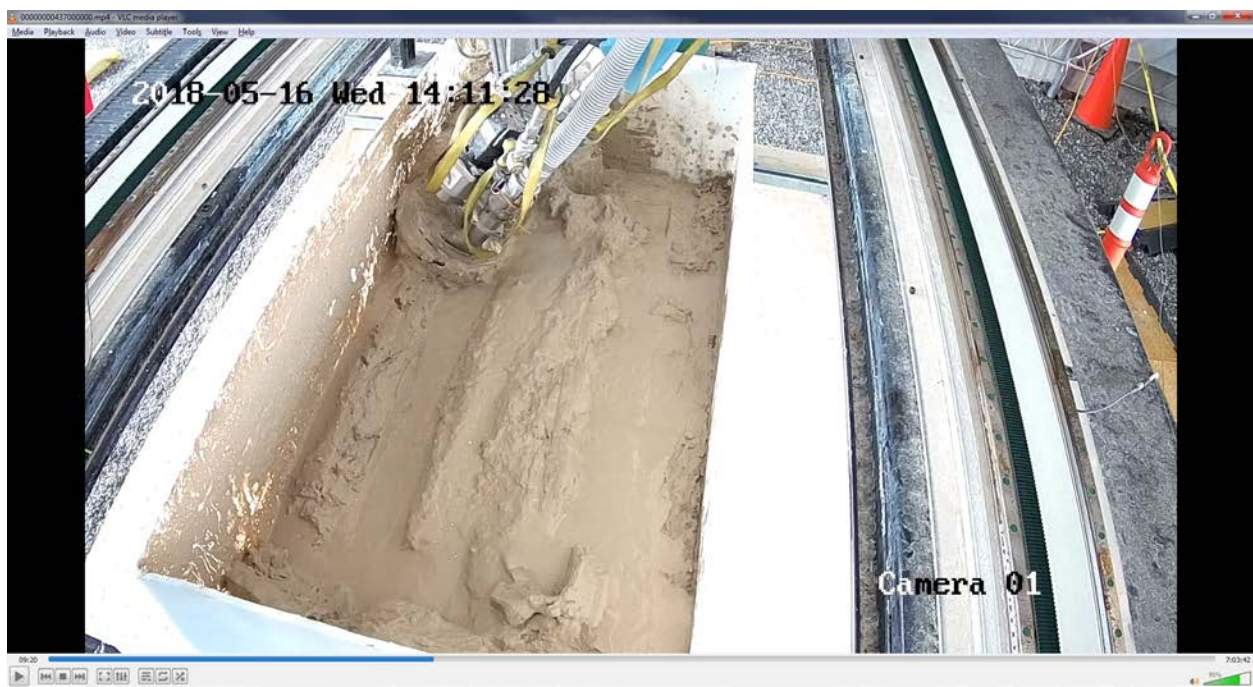


Figure TS24 – Pass 7 – Leg 1 – End

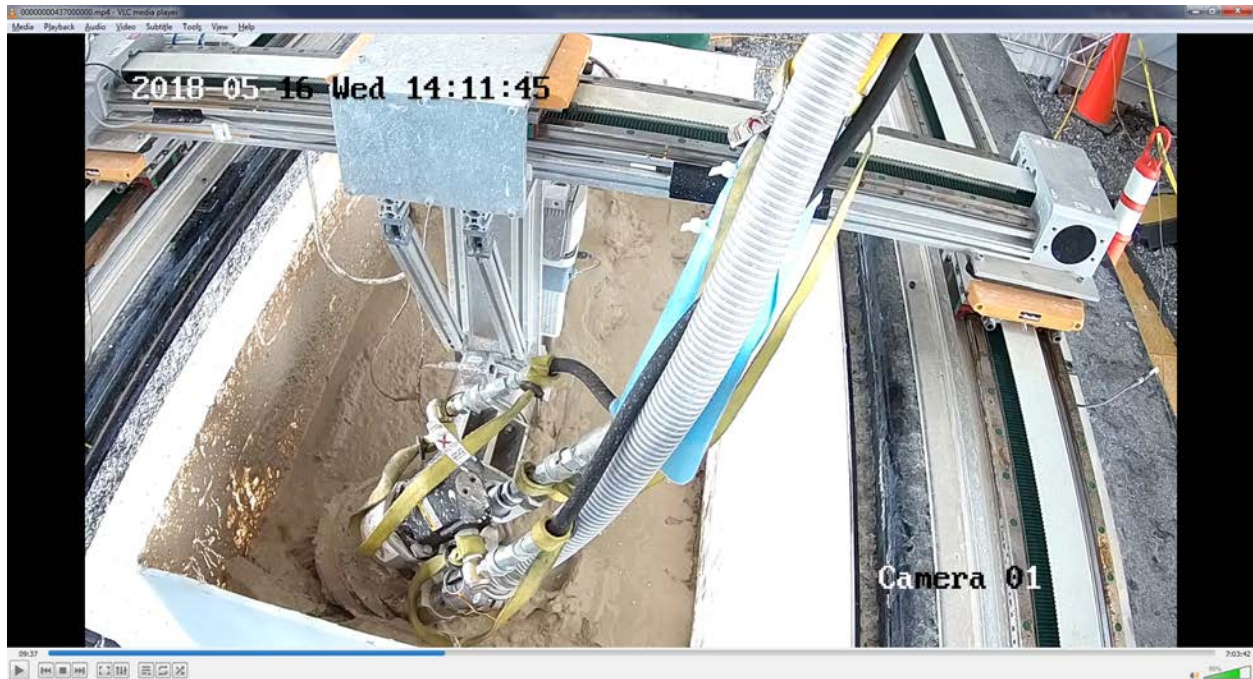


Figure TS25 – Pass 7 – Leg 2 – End



Figure TS26 – Pass 8 – Leg 1 – End

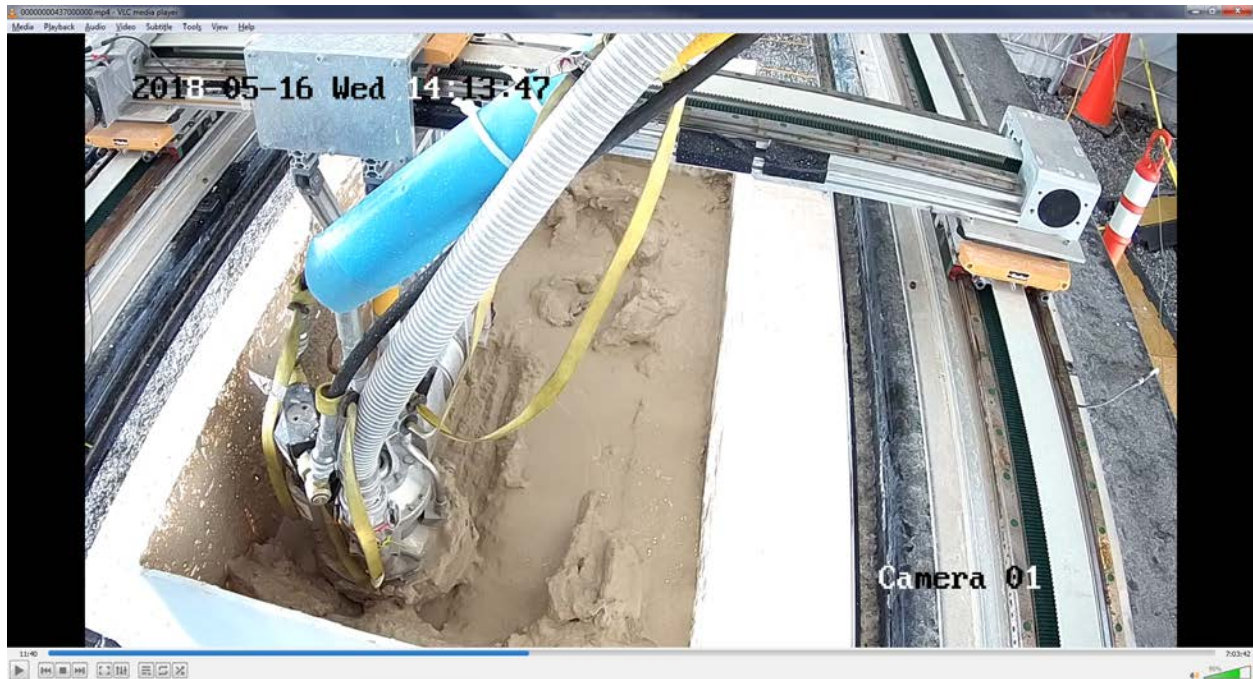


Figure TS27 – Pass 8 – Leg 2 – End



Figure TS28 – Pass 9 – Leg 1 - End

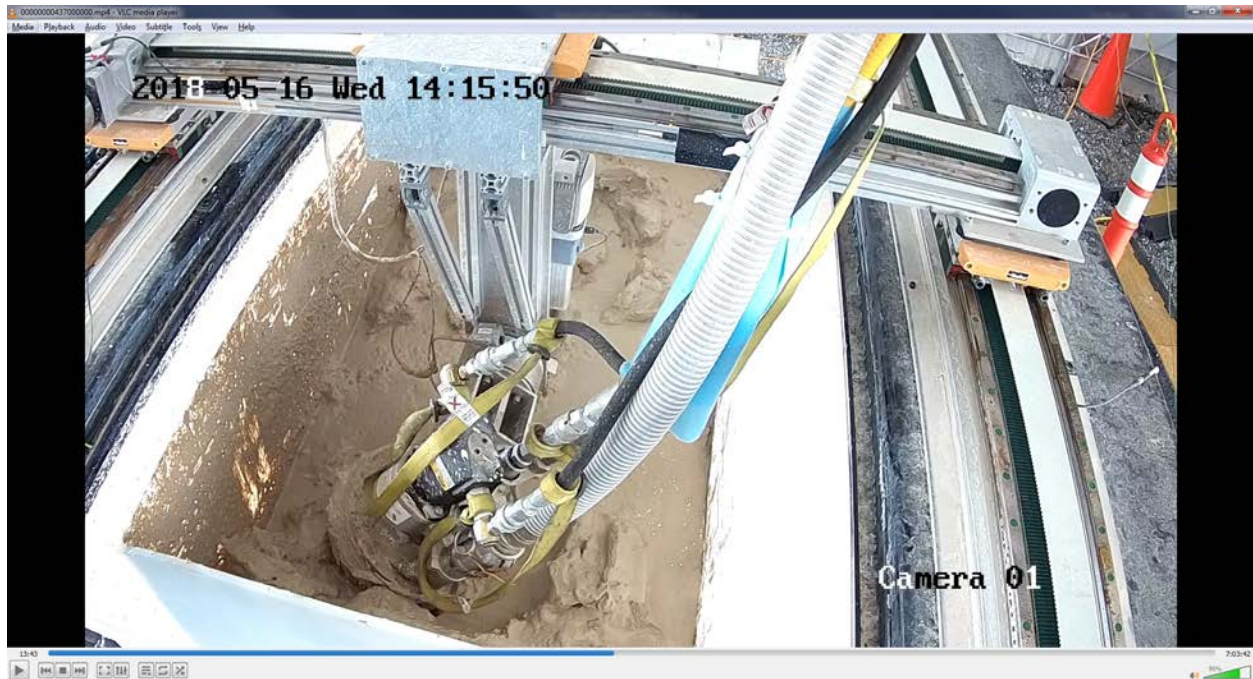


Figure TS29 – Pass 9 – Leg 2 – End



Figure TS30 – Pass 9 – Leg 3 – End



Figure TS30 – Pass 9 – Leg 3 – End (HWEE in raised position)



Figure TS31 – Removing simulant shelf in Simulant tank – Load 1



Figure TS32 – Load 1 removed



Figure TS33 – Load 2 being removed



Figure TS34 – Load 2 removed.



Figure TS35 – Load 3 being removed.



Figure TS36 – Load 3 removed.



Figure TS37 – Load 4 being removed.



Figure TS38 – Load 4 removed.



Figure TS39 – Load 5 being removed.



Figure TS40 – Load 5 removed.



Figure TS41 – Setting HWEE pressure in Capture Tank



Figure TS42 – Pass 10 – Leg 1 – End



Figure TS43 – Pass 10 – Leg 2 – End



Figure TS44 – Pass 10 – Leg 3 – End



Figure TS45 – Pass 10 – Leg 4 – End



Figure TS46 – Pass 10 – Leg 5 – End



Figure TS47 – Pass 10 – Leg 6 – End



Figure TS48 – Pass 11 – Leg 1 – End



Figure TS49 – Pass 11 – Leg 2 – End



Figure TS50 – Pass 11 – Leg 3 – End



Figure TS51– Pass 11 – Leg 4 – End



Figure TS52– Pass 11 – Leg 5 – End



Figure TS53– Pass 11 – Leg 6 – End



Figure TS54– Pass 11 – Tilt 35° - Leg 1 – End



Figure TS55– Pass 12 – Leg 1 – End



Figure TS56– Pass 12 – Leg 2 – End



Figure TS57– Pass 12 – Leg 3 – End



Figure TS58– Pass 12 – Leg 4 – End



Figure TS59– Pass 12 – Leg 5 – End



Figure TS60– Pass 13 – Leg 1 – End



Figure TS61– Pass 13 – Leg 2 – End



Figure TS62– Pass 13 – Leg 3 – End



Figure TS63– Pass 13 – Leg 4 – End



Figure TS64– Pass 13 – Leg 5 – End



Figure TS65– Pass 13 – Leg 6 – Start



Figure TS66– Pass 13 – Leg 6 – Middle



Figure TS67– Pass 13 – Leg 6 – End



Figure TS68– Pass 13 – Leg 1 – End – Suction Clean – Flushing during Y-axis jogs.



Figure TS69– Pass 13 – Leg 2 – End – Suction Clean – Flushing during Y-axis jogs.



Figure TS70– Pass 13 – Leg 3 – End – Suction Clean – Flushing during Y-axis jogs.



Figure TS71– Pass 13 – Leg 4 – End – Suction Clean – Flushing during Y-axis jogs.



Figure TS72– Pass 13 – Leg 5 – End – Suction Clean – Flushing during Y-axis jogs.



Figure TS73– Pass 13 – Leg 6 – End – Suction Clean – Flushing during Y-axis jogs.



Figure TS74– HWEE Topographic Simulant Retrieval Completed – View From Above

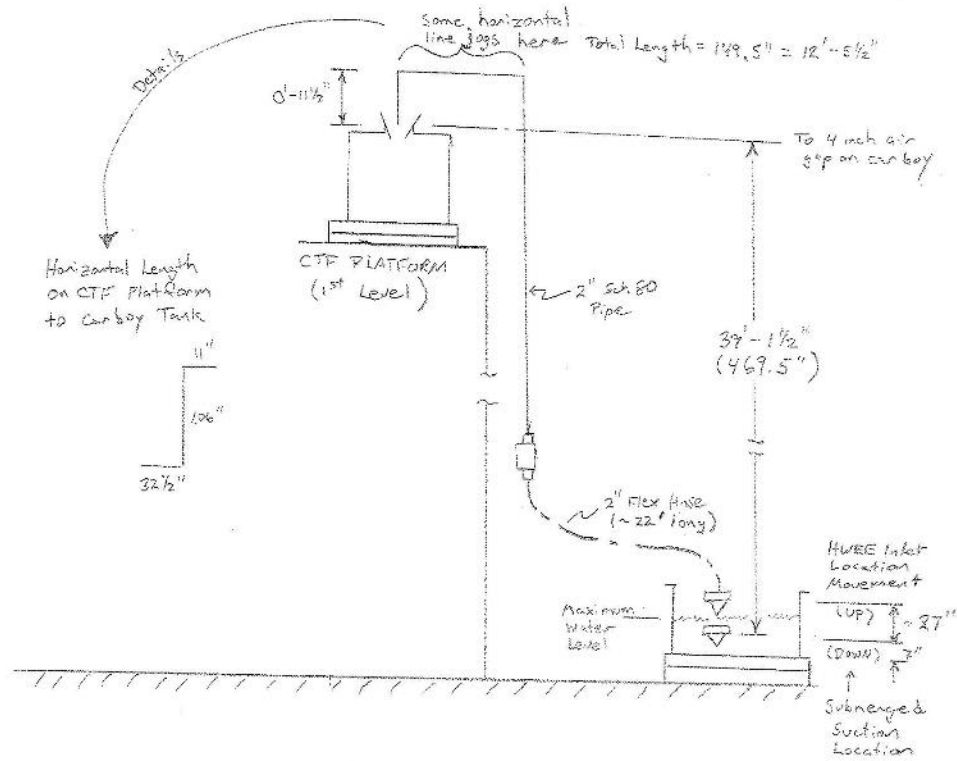


Figure TS75– HWEE Topographic Simulant Retrieval Completed – View From Above with HWEE moved.

Appendix D: Jet Pump Lift Test Summaries

HWEE Vertical Test Configuration (measured)

5/22/18



Appendix F: General Test Information

Appendix intentionally left blank.

Appendix G: Retrieval Rates and Slurry Dilution Ratio

This appendix provides the methodology for calculation of retrieval rate and slurry dilution ratio from Berglin et al. (2018).

The retrieval rate, volume of simulant retrieved per time, is calculated using the mass, volume, and temperature measurements of the retrieval tank contents. During HWE operation, the measured total mass added to the retrieval tank, MR, comprises the mass of simulant transferred, MSR, and mass of water, MHR, transferred to the retrieval tank by the HWEE and jet pump. From that conservation of mass, the mass fraction of simulant in the retrieval tank, WSR, is defined by

$$WSR = \frac{\frac{1}{\rho_H} - \frac{1}{\rho_R}}{\frac{1}{\rho_H} - \frac{1}{\rho_S}} \quad (C.1)$$

where ρ_H is the water density and ρ_S is the as-prepared simulant density. The bulk density of the retrieved simulant and water, ρ_R , is given by

$$\rho_R = \frac{MR}{VR} \quad (C.2)$$

with VR as the measured total volume added to the retrieval tank. The water density in the retrieval tank is calculated from the temperature by

$$\rho_H = 999.85308 + 6.32693E - 2 \times T - 8.523829E - 3 \times T^2 + 6.943248E - 5 \times T^3 - 3.821216E - 7 \times T^4 \quad (C.3)$$

where T is the measured temperature in Celsius (Jones 1992). Equation (C.3) is applicable to air-free water over the temperature range of 5 to 40° C.

The mass of simulant in the retrieval tank is then simply

$$MSR = MR \times WSR \quad (C.4)$$

and the retrieval rate, RR, is thus

$$RR = \frac{\frac{MSR}{\rho_S}}{t} \quad (C.5)$$

where t is the test time.

The dilution ratio is the simulant retrieval rate multiplied by the test time divided by the volumetric water usage of the system, or

$$DR = \frac{RR \times t}{\frac{MH}{\rho_H}} \quad (C.6)$$

and MH is the total water mass used during retrieval; the water added to the retrieval tank and potentially to the simulant tank by the HWEE and the jet pump. The water mass added to the retrieval tank is

$$MHR = MR \times (1 - WSR) \quad (C.7)$$

and the mass of any water potentially added to the simulant tank, MHS, is

$$MHS = MS1 - (MS0 - MSR) \quad (C.8)$$

where MS1 is the total mass in the simulant tank at the completion of the test, and MS0 is the initial simulant mass in the simulant tank.

References

Jones FE. 1992. ITS-90 Density of Water Formulation for Volumetric Standards Calibration. *Journal of Research of NIST*. May-June; 97(3): 335 – 340.



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