



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Hanford Waste End Effector Prototype Test Plan – Phase II

Prepared for Washington River Protection Solutions

April 2018

EJ Berglin
BE Wells
CA Burns



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

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062

www.osti.gov
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
or (703) 605-6000
email: info@ntis.gov
Online ordering: <http://www.ntis.gov>

Executive Summary

This test plan describes the Phase II testing program of the Hanford Waste End Effector (HWEE) at the Washington River Protection Solutions (WRPS) Cold Test Facility (CTF) using a Pacific Northwest National Laboratory (PNNL)-designed testing setup. This task builds on Phase I development testing completed in August 2017 and reported in PNNL-26856 to address some key actual tank waste challenges. The task includes demonstrating 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 will start to assess the lifting capabilities of this device for transporting waste out of an underground tank. The 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 have been modified and upgraded to implement the Phase II test program and measure various process parameters. The tests will involve retrieval of water and kaolin (sludge) simulant to determine pumping rate, dilution factors, and screen fouling rate.

Acronyms and Abbreviations

ALC	air lift circulator
ASTM	American Society for Testing and Materials
CTF	Cold Test Facility
DOE	U.S. Department of Energy
FIO	For Information Only
FNPT	female national pipe thread
HMS	hose management system
HWEE	Hanford Waste End Effector
M&TE	measurement and test equipment
PNNL	Pacific Northwest National Laboratory
PRM	pressure reducing manifold
PUREX	plutonium uranium extraction
RPM	revolutions per minute
WRPS	Washington River Protection Solutions

Contents

Executive Summary	iii
Acronyms and Abbreviations	iv
1.0 Introduction	1.1
2.0 Specifications and Data Quality Objectives	2.1
2.1 Phase II Requirements.....	2.1
2.2 Prior Testing Results	2.4
2.3 Data Quality Objectives	2.6
3.0 Waste Retrieval End Effector Description	3.1
4.0 Test Approach	4.1
4.1 Test Setup.....	4.1
4.2 HWEE Retrieval Tests	4.1
4.3 Jet Pump Vertical Lift Tests.....	4.2
4.4 Test Equipment and Instrumentation	4.6
4.4.1 Units under Test	4.7
4.4.2 Equipment	4.7
4.4.3 Instrumentation.....	4.8
4.4.4 Simulant Development.....	4.9
4.4.5 Simulant Preparation	4.25
5.0 Test Instructions	5.1
5.1 Instrument Verification and Cross-check.....	5.2
5.2 HWEE Component Testing.....	5.2
5.3 HWEE Retrieval Tests	5.4
5.3.1 Pre-test Procedure	5.4
5.3.2 Test Procedure.....	5.4
5.3.3 Post-test Procedure.....	5.8
5.4 Jet Pump Vertical Lift Tests.....	5.8
5.4.1 Pre-test Procedure	5.9
5.4.2 Test Procedure.....	5.9
5.4.3 General Procedures for all Jet Pump Vertical Lift Testing	5.10
5.4.4 Post-test Procedure	5.11
6.0 Data Evaluation	6.1
6.1 Planned Analyses	6.1
6.2 Water Usage of HWEE	6.1
6.3 Retrieval Rates and Slurry Dilution Rates – Retrieval Tests	6.1
6.4 Pumping Rate, Water Usage, and Retrieval Rates – Jet Pump Vertical Lift Test.....	6.3
7.0 Project Record System.....	7.1

7.1	Software and Control	7.1
7.2	Engineering Records	7.1
7.3	Calibration Records.....	7.1
7.4	Quality Assurance	7.2
8.0	Facility and Safety Considerations	8.1
8.1	Electrical Supply	8.1
8.2	Water	8.1
8.3	Compressed Air.....	8.1
8.4	Safety Precautions	8.1
8.5	Training and Qualification Requirements	8.4
8.6	Waste Simulant Minimization and Management	8.4
9.0	References	9.1
	Appendix A M&TE Calibration	A.1
	Appendix B Piping and Instrumentation Diagram.....	B.1

Figures

Figure 3.1. Hanford Waste End Effector Concept	3.2
Figure 4.1. HWEE Retrieval Overall Test Setup	4.1
Figure 4.2. HWEE Retrieval Test Setup – View 1	4.2
Figure 4.3. HWEE Retrieval Test Setup – View 2	4.2
Figure 4.4. HWEE Vertical Test Setup – View 1	4.3
Figure 4.5. HWEE Vertical Test Setup – View 2	4.4
Figure 4.6. HWEE Vertical Test Setup – View 3	4.4
Figure 4.7. HWEE Vertical Test Setup – View 4	4.5
Figure 4.8. Jet Pump Vertical Lift Test Setup.....	4.6
Figure 4.9. Shear Strength Profile in A-101 (from Wells et al. 2011)	4.11
Figure 4.10. A-106 Core Sample Locations (Riser Information SD-RE-TI-053 Rev 8, Core Locations from Rogers [1993])	4.13
Figure 4.11. Core - 1, Riser – 17, Segment – 3, Bottom of Sediment (Rogers 1993)	4.13
Figure 4.12. Core - 1, Riser – 17, Segment – 3, Close-up, Inferred Extrusion Length Locations Denoted	4.13
Figure 4.13. Core - 2, Riser – 20, Segment – 3, Bottom of Sediment (Rogers 1993)	4.14
Figure 4.14. Core - 2, Riser – 20, Segment – 3, Close-up, Inferred Extrusion Length Locations Denoted	4.14
Figure 4.15. Core - 2, Riser – 20, Segment – 2, “Middle” of Sediment (Rogers 1993)	4.14
Figure 4.16. Core - 2, Riser – 20, Segment – 2, Close-up, Inferred Extrusion Length Locations Denoted	4.14
Figure 4.17. Extrusion Length Estimated Shear Strength (Upper Bound) as a Function of Elevation in Sediment	4.15
Figure 4.18. A-1016 Extrusion Length Estimated Shear Strength Range in Comparison to Hanford Waste Sediment Characterization (Data from Wells et al. 2011).....	4.16
Figure 4.19. A-106 Waste Surface Photograph Mosaic.....	4.17
Figure 4.20. A-106 Waste Surface, Task Wall with Stiffener Rings, Equipment Risers, and ALC. Yellow waste surface with gray “mounds” around risers, ALC, and along tank wall.	4.18
Figure 4.21. A-106 Waste Surface, Equipment Riser and ALC	4.19
Figure 4.22. A-106 Waste Surface Level Comparison	4.20
Figure 4.23. A-106 Waste Surface, ALC and Stiffener Ring Spacing Dimensions, “Mounds” Apparent	4.21
Figure 4.24. A-106 Waste Surface, Stiffener Ring Spacing Dimension, “Mounds” Apparent	4.22
Figure 4.25. A-106 Waste Surface Showing Mound Features.....	4.22
Figure 4.26. Calculated Approximate Mound Vertical Extent as a Function of Waste Shear Strength ..	4.23
Figure 4.27. Simulant Configuration for Waste Layering Test	4.24
Figure 4.28. Simulant Configuration for Waste Topography Test	4.25

Tables

Table 2.1. Requirements for HWEE Phase II Testing	2.1
Table 2.2. Effectiveness Tests Results Summary	2.5

Table 2.3. HWEE Phase I Data Requirements.....	2.7
Table 4.1. Phase I HWEE Simulants	4.25
Table 5.1. HWEE Prototype Phase II Tests.....	5.1
Table 5.2. Instrument Field Checks	5.2
Table 5.3. Water Testing Summary	5.3
Table 8.1. Job Hazards Assessment	8.2

1.0 Introduction

This test plan describes the Phase II testing program of the Hanford Waste End Effector (HWEE) at the Washington River Protection Solutions (WRPS) Cold Test Facility (CTF) using a Pacific Northwest National Laboratory (PNNL)-designed testing setup. This task builds on Phase I development testing completed in August 2017 and reported in PNNL-26856 to address some key actual tank waste challenges. The task includes demonstrating 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 will start to assess the lifting capabilities of this device for transporting waste out of an underground tank. The Phase II development testing is defined in the WRPS Statement of Work (SOW) and builds on Phase I achievements supporting Hanford single shell tank retrievals. The 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 are modified and upgraded to implement the Phase II test program and measure various process parameters to perform effectiveness testing. Testing will employ benign simulant materials, prepared and characterized by PNNL, as recommended in PNNL-26206 (Gauglitz et al. 2017) and similar to the kaolin (sludge) material used during Phase I. The tests will involve retrieval of water and kaolin (sludge) simulant to determine pumping rate, dilution factors, and a demonstration of vertical pumping capability.

The HWEE used in Phase II uses the HWEE from Phase I testing that was fabricated by HiLine Engineering & Fabrication, Inc. (HiLine) based on the procurement specification RPP-SPEC-61356. Prior to HWEE use in this Phase II testing, the HWEE is inspected and reconditioned as needed to start operating conditions. In addition, upgrades to the HWEE are being implemented by HiLine, including a more robust inlet screen, internal flush jet modification for lower water usage, and removal of the external flush mole that was not used during Phase I retrieval testing. PNNL is adding some limited rotational capability to the HWEE along one translational direction to gain some additional movement capability and flexibility needed for Phase II demonstrations of more complex retrieval mining techniques.

As explained in the Phase I test plan, the HWEE is a water-based scarifier originally developed by PNNL for U.S. Department of Energy (DOE) 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, specifically, the Gunite and Associated Tanks as described in PNNL-26037 (Hatchell et al. 2016). The HWEE is being assessed for potential use in Hanford tank retrievals because it is expected to use less water during waste retrieval than other water-based methods (e.g., sluicing) previously used in Hanford tanks. This is primarily because the HWEE uses three rotating high-pressure jets for dislodging the waste and a high-velocity conveyance system to retrieve the water and the waste locally at the point of waste dislodging.

2.0 Specifications and Data Quality Objectives

This section describes the requirements for Phase II HWEE testing, summarizes the results of previous Phase I testing, and presents the data quality objectives for Phase II testing.

2.1 Phase II Requirements

Requirements related to Phase II HWEE testing are listed in Table 2.1. These requirements are the primary drivers for HWEE Phase II testing and are based on the HWEE Phase II Statement of Work (Wooley 2018) Section 3.4.

Table 2.1. Requirements for HWEE Phase II Testing

Item	Source	Description	Impact to HWEE Testing Requirement
A	SOW 3.1	Simulant Physical Property Definition and Simulant Comparison.	Simulant selection is based on review of HWEE Phase I testing results in PNNL-26856 (Berglin et al. 2017) and needs of Phase II. Simulant properties and definition for Phase II testing are included in this test plan for simulant development (section 4.2.3) and simulant preparation (section 4.2.4). The simulant selected represents a sludge waste form use in Phase I that is kaolin clay based. For Phase II, two sludge forms have been developed to provide a weak and strong shear strength kaolin clay sludge.
B	SOW 3.2	HWEE Support Phase II – Assessment of Modification of the HWEE from Phase I for Phase II.	The HWEE modifications to flushing components have been assessed by PNNL and submitted to WRPS (Hatchell 2018) and include reduced jet size on the HWEE internal flush jet and removal of the HWEE flush mole.
C	SOW 3.3	Test Facility Preparation Phase II.	The WRPS CTF will be used as the location to perform testing like Phase I. PNNL is providing the associated test equipment for Phase II testing of the HWEE and all necessary modification upgrades for CTF testing.
D	SOW 3.4	Phase II End Effector Testing.	See subsections below.
D.1	SOW 3.4 Bullet 1	Continue to Optimize the Jet Pump for Lower Water Usage.	Phase II testing jet pump operation will mimic Phase I without optimization. Results from Phase I testing indicate that jet pump water usage may be reduced by reducing the pressure based on flooded suction data (see Test Report section 5.1.2.1 and 5.1.1.4). However, much of the HWEE operation is with non-flooded suction, and the effects of pressure reduction for this condition are unknown. Jet pump component testing for non-flooded suction is believed to be complex and is out of scope for Phase II.

Item	Source	Description	Impact to HWEE Testing Requirement
D.2	SOW 3.4 Bullet 2	Continue to Optimize Mining Paths to Maximum The Retrieval Rate.	The HWEE is being modified to include a tilt function that will give additional mining flexibility. In addition, PNNL is looking at the feasibility of increased flexibility in the programmed scanner motions that will allow additional motions beyond the serpentine path restriction of Phase I as budget and time permits. From experience gained from Phase I mining operation, new mining strategies are planned for Phase II that will use any new mining flexibility described above that will be available during Phase II retrieval testing.
D.3	SOW 3.4 Bullet 3	Develop Automatic Screen Cleaning Methods. Incorporate Pneumatic Actuated Valves for the Screen Flush.	The HWEE high-pressure system is being upgraded to include a pneumatic actuated valve associated with the HWEE internal flush. Automated screen flushing will be done by activation of this new valve.
D.4	SOW 3.4 Bullet 4	Continue to Optimize HWEE Water Usage/Water Remaining.	Water remaining depends on the ability of the HWEE to access and retrieve the water used during waste retrieval operations. The water used by the HWEE waterjets during retrieval simulations and the water remaining in the simulant tank will be measured by mass and/or volume. The simulant tank for Phase II has been changed to eliminate the inaccessible void volumes at the end of the tank where water would accumulate. A secondary tank (or equivalent feature) will be used to set HWEE water pressures. Pneumatic valve(s), like that associated with the internal flush, will be used to better regulate water usage. If the HWEE internal flushing smaller jet size proves feasible during pretesting, flush water usage will be significantly reduced relative to Phase I.
D.5	SOW 3.4 Bullet 5	Determine HWEE Waste Dilution Ratio (Gallons of Water vs. Gallons of Simulant Removed).	Minor change from Phase I. The waste dilution ratio for Phase II will be determined by monitoring the weight, volume, and temperature of the water and simulant conveyed to the retrieval tank. The retrieval tank for Phase II has been upgraded to include a level and temperature sensor to more precisely and actively measure the contents deposited into the retrieval tank during HWEE retrieval. Phase I testing only included weight measurement and occasional crude level measurements with a scale from outside of the tank.

Item	Source	Description	Impact to HWEE Testing Requirement
D.6	SOW 3.4 Bullet 6	Determine HWEE Reaction Forces (Standoff Distance, Traverse Velocity, High-pressure Water Flow).	No change from Phase I. The HWEE reaction forces will be measured along with standoff distance, traverse velocity, and water flow/pressure as appropriate. Standoff distance will be initial location of HWEE above the simulant plane in a test run and will not include simulant removed from that plane during the test run.
D.7	SOW 3.4 Bullet 7	Determine Frequency of Back Flushing or Cleaning the HWEE and Associated Water Usage.	Flushing will be done periodically similar to Phase I operations. Phase II will not attempt to optimize flushing water usage, because that would take a separate testing program, but will continue to reduce water usage while maintaining that the HWEE screen remains clear. Conveyance rate monitoring from the HWEE will be used to assess screen clogging and the need for additional flushing. Modifications to a smaller internal flush jet size will reduce water usage. Pneumatically operated valves will all full flush pressure and flow to be achieved faster and reduce water usage. Data logging will be used to track flush times with greater accuracy.
D.8	SOW 3.4 Bullet 8	Determine HWEE adaptability to layered simulants (different strengths/erosion characteristics).	This is a new challenge from Phase I. For Phase II, the HWEE mining flexibility has been upgraded to include HWEE head tilt in one direction and additional mining path flexibility.
D.9	SOW 3.4 Bullet 9	Determine HWEE adaptability to uneven surfaces.	Same as response in D.8.
E	SOW 3.5	Deployment and Conveyance System Development	See subsections below.
E.1	SOW 3.5	Design/procure and construct a simple external HWEE conveyance system with vertical lift capability of at least 35 feet.	A vertical test apparatus has been designed that uses the CTF tank structure and platforms near the elevator to test the ability of the jet pump to achieve a minimum 35 feet of vertical lift. The HWEE is not used for this testing, but the HWEE inlet screen and conveyance length to the jet pump will be mocked up to simulate retrieval conditions and flow restrictions.

Item	Source	Description	Impact to HWEE Testing Requirement
E.2	SOW 3.5	Demonstrate jet pump capability to lift water/simulant materials to an overall height of at least 35 feet.	Jet pump configured in vertical orientation with suction end simulating HWEE Phase II retrieval flow testing conditions (suction only through HWEE screen) with the additional lift height on the jet pump discharge side to achieve at least 35 feet. Measure jet pump flow rate for lift with water only operating with fully flooded inlet. Demonstrate lift using typical retrieval three-phase flow operations with water and/or water with kaolin (sludge) simulant mix. Data collected from the 35-foot lift test, relevant data from HWEE Phase I testing, and consultations with the jet pump vendor shall be used to extrapolate jet pump performance at 60 assuming a linear extrapolation. Note that there was no data found to support a linear extrapolation.

2.2 Prior Testing Results

Prior testing related to this Phase II testing effort was completed in 2017 and is now designated as Phase I. The Phase I testing results are documented in PNNL-26856 and summarized in the Executive Summary as follows:

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

Table 2.2.¹ Effectiveness Tests Results Summary

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

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

Phase I tested three separate waste simulant types individually in a single layer with flat topography. As a result of Phase I testing, several retrieval challenges and HWEE testing and equipment upgrades were noted that could further define the HWEE capabilities and performance in Hanford waste tank retrieval assessments in Phase II as follows:

- 1) **More challenging waste retrieval mining to better mimic actual Hanford tank conditions as follows:**
 - a) Layered waste simulant mining – A layered simulant (see Section 4.4.4.4 “Layer Waste Simulant Target”) has been specified using the kaolin (sludge) waste form from Phase I with modified formulations to provide both a strong and weak shear strength (see Section 4.4.4.2 “A-106 Waste

¹ Table was numbered ES-1 in the original document.

Shear Strength”) kaolin material. The weaker kaolin will be sandwiched between layers of strong kaolin resulting in an overall depth 14 inches. This results in an increased mining depth over Phase I, which had a depth of 8 inches.

- b) Topography waste simulant mining – A stepped and jagged simulant profile (see Section 4.4.4.4 “Waste Topography Simulant Target”) has been specified to mimic more challenging tank waste profile as might be found near the tank walls or bottom corners where waste form is typically not flat. Maximum depth of this waste profile matches the layered waste depth of 14 inches and will use the strong shear strength kaolin simulant formulation (see Section 4.5.4).
- 2) **More challenging waste vertical conveyance of the jet pump to assess if waste can be lifted out of a Hanford waste tank or at least to a higher staging location.** Phase I testing demonstrated a suction lift through the HWEE of around 6 feet through approximately 15 feet of conveyance hose to the jet pump in a horizontal configuration; this resulted in no additional lift on the jet pump discharge. In Phase II, a jet pump vertical conveyance test has been configured that will mimic the Phase I suction lift and conveyance to the jet pump without the HWEE but with a simulated HWEE inlet screen. Additionally, the jet pump will be oriented in a vertical configuration to allow additional vertical discharge resulting in an overall lift height (suction + discharge) of at least 35 feet (see Section 4.3).
 - 3) **HWEE mining capabilities made more flexible to meet new mining challenges.** During Phase I testing, the HWEE head was fixed to motions in the three x-y-z planes and set programmed mining paths that limited mining efficiency. In Phase II, a rotation capability has been added along the x-axis plane to allow more flexible mining paths, including wall cleaning in one-dimension.
 - 4) **HWEE Inlet Screen made more robust.** During Phase I testing, the HWEE inlet screen was partial breached by the internal flush spray during testing for water usage at the higher pressures and was patched sufficiently to complete Phase I retrieval testing. In Phase II, the HWEE inlet screen design has been upgraded to be more robust.
 - 5) **HWEE water usage reduced.** During Phase I testing, water usage, especially for flushing, was deemed to be excessive and could be reduced. The HWEE internal flush jet size has been reduced to cut down water flow when flushing. The slow manual valve operation for HWEE internal flush activation is being upgraded to a faster-acting valve with pneumatic activation that will allow screen cleaning with less water used. The HWEE flush mole, not used in Phase I retrieval, is not being used in Phase II because it was demonstrated that the HWEE internal flush was adequate for clearing the HWEE of kaolin simulant.
 - 6) **Instrumentation upgrades to improve retrieval and water dilution rate calculations.** Instrumentation has been added to the retrieval tank, fluid level, and temperature so that along with weight, the simulant retrieved and water used can be actively measured. Other anticipated upgrades include active linear motion monitoring of the gantry 3D motion as waste is retrieved, rotation monitoring of the new HWEE head tilt activation, and the addition of signal indicators that can track valve positions (e.g., flush water activation) or test condition (key data marker).

The conceptual design, development, and previous testing of HWEE designs is described in the HWEE Phase I test plan PNNL-26856 (Berglin et al. 2017).

2.3 Data Quality Objectives

HWEE specifications that require testing to verify compliance were presented in Section 2.1.

Table 2.3 summarizes the objectives of the tests in terms of data requirement that will be fulfilled, the type of data that will be collected, and the desired accuracy. The desired accuracy is based on qualitative judgment on accuracy required to determine if the end effector performs adequately or requires design modifications.

Table 2.3. HWEE Phase I Data Requirements

Data Requirement	Data Type	Target Accuracy Objective
Retrieval		
Determine slurry retrieval rate and slurry dilution ratio for different test material configurations, including: Kaolin (sludge) in layered configuration Kaolin (sludge) with uneven surfaces	Test data Video record	+/-10%
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.

3.0 Waste Retrieval End Effector Description

The HWEE design used in Phase I will be used in Phase II retrievals with some minor changes that include the following:

- Tilt mechanism added in one direction
- Internal flush jet size reduced to cut down water flow (Hatchell 2018 letter report)
- External mole flush removed (Hatchell 2018 letter report)
- Inlet screen redesigned to be more robust
 - The previous screen had a hexagonal cell with an open area of 0.1217 in² per cell (with 0.375” flat to flat and no corner rad)
 - The revised screen had a hexagonal cell with an open area of 0.1150 in² per cell (with 0.365” flat to flat and a 0.031” corner radius)
 - The difference in open area between the previous screen and the revised screen is 5.5%; these changes are not expected to affect the performance of the HWEE
 - The bar thickness of the revised screen increased by 0.010 inches (+20%) relative to the previous screen.

The Phase II HWEE design with tilt mechanism update is shown in Figure 3.1. More details of the HWEE design and its development can be found in the Phase I test plan PNNL-26549 (Berglin et al. 2017), Section 3.0 and Phase I test report PNNL-26856 (Berglin et al. 2017). The three rotational jet nozzles installed in the HWEE are the same as Phase I (0.038-inch diameter each). HWEE is designed to operate up to 10,000 psi pressure and rotate the jets up to 300 RPM.

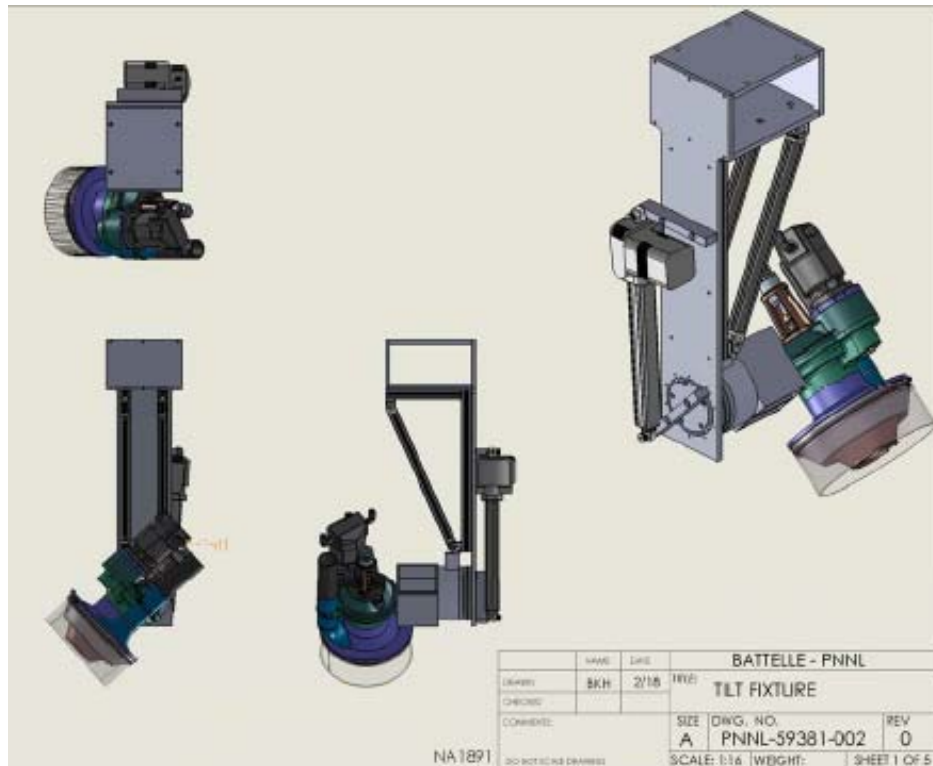


Figure 3.1. Hanford Waste End Effector Concept

The following retrieval descriptions are those used successfully in Phase I testing. Actual test results obtained during this testing sequence using the HWEE scarifier with enhanced capabilities from Phase I testing may modify some of the operating parameters and results listed below.

Kaolin (Sludge) Retrieval: Kaolin will be retrieved by operating the HWEE in the range of 1000 psi and 300 RPM. The pressure, rotation speed, and traverse speed should be adjusted to achieve a 1-inch depth of cut and very small fragments of dislodged material. By using a horizontal trajectory, the amount of sludge that is forced into the inlet can be controlled. The inlet shroud should be extended 1–2 inches into the waste (up to the top of the skirt) to limit aerosol generation, and the waterjets will cut clearance for the HWEE. Retrieval will generally consist of first performing horizontal mining using the x and y axis scanner motions along with HWEE head tilt to remove a layer of simulant material. The HWEE is then lowered into remaining simulant below using the gantry z-axis motion, and then horizontal mining is used to remove the next layer of simulant material. This process is repeated until all simulant that can be accessed by the HWEE is removed. Different mining strategies likely will be used to remove the waste simulant that is layered versus that with topography. During retrieval activities, frequent screen flushing is planned; however, a reduction in pumping rate may indicate the need to clear the screen by additional flushing.

4.0 Test Approach

The HWEE will be installed in the PNNL testing location at WRPS's CTF. The test setup, equipment, instrumentation, and simulants are discussed in this section.

4.1 Test Setup

Before starting Phase II retrieval testing, the HWEE will be static and operationally pressure tested by HiLine Engineering per the requirements of ASME B31.3-2014 (ASME 2014) and stamped with the maximum operating pressure². The conveyance jet pump is similarly pressure test stamped by the supplier KMT Aqua-Dyne. Testing will only proceed when the high-pressure system is approved for operation by the appropriate safety authorities at PNNL and WRPS.

Two separate tests are planned at CTF: the HWEE retrieval tests using a temporary tent enclosure and the jet pump vertical lift tests using the CTF tank structure platform shown in Figure 4.1.

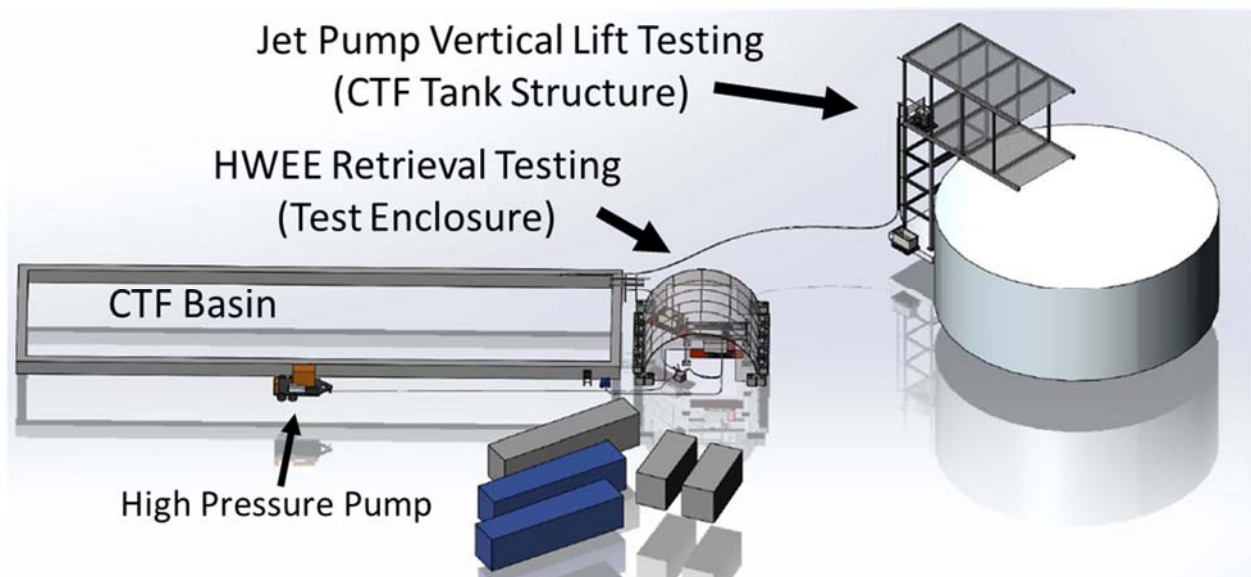


Figure 4.1. HWEE Retrieval Overall Test Setup

4.2 HWEE Retrieval Tests

An overview of the HWEE retrieval test setup is shown in Figure 4.2 and Figure 4.3. The HWEE is installed on the PNNL-designed gantry system. The gantry, conveyance line management arm, jet pump, and ancillary equipment near the HWEE are enclosed in a large tent. A high-pressure pump is staged nearby and hoses with quick connectors are used to supply high-pressure water to the HWEE jets, flush, and jet pump. A material receipt tank (retrieval tank) is located close to the test bed (simulant tank) to minimize pumping distance. Conveyance hoses/piping are used to connect the HWEE and jet pump to transport retrieved materials from the simulant tank to the retrieval tank. Instrumentation will be installed to measure process parameters, reaction forces, and retrieval performance. Simulant materials will be prepared and characterized.

² See TR-1711-WRP-241-001 Rev 0 Test Report Hanford Waste End Effector Refurbishment

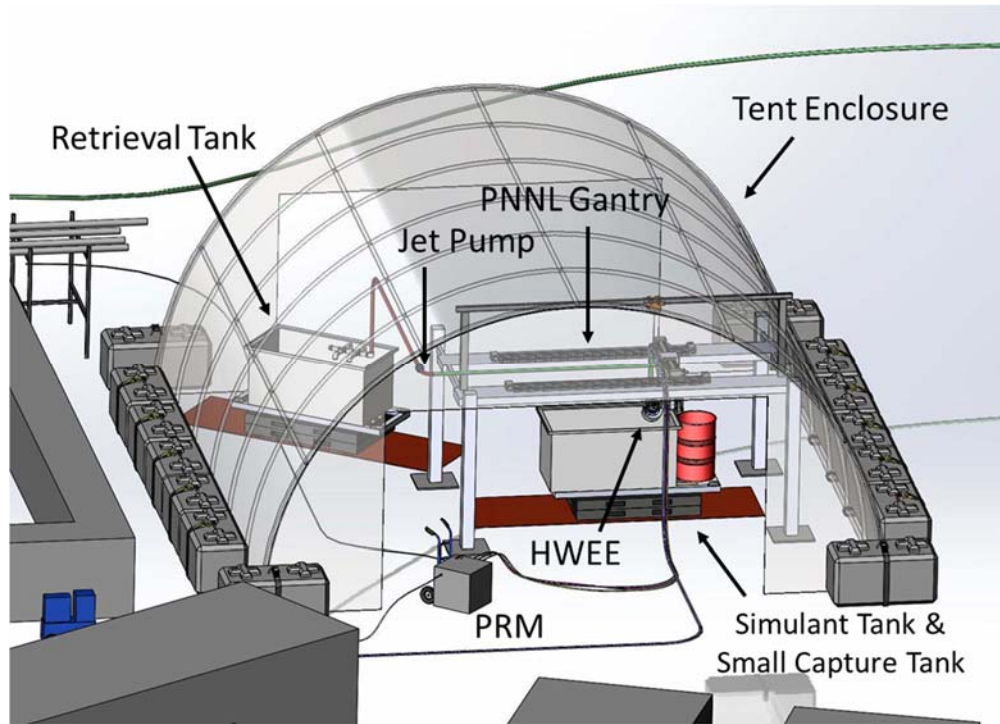


Figure 4.2. HWEE Retrieval Test Setup – View 1

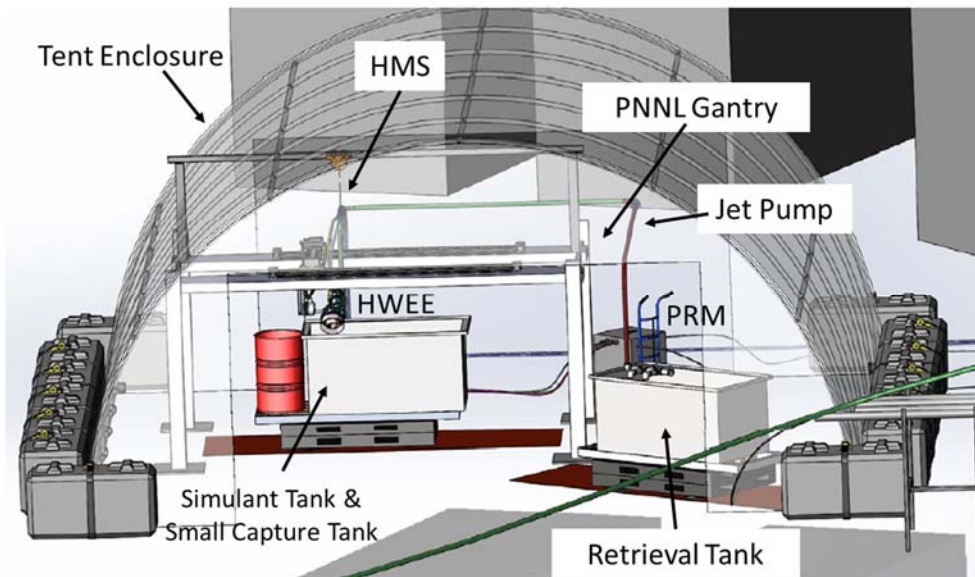


Figure 4.3. HWEE Retrieval Test Setup – View 2

4.3 Jet Pump Vertical Lift Tests

An overview of the jet pump vertical lift test setup is provided in Figure 4.4 through Figure 4.7. The jet pump, shown in Figure 4.8, is installed vertically to the CTF tank support structure along with associated conveyance lines. A high-pressure pump is staged nearby to supply high pressure water to the jet pump. The supply tank, located at ground level, holds water/simulant that is drawn in by the jet pump suction,

lifted vertically at least 35 feet through conveyance hose/piping, and then discharged into the receipt tank (carboy) located on the first platform of the CTF structure. Instrumentation will be installed to measure process parameters related to assessing lift performance.

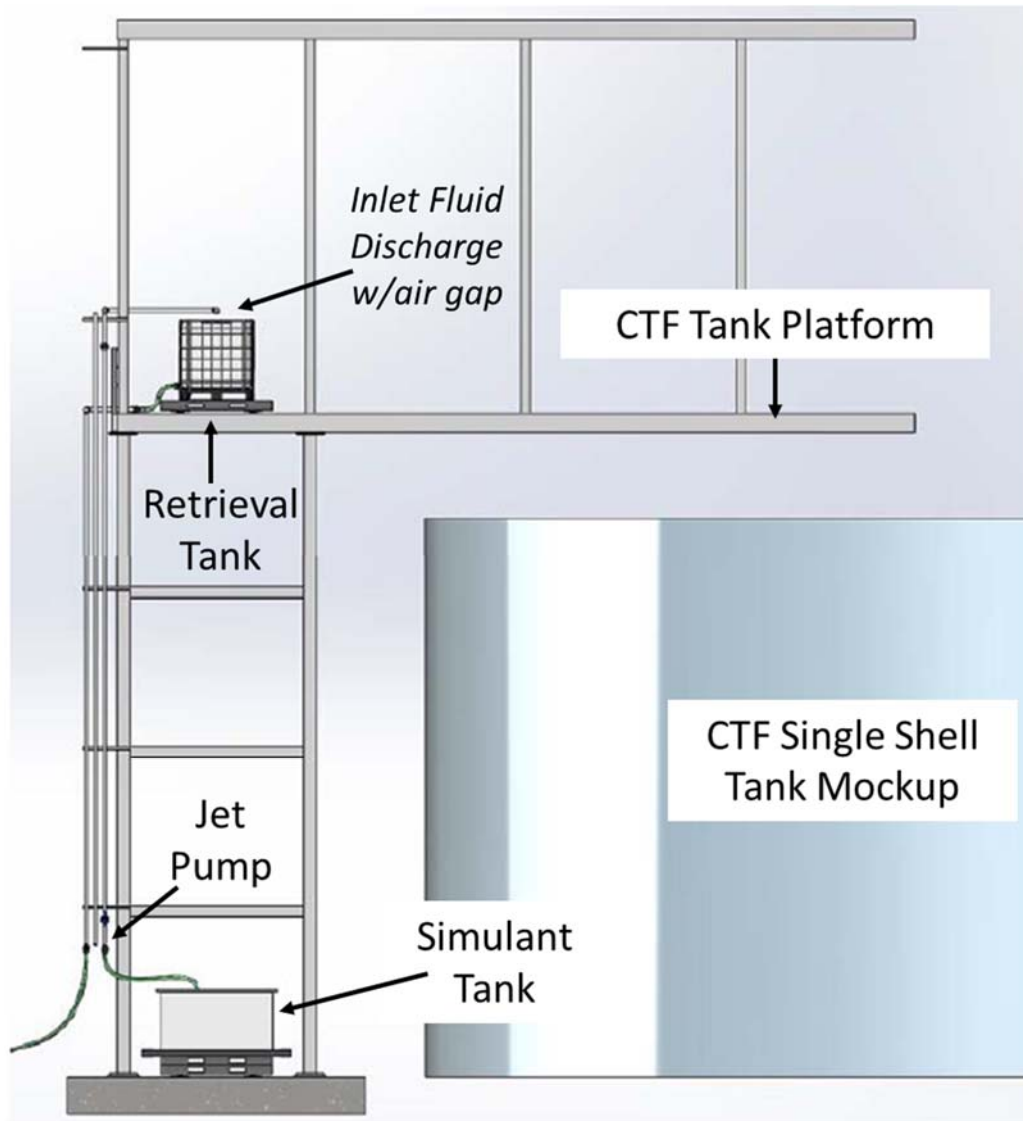


Figure 4.4. HWEE Vertical Test Setup – View 1

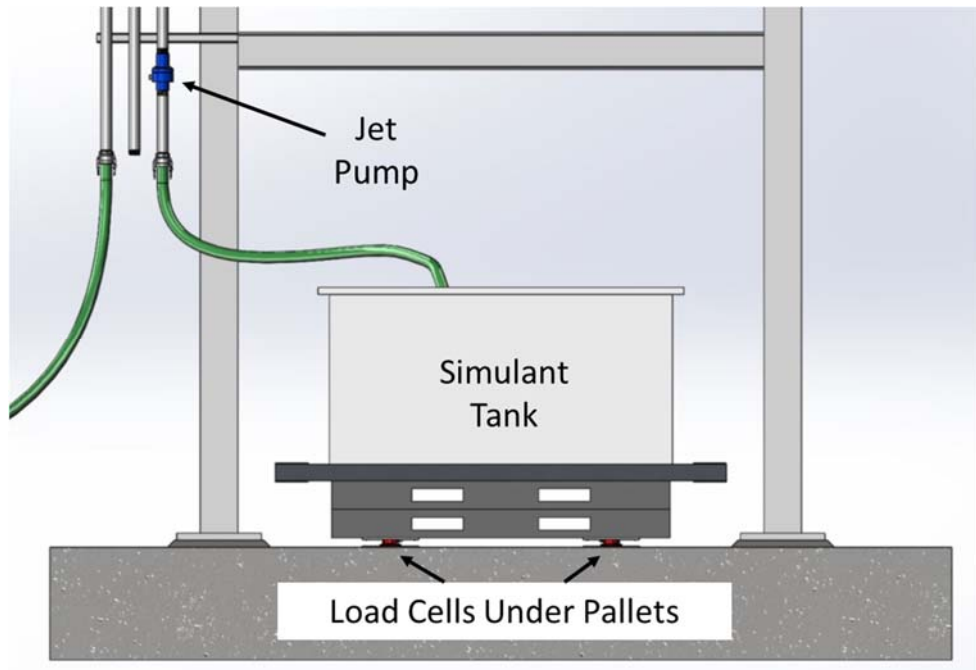


Figure 4.5. HWEE Vertical Test Setup – View 2

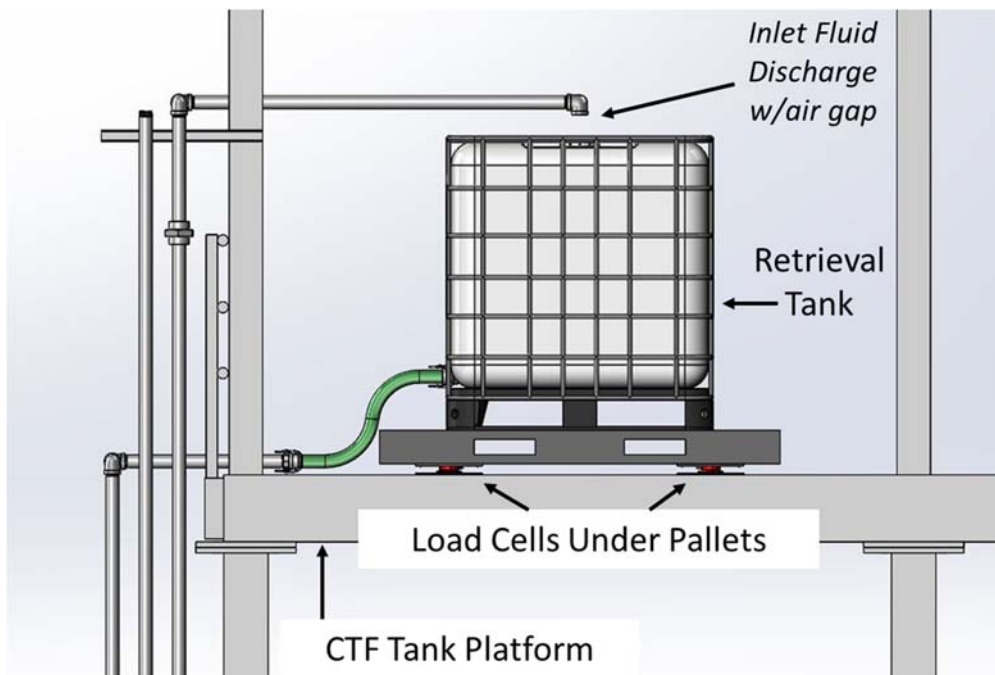


Figure 4.6. HWEE Vertical Test Setup – View 3

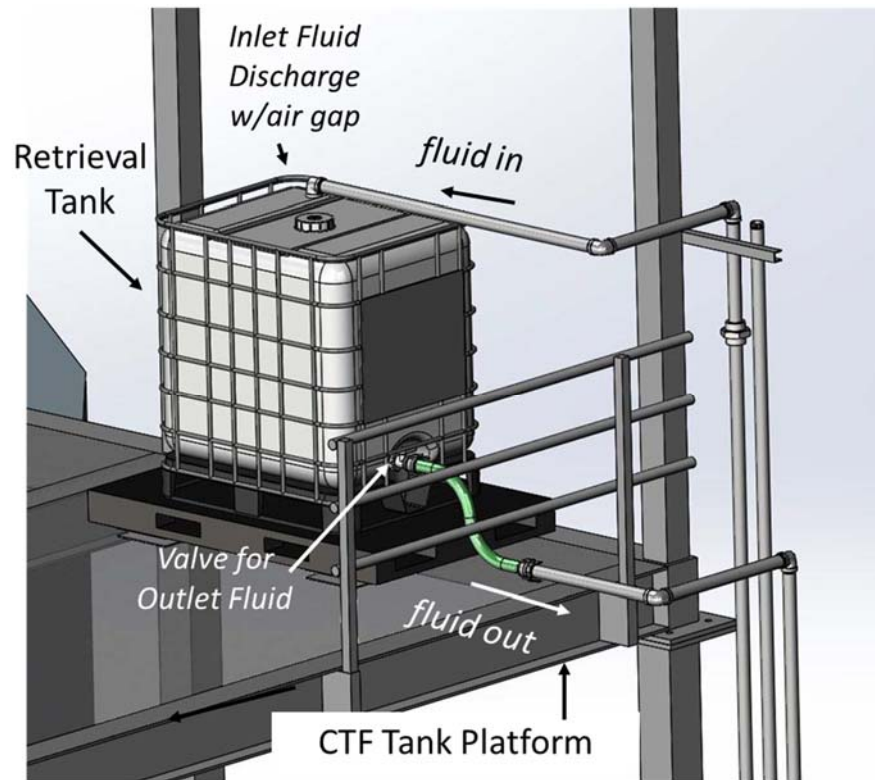


Figure 4.7. HWEE Vertical Test Setup – View 4

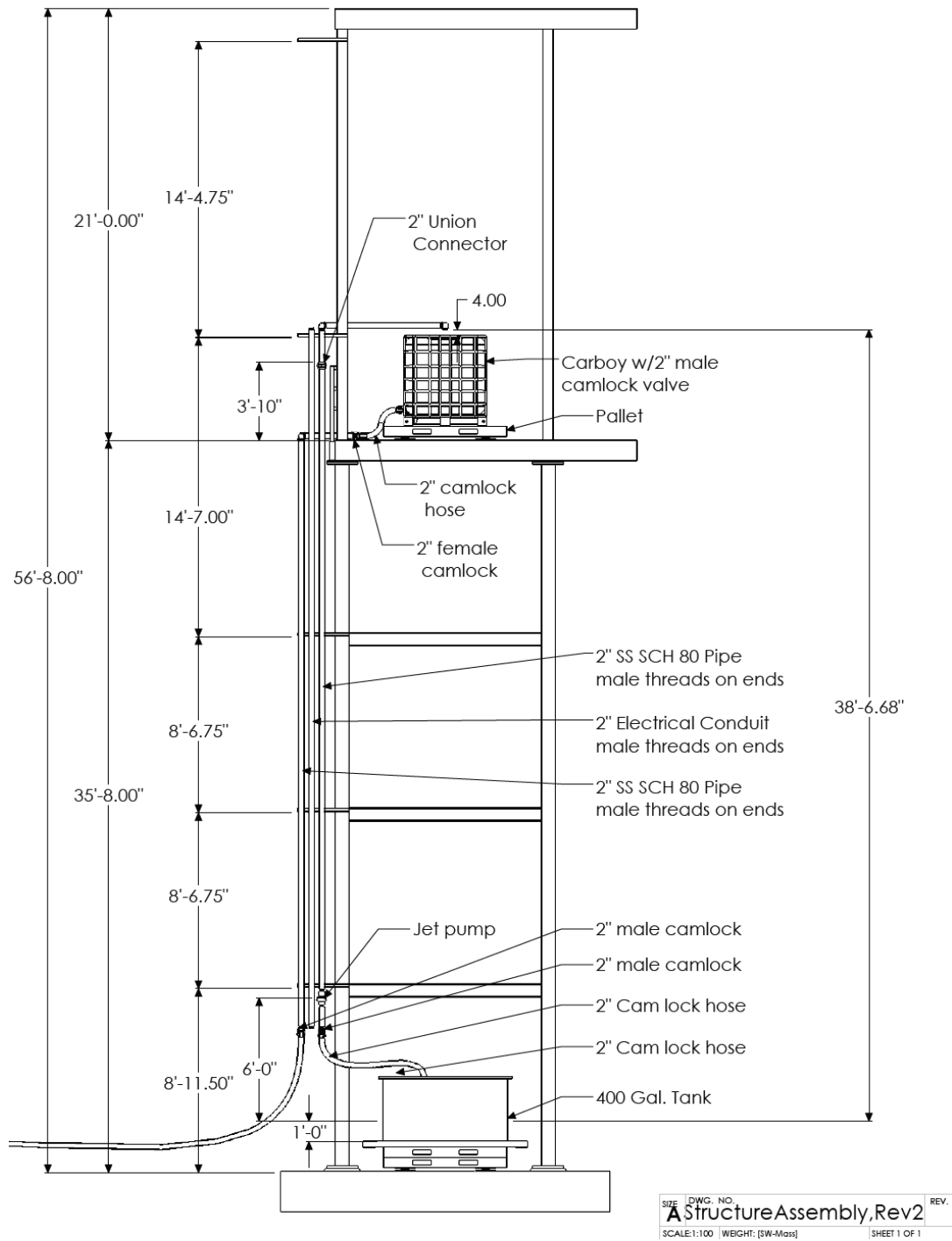


Figure 4.8. Jet Pump Vertical Lift Test Setup

4.4 Test Equipment and Instrumentation

The following sections provide a description of the test equipment and instrumentation.

4.4.1 Units under Test

Items under test are listed below.

- **Hanford Waste End Effector (HWEE).** See Section 3.0 for description and listing of changes.
- **Jet Pump.** The jet pump that will be used for testing is AquaDyne model 61102958 Dyna-vac with 2" FNPT connections at each end and 6 nozzles (0.031-inch diameter each). The jet pump is oriented horizontally for retrieval testing and vertically for jet pump lift testing.

For retrieval (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 (no HWEE connected) but may have a HWEE simulated inlet screen.

4.4.2 Equipment

Test equipment required for HWEE retrieval testing is listed below.

- **PNNL Gantry.** The gantry system provides a horizontal work space of 8 feet by 3 feet at speeds up to 300 in/min.
- **High-pressure Pump.** A high-pressure pump will be used to supply high-pressure water to the jet pump and HWEE. The minimum requirement capacity of the pump is 25 gallons/minute at 10,000 psi. A foot pedal will be used to start/stop high-pressure operations as applicable.
- **High-pressure Hose.** High-pressure hoses will be routed from the high-pressure pump to the HWEE and jet pump. The pressure and flow rate will be regulated in each line independently by the high-pressure pump and/or pressure-reducing manifold (PRM).
- **PRM.** The PRM manifold is a secondary pressure regulator that can be installed in the high-pressure line connected to the HWEE to allow the pressure to be reduced below the pump pressure, if desired.
- **Automated Shutoff Valves.** Automated shutoff valves are available to allow independent remote on/off switching of any high-pressure outputs (i.e., HWEE jet, HWEE internal flush line, and jet pump) using a pneumatic actuator activated by an electric solenoid for remote operation.
- **Air Source.** An air source, such as a compressor or air tank, will be required to power the pneumatics on the automated shutoff valves.
- **Hose Line Management System (HMS).** A hose management system will be used to support the conveyance line, high-pressure water jet hoses, and hydraulic rotary motor hoses attached to the HWEE as it moves over the test bed (simulant tank).
- **Conveyance Line.** Two-inch diameter opaque flexible hose will connect from the HWEE to the jet pump supported by the HMS. A two-inch diameter pipe will connect the jet pump discharge to a retrieval tank. For retrieval testing, the length of line from the end of the jet pump to the receipt tank is less than 20 feet and includes minimal suction lift (< 12 feet) and not discharge lift. For jet pump vertical lift testing, additional 2-inch pipe is added to the jet pump discharge side to achieve desired overall lift height of at least 35 feet and any required routing to retrieval tank.
- **Hydraulic Power Unit.** A small hydraulic power unit will be acquired to operate the HWEE hydraulic motor. The flow requirement for the motor is 3 gallons/minute at 3000 psi. Hydraulic hoses will be routed from the hydraulic power unit to the HWEE using the HMS.

- **Simulant Tank.** Simulant will be placed in a poly tank with nominal dimensions of 6 feet long, 3 feet wide, and 3 feet deep. Water testing (i.e., no simulant) may use other tanks in place of the described poly tank.
- **Water Capture Tank.** A small water capture tank may be used next to or near the simulant tank to allow the HWEE to be positioned outside of the simulant tank for setting water pressure to the HWEE components at pretest and for any other non-test functions to minimize water deposited into the simulant tank with test simulant.
- **Retrieval Tank.** For retrieval testing, simulant will be retrieved in a poly tank with nominal dimensions of 6 feet long, 3 feet wide, and 3 feet deep. For jet pump vertical lift testing, carboy tank(s) of around 330 gallons may be used.
- **Fluid Transfer System.** A fluid transfer system, like a diaphragm pump with hosing, is used to move fluid (e.g., water and simulant fluid mixtures) as needed from/to various test equipment (such as tanks) and final transport to the CTF basin.
- **Test Enclosure.** For retrieval testing, the gantry with associated HWEE/jet pump and HMS, simulant and retrieval tanks will be enclosed in a large tent enclosure.

Test equipment required for jet pump vertical lift testing will use a portion of HWEE retrieval test equipment that will include the high-pressure pump, high-pressure hose, jet pump, and conveyance hose used in HWEE retrieval. The supply and receipt tanks used in this testing may be plastic or metal tanks.

4.4.3 Instrumentation

A measurement and test equipment list (M&TE) is provided in Appendix A. A piping and instrumentation diagram is provided in Appendix B. The instrumentation for all testing is briefly described below. As shown in Appendix A, certain instruments will be calibrated by an ISO 17025 Accredited Calibration Laboratory. Other instruments that are not calibrated but will be used to supplement or provide context for reported information will be designated as For Information Only (FIO). For example, a string potentiometer will be used to determine when the HWEE is in motion but will not be used to support subsequent design efforts.

- **Data Acquisition System.** The sensors required for test will be connected to a data acquisition system. This module also provides electrical isolation between the data acquisition computer and the sensors, which reduces the risk of electrical overload at the computer. The computer platform will be a laptop running Windows 7, which will allow rapid sampling (up to 1000 Hz) of instrumentation and process control signals. The data acquisition system also provides some control functions for HWEE equipment (e.g., gantry automated x and y-axis program movements, etc.).
- **Waterjet Pressure Transducers.** A visual pressure gauge is included in the high-pressure pump. The gauge is downstream of the pressure-reducing valve, so that the gauge can be used to set the discharge pressure supply to the jet pump and PRM. A second visual pressure gauge is included on the PRM that can be used to set lower discharge pressures to the HWEE components (i.e., rotating jets and flush)
- **Force-Torque Sensor.** To measure the dynamic forces due to suction, inertia, and waterjet reaction, a sensor that measures forces and torques along three axes is attached to the HWEE mounting beam. At the beginning of each test, the sensor will be “zeroed” to eliminate steady state offset due to the weight of the end effector and loading from the hoses.
- **HWEE Speed Sensor.** A tachometer will be installed on the HWEE to calibrate the hydraulic pump flow rate and valve position with manifold speed.

- **Tank Load Cells.** Load cells will be installed on both the simulant tank and receipt tank to measure the weight of water/simulant transferred during retrieval simulations. These load cells will also be used on the supply and receipt tanks associated with jet pump vertical lift testing.
- **Tank Level.** A tank level monitor will be installed on the retrieval tank to measure the surface height of the fluid for determining fluid volume.
- **Tank Temperature.** A tank fluid temperature sensor or sensors may be installed to measure fluid temperature in the retrieval tank.
- **Position (X, Y, Z axis).** Position of the HWEE in 3D space will be monitored using a variety of sensors. At the start of HWEE retrieval, a 3D “Home” position will be set. For horizontal x and y axis motions, the scanner will use its encoders for determining relative positional movements, and these may be supplemented by linear string pots that will measure absolute starting point. For vertical z axis motions, a scale and linear string pot will be used to read the vertical position relative to a starting point. Limit switches are provided in the X, Y horizontal plane to keep the HWEE within the “safe” confines of the movement operation being attempted (i.e., tank walls, mining inside a wood frame structure, etc.).
- **Position (Tilt rotation).** Rotation position of the HWEE around the x-axis may be measured using either a linear string pot or rotary sensor.
- **On/Off Actuation.** Monitoring of various equipment on/off functions (e.g., high-pressure water activation to HWEE, flush, jet pump) or test sequence points (e.g., “good data button”) may be conducted.

4.4.4 Simulant Development

WRPS has specified that the waste in A-106 is to be evaluated for Phase II testing of the HWEE. Two simulant configuration options using existing simulant materials were defined to represent key waste properties that are not addressed in Phase I:

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

Further requirement for the simulant design was that the configurations will address key waste properties that can affect the HWEE retrieval performance but do not quantify the erosion characteristic of the simulant relative to representing the essentially unknown specific erosion rate characteristics of Hanford tank waste. This aspect of the simulant design follows that of the Phase I testing of the HWEE, which employed a range of simulant materials, previously designed to represent the characteristics of hard saltcake and sludges expected in Hanford waste tanks (Powell 1996), as identified in (Gauglitz et al. 2017) to represent A-105 tank waste.

Historical information from A-106 waste, including tank history, sampling reports, and images, was investigated as follows:

- Waste layering: Data for waste strength with depth. Following Phase I approach, waste shear strength used for erosion characteristic metric.
- Waste surface topography for selected tank: Image review.
 - Waste characterization of selected topography: Following Phase I approach, waste shear strength used for erosion characteristic metric.

The A-106 waste history is summarized in Section 4.4.4.1. Inference of the potential waste properties based on the waste history is provided. The methodology and results for shear strength are provided in Section 4.4.4.2, and the waste surface topography basis is presented in Section 4.4.4.3. The selected representative simulant targets are provided in Section 4.4.4.4.

4.4.4.1 Summary of A-106 Waste History

There are limited characterization data for A-106 waste. One methodology used to define waste properties for an uncharacterized waste tank is to relate the properties by waste type (e.g., Yarbrough 2013).³ Although this approach has been shown to be problematic for some waste characteristics,⁴ the A-106 waste history was reviewed as a first step to ascertain what waste types are in the tank to provide a potential range of the property of interest which is shear strength (see Section 4.4.4.2).

Tank A-106 entered service in 1957. The waste fill and removal history from Sturman (2016) is summarized below:

- ~1957 – 1961: Received de-entrained water and plutonium uranium extraction (PUREX) condensate waste from the boiling waste tanks in the A Tank Farm
- ~1960 – 1968: Received PUREX high-level waste followed by carbonate waste and organic wash waste
- On May 15, 1963, the in-tank temperature for tank 241-A-106 was 312 °C (594 °F), the highest temperature recorded for any of the Single-Shell Tanks
- ~1969: Received a... r... (AR) sludge waste from tank 241-A-104 and other A and AX farm tanks
- ~1970 – 1975: Received s... r... r... (SRR) waste
- ~1970 – 1974: Tank was intermittently sluiced (three campaigns) for strontium and cesium recovery
- ~1974 – 1976: Received predominantly B Plant waste with some AR and SRR waste
- The tank contained evaporator waste between the third quarter of 1976 and the first quarter of 1978
- ~1977: Sluiced a fourth time. During this time, the tank was part of an in-farm sluicing operation and received sludge waste from tanks 241-A-101, -102 and -103.
- ~1978 – 1980: Received and sent supernatant to tank 241-A-102
- The tank was administratively interim stabilized in August 1982 and intrusion prevention was completed in December 1982

The described process history of A-106 resulted in three waste types (Wells et al. 2011)⁵

- A1 saltcake, ~36.8 % by volume
- AR sludge, ~26.4% by volume
- SRR sludge, ~36.8% by volume

³ Hanford processing produced 55 clearly identified and distinctly different waste types (Higley and Place 2004).

⁴ Wells, BE. 2016. *Prototypic Settling Behavior Evaluation for Direct Feed Low-Activity Waste (DFLAW)*. Attachment to LTR-EMSP-0104. Pacific Northwest National Laboratory, Richland, WA.

⁵ From 2002 Best Basis Inventory.

Wells et al. (2011) provided maximum waste shear strength by tank and waste type. The maximum shear strength data for A1 saltcake is 700 Pa, tank A-101 (99% A1 saltcake by volume). There are no shear strength measurements for Hanford waste types AR sludge and SRR sludge.

With respect to waste layering, the shear strength profile in the A-101 waste is shown in Figure 4.9. Although there is significant scatter in the data, weaker layers may be shown at the top and bottom measurement elevations. Data specific to A-106 waste are discussed in Section 4.2.3.2.

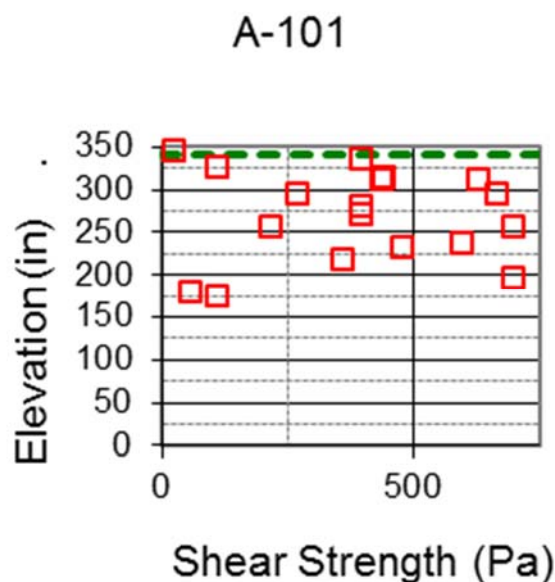


Figure 4.9. Shear Strength Profile in A-101 (from Wells et al. 2011)

4.4.4.2 A-106 Waste Shear Strength

American Society for Testing and Materials Method C1750-17 (ASTM C1750-1 n.d.) provides general considerations for the development, verification, validation, and documentation of high-level waste tank simulants. As described by that standard, the first step should be to determine what the simulant is to be used for, whereby the key processing properties required for development of the simulant are determined. Gauglitz et al. (2017) identified sediment mobilization or erosion with the fluid jets as a primary simulant use for the HWEE testing. Because information on the erosion behavior of Hanford waste is generally not known, the yield stress in shear (shear strength) is used as the parameter to represent the erosion rate of the simulants, which follows the approach of the Phase I simulants and prior work (e.g., Powell 1996).⁶

No measurement data for the shear strength of A-106 are identified. Thus, an alternative methodology, “extrusion length” (Gauglitz and Aiken 1997, Rassat et al. 2003), is employed that relates waste core extrusion behavior to the sample extrusion behavior to that of simulants of known shear vane-measured shear strength. Although the waste-extrusion techniques rely on the behavior of ex-tank core extrusion, they may be as representative of *in situ* conditions as available ex-tank samples (Gauglitz et al. 2009).

⁶ The shear strength of a sediment provides an upper bound for erosion and can be associated with a maximum erosion rate, but different materials with the same shear strength may erode at substantially different rates under the same applied stress (Wells et al. 2009). Specific examples are provided in Gauglitz et al. (2017).

The methodology developed in Rassat et al. (2003) specifically relates the shear strength (τ) to the extrusion length (L) of a core sample from the maximum tensile stress in a round cantilever beam at the proportional limit as

$$\tau = K \frac{\rho g L^2}{D} \quad (4.1)$$

where ρ is the waste density (sediment density in A-106 is 1,700 kg/m³ from Yarbrough [2013]), g is the gravitational acceleration, and D is the core diameter (1.246 inches). The proportionality coefficient, K , is determined from the simulant data of Gauglitz and Aiken (1997) and varies depending on the simulant. The two simulants of Gauglitz and Aiken (1997) were chosen to reflect the wide variety of mechanical behaviors typical of wastes from the Hanford tanks, and the K values from these simulants are referred to in Rassat et al. (2003) as the extrusion length bounds.

The methodology has been shown to have representative results for the shear strength of actual waste compared to other measurement techniques (Rassat et al. 2003). Waste extrusion results are included in the waste group assignments reflect a tank's propensity to retain a significant volume of flammable gases and the potential of the waste to release retained gas via buoyant displacement events (Yarbrough 2013) and have been used to understand waste characteristics for waste feed delivery (e.g., Gauglitz et al. 2010) as well as for process vessel performance in the Hanford Tank Waste Treatment and Immobilization Plant (e.g., Gauglitz et al. 2009).

As described in the references, core extrusion video is employed so that the length of waste horizontally extruded from a core can be observed. No extrusion video for waste cores from A-106 was identified, but three images of the waste were available immediately following extrusion. The images were therefore used. Two core samples were taken from A-106 in 1986, which was after the tank was administratively interim stabilized and intrusion prevention was completed. Therefore, these cores are judged to be as representative of the waste currently in A-106 as are available. The waste cores were taken from riser 17 and riser 20 as shown in Figure 4.10. The dates of the respective core samples are also provided in the figure.

The extruded image of waste Core - 1, segment - 3 is provided in Figure 4.10. This segment is from the bottom of sediment. To more readily observe the potential "breaks" in the extruded waste, Figure 4.11 provides a close-up view. As noted previously, video allows the observer to see the length of horizontally extruded material prior to a break. From images, it is not possible to determine whether the breaks are due to the horizontal extrusion. However, it is conservative (i.e., higher strength is achieved with longer extrusion length) to assume that the material between the observable breaks was self-supporting during the horizontal extrusion.

Included in Figure 4.12 are orange bars denoting the selected break locations, and the Equation (4.1) " L " and " D " are labeled. Two segments are labeled. The separation between the bars (length and diameter) is measured via calipers. With the actual core diameter known, the inferred "actual" extrusion length can thus be approximated. The same approach was used for the remaining two available A-106 waste core extrusion images as shown in Figure 4.13 through Figure 4.16.

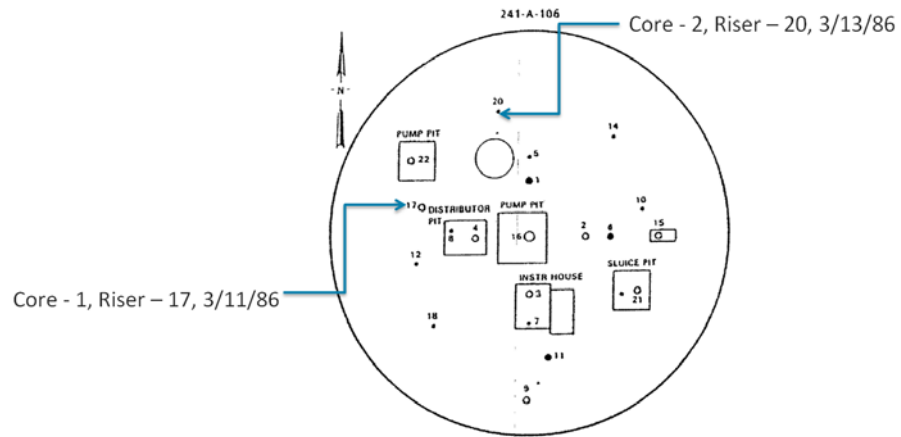


Figure 4.10. A-106 Core Sample Locations (Riser Information SD-RE-TI-053 Rev 8, Core Locations from Rogers [1993])

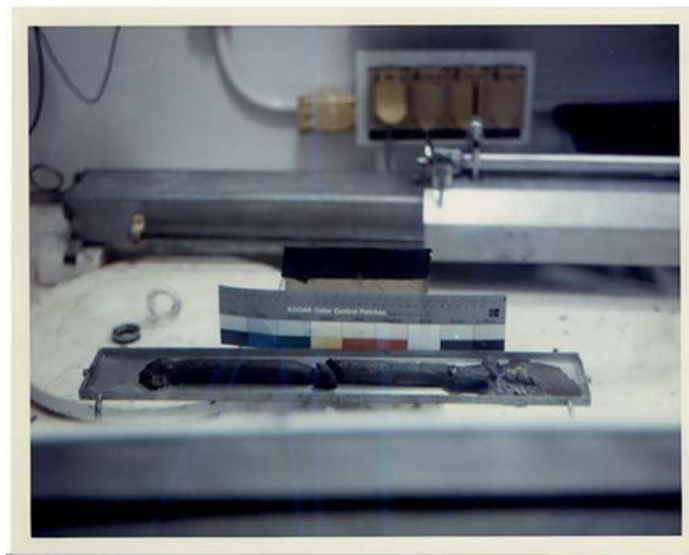


Figure 4.11. Core - 1, Riser - 17, Segment - 3, Bottom of Sediment (Rogers 1993)

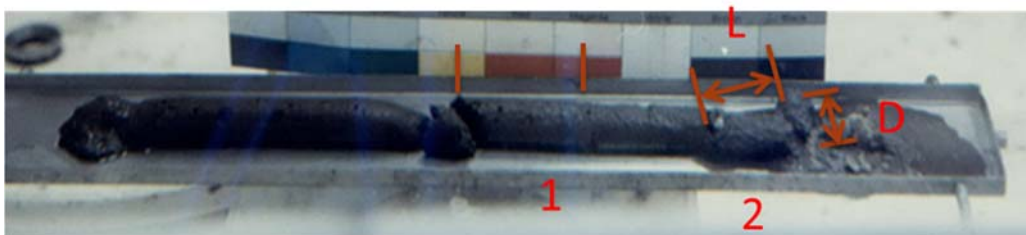


Figure 4.12. Core - 1, Riser - 17, Segment - 3, Close-up, Inferred Extrusion Length Locations Denoted

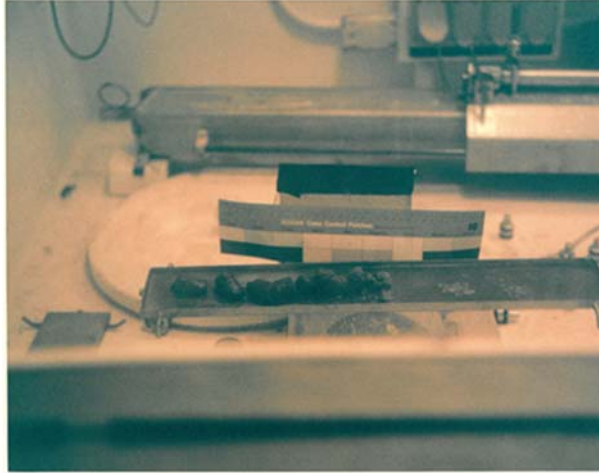


Figure 4.13. Core - 2, Riser - 20, Segment - 3, Bottom of Sediment (Rogers 1993)

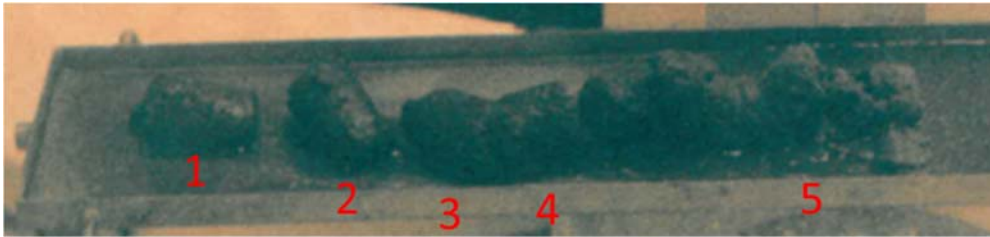


Figure 4.14. Core - 2, Riser - 20, Segment - 3, Close-up, Inferred Extrusion Length Locations Denoted

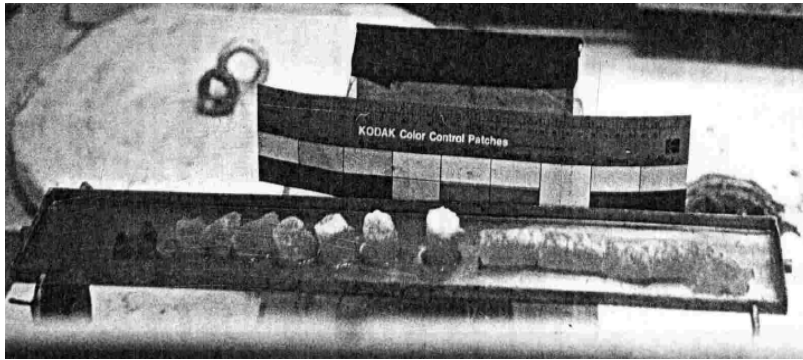


Figure 4.15. Core - 2, Riser - 20, Segment - 2, "Middle" of Sediment (Rogers 1993)

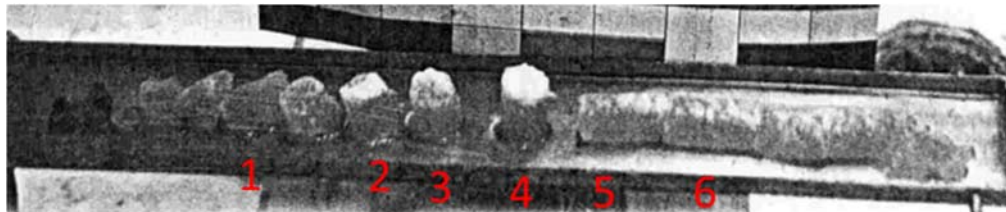


Figure 4.16. Core - 2, Riser - 20, Segment - 2, Close-up, Inferred Extrusion Length Locations Denoted

A total of 13 extrusion length estimates for shear strength were made, two from Core 1 and eleven from Core 2. The resultant "upper bound" shear strength results (i.e., higher K value; see Equation [4.1]) are

plotted in Figure 4.17 as a function of elevation in the sediment. The sediment depth from Yarbrough (2013) is also shown. Estimate elevation is approximated as the summation of the extrusion lengths with non-extrusion length core portions accounted for. With no images for Segment 3, there are no data for the top of the sediment.

There is agreement between the Core 1 and 2 estimates shown for the ~0.4 m elevation, but an increase in shear strength is shown for increasing elevation in Core 1, whereas a low shear strength middle is shown for the more complete profile of Core 2. The maximum estimated shear strength upper bound value is 3,375 Pa (Core 1). The lower bound estimate (i.e., lower K value) is, from the ~0.25 m elevation result, 284 Pa. Both of the indicated shear strength profiles are unique with respect to the limited data set presented in Wells et al. (2011) where the majority of the wastes are shown to increase in shear strength with depth into the sediment. Increased strength at the waste surface does match waste descriptions, however (e.g. Gauglitz et al. 2017).

The extrusion length shear strength estimates for A-106 are on the order of and higher than waste of a similar waste type (Figure 4.9) and represent the approximate 25th to 92nd percentile of Hanford waste sediment shear strength as measured by a shear vane (see Wells et al. 2011) as shown in Figure 4.18. The cumulative probability shown in Figure 4.18 is strictly based on measurement count. Therefore, the extrusion length shear strength estimates for A-106 are used for simulant design for the Phase II HWEE testing.

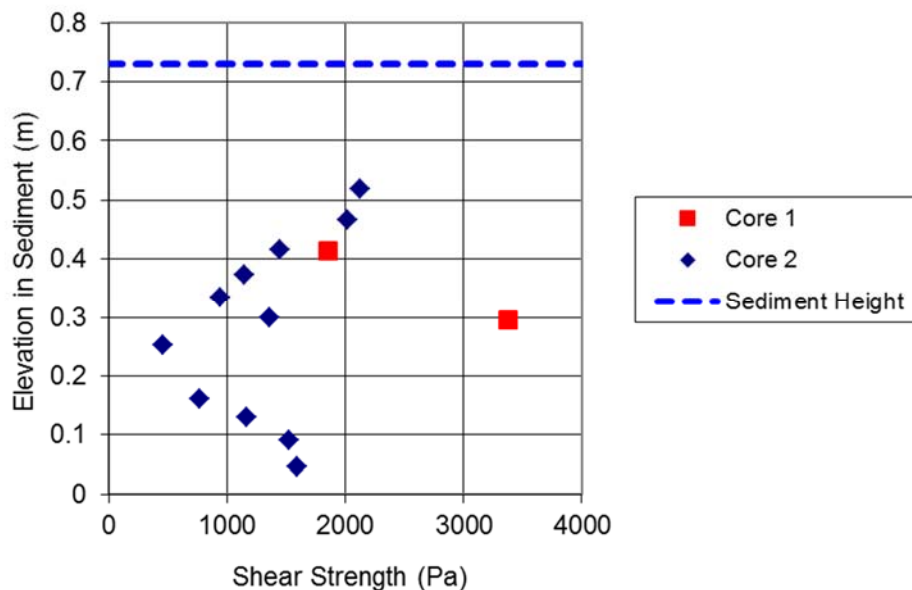


Figure 4.17. Extrusion Length Estimated Shear Strength (Upper Bound) as a Function of Elevation in Sediment

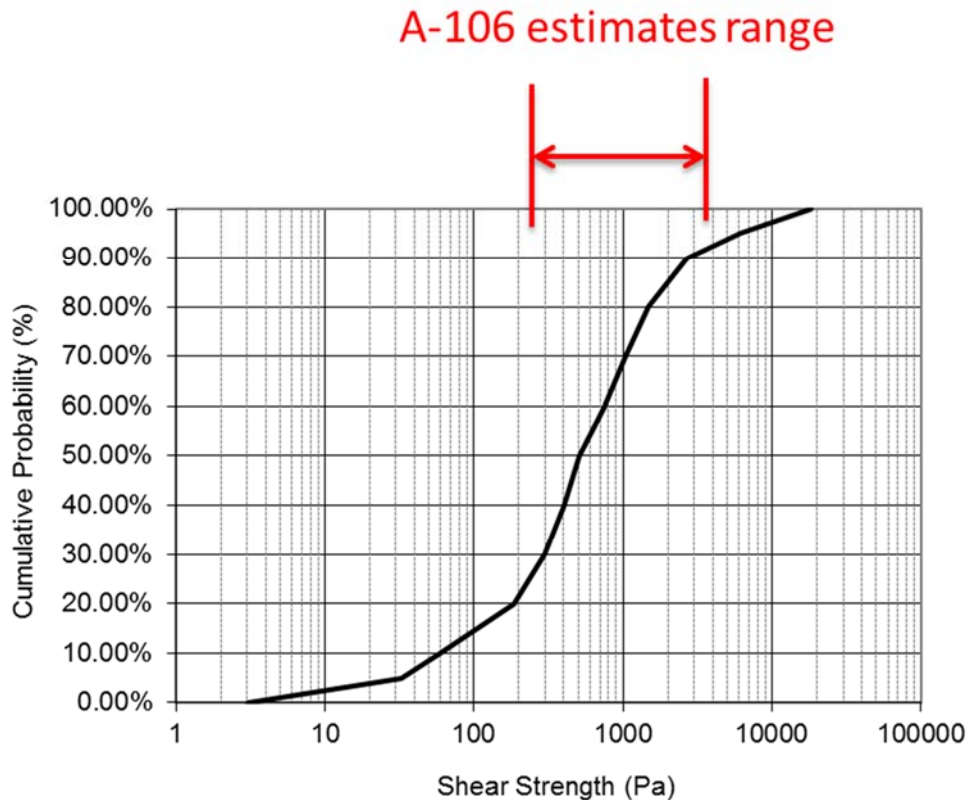


Figure 4.18. A-1016 Extrusion Length Estimated Shear Strength Range in Comparison to Hanford Waste Sediment Characterization (Data from Wells et al. 2011)

4.4.4.3 A-106 Surface Topography

The surface topography in A-106 is assessed via waste surface photographs. Topographical dimensions are inferred from comparison to tank wall stiffener rings/riser pipe/etc. actual dimensions to waste configuration.

Images of the A-106 waste surface in 1982 are available. Taken when the tank was administratively interim stabilized and intrusion prevention was completed in 1982 (Section 4.2.3.1), the images judged to be as representative of the waste currently in A-106 as are available (current waste surface level comparison is subsequently made). The composite waste surface image of A-106 is shown in Figure 4.19.⁷ The indication is a relatively flat waste surface with “mounds” and depressions around equipment risers, air lift circulators (ALCs), and the tank walls as confirmed by the example images of Figure 4.20 and Figure 4.21.

From an as-built drawing (H-2-55911 Rev. 1), nine stiffener rings are in A-106 with a 3-foot 5-inch vertical separation. The waste surface height from Yarbrough (2013) is slightly above the first stiffening ring as depicted in the excerpt of the as-built drawing in Figure 4.22. This leaves eight rings above the waste surface level, which corresponds with the 1982 images also shown in Figure 4.22, providing indication that the images are representative of the waste currently in A-106.

⁷ TWINS. <https://twins.labworks.org/twinsdata/Forms/About.aspx>

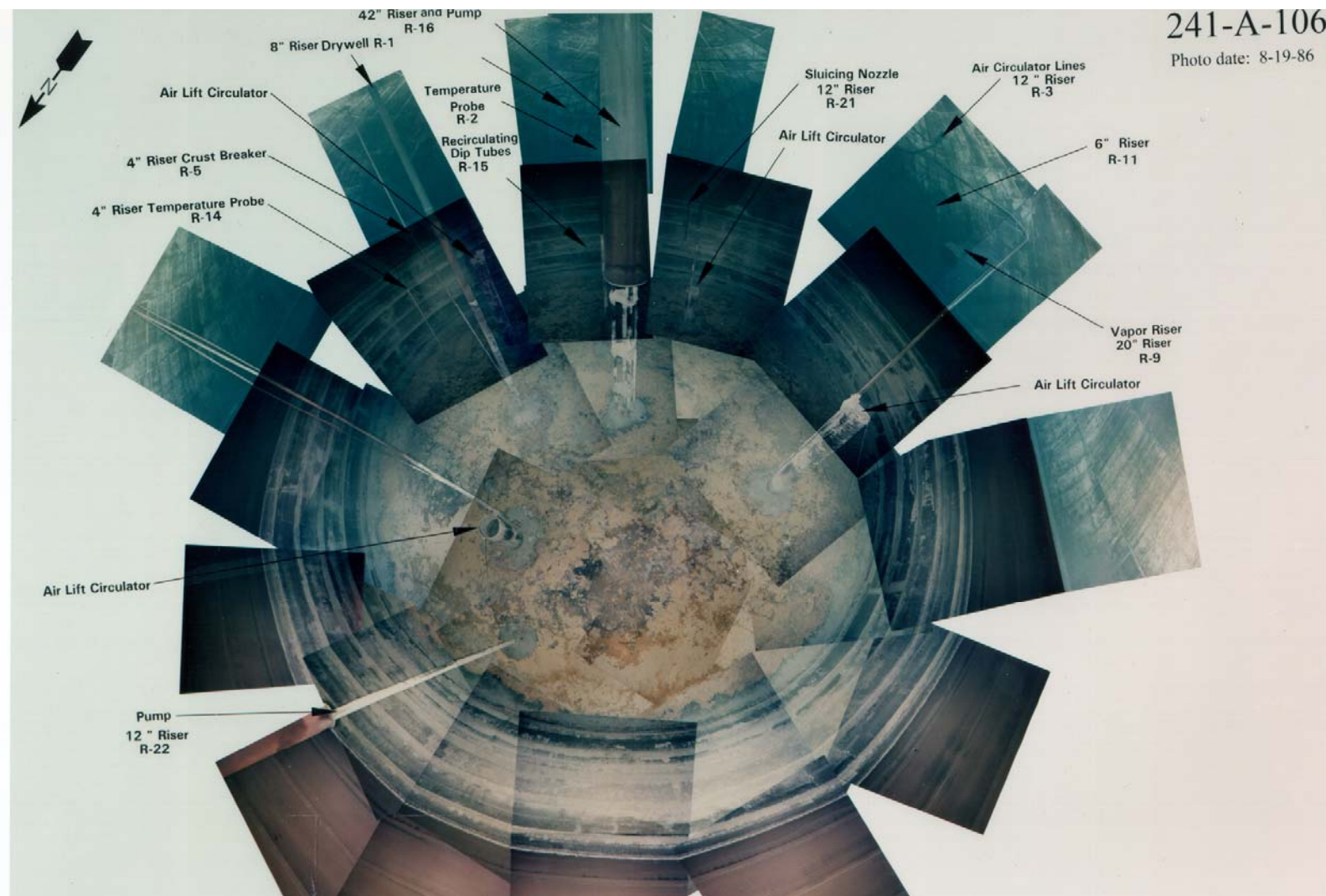


Figure 4.19. A-106 Waste Surface Photograph Mosaic

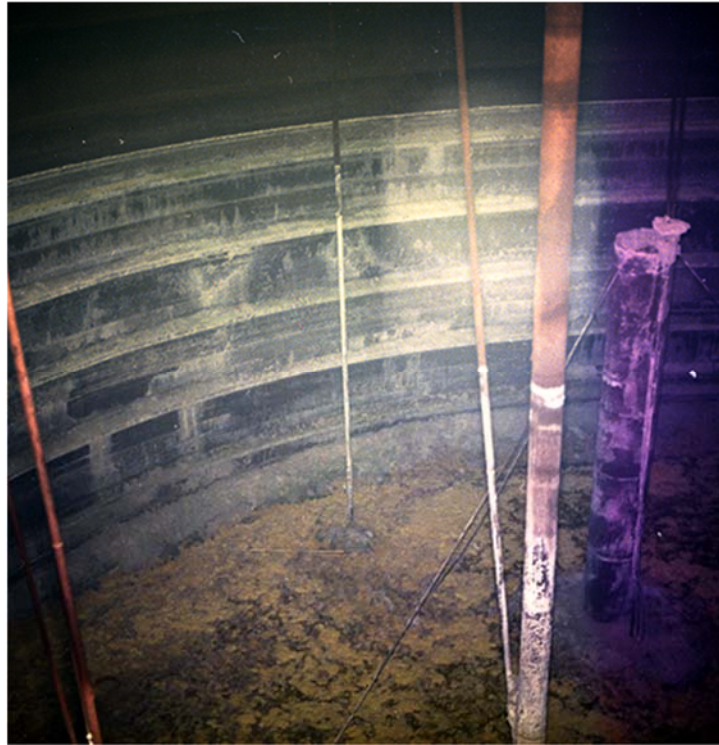


Figure 4.20. A-106 Waste Surface, Task Wall with Stiffener Rings, Equipment Risers, and ALC. Yellow waste surface with gray “mounds” around risers, ALC, and along tank wall.



Figure 4.21. A-106 Waste Surface, Equipment Riser and ALC

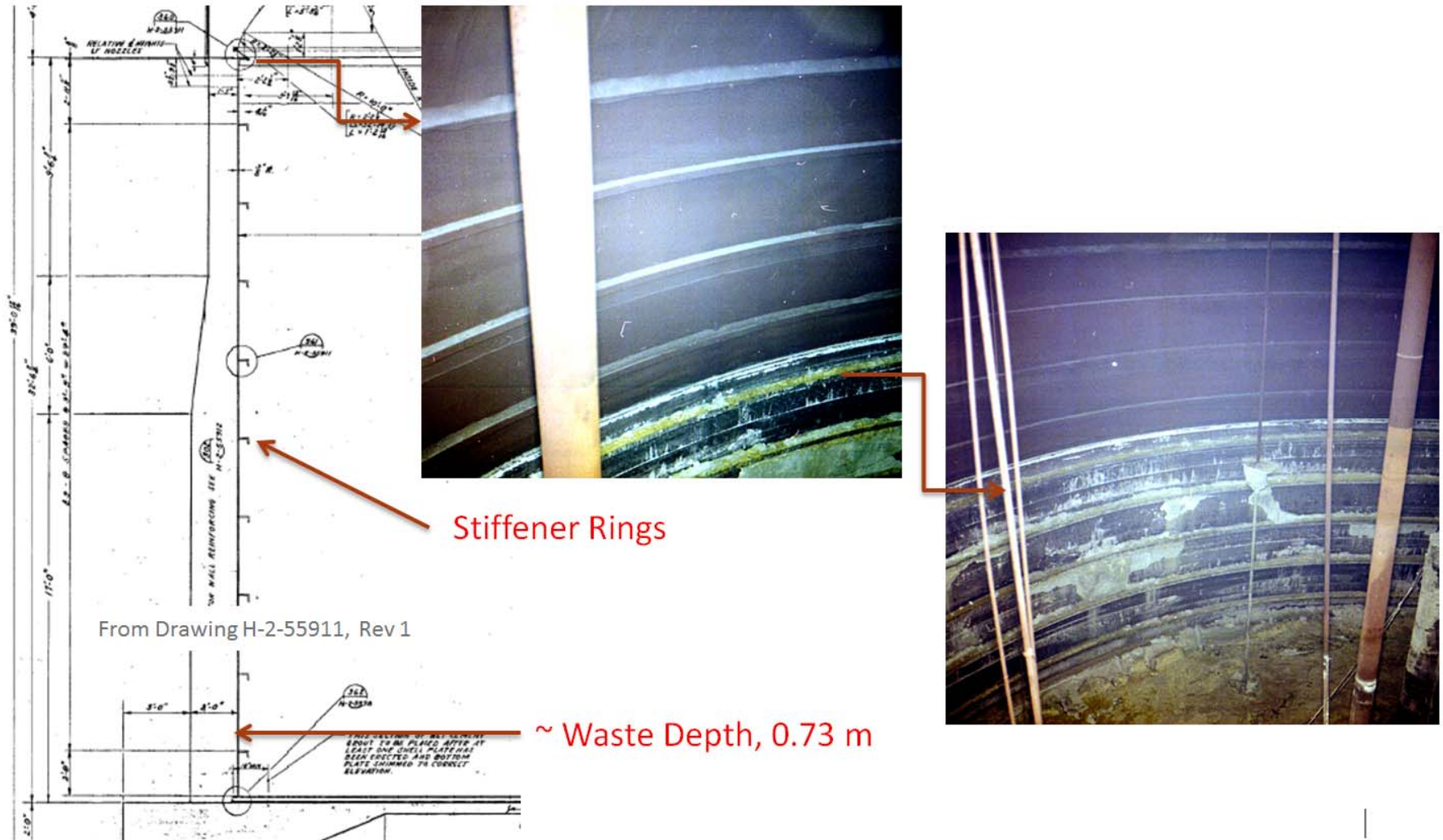


Figure 4.22. A-106 Waste Surface Level Comparison

Dimensional comparison is provided in Figure 4.23 and Figure 4.24. The stiffener ring spacing and ALC (24 inches) dimensions are shown for visual comparison to the mound features. It is inferred that the mounds may extend vertically over one foot above the surrounding waste, and the topography may be vertical. Further, as illustrated by the images in Figure 4.25, the vertical “face” can be quite irregular (see also Figure 4.21).

The over one-foot estimate for the vertical extent of the mounds can be considered via an expression for the maximum angle of repose, θ , for a granular sediment⁸ given by

$$\tan \theta = \frac{8\tau\Delta\rho gH}{(\Delta\rho gH)^2 - 16\tau^2} \quad (4.2)$$

where H is the vertical distance and $\Delta\rho$ is the density difference between the sediment and surrounding fluid (air). With a nearly vertical slope, which would give an upper bound (e.g., 89.9°), a sediment density of 1.7 g/mL (Yarbrough 2013), and air density of 1.255 g/mL, the maximum vertical height as a function of waste shear strength is approximated in Figure 4.26. A vertical height of up to approximately 0.8 m is indicated for a shear strength of 3,375 Pa, so it is reasonable for the A-106 to have mounds with a vertical extent of one foot at 3,375 Pa.

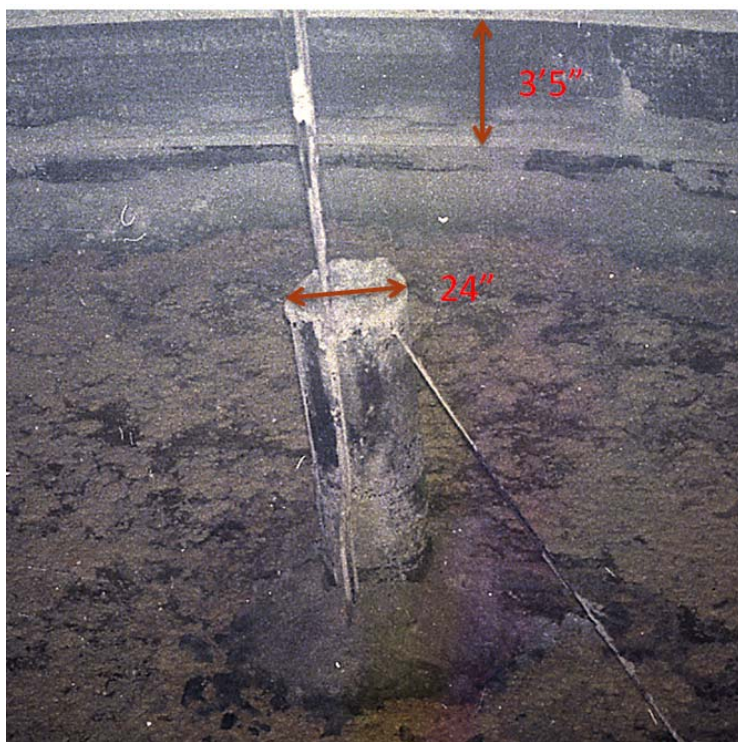


Figure 4.23. A-106 Waste Surface, ALC and Stiffener Ring Spacing Dimensions, “Mounds” Apparent

⁸ Meyer PA, CW Stewart, SD Rassat, RT Allemann, G Terrones, and DP Mendoza. May 1999. *Potential Gas Release by Bubble Slurry Flow Through a Hole in the Crust Layer in SY-101*. Letter Report TWS99.27, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

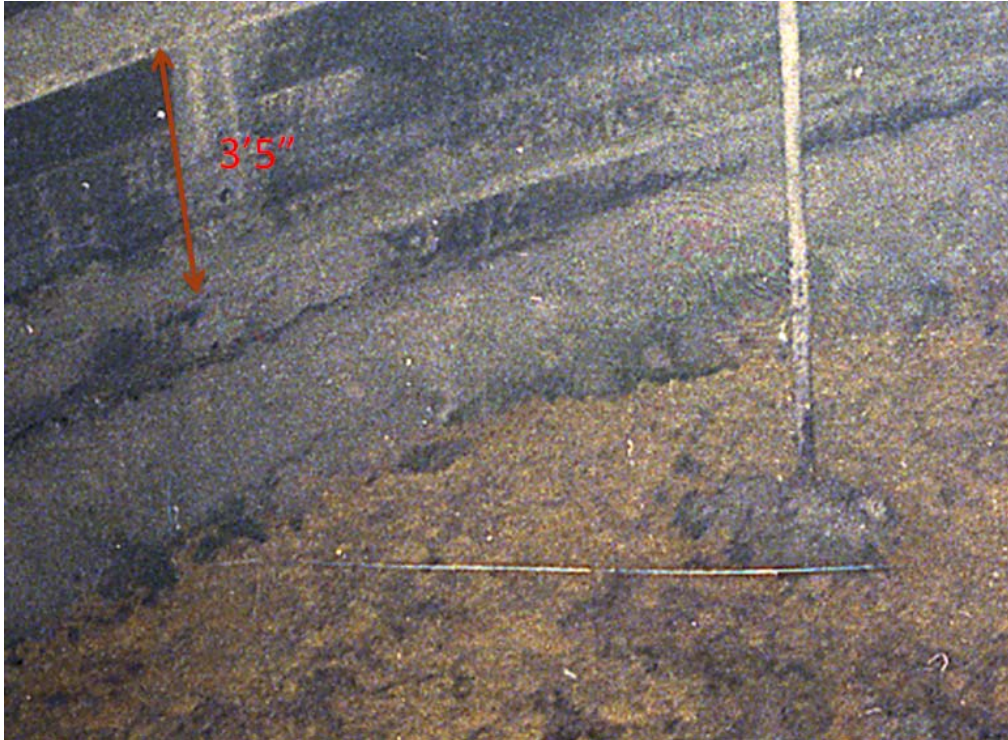


Figure 4.24. A-106 Waste Surface, Stiffener Ring Spacing Dimension, “Mounds” Apparent



Figure 4.25. A-106 Waste Surface Showing Mound Features

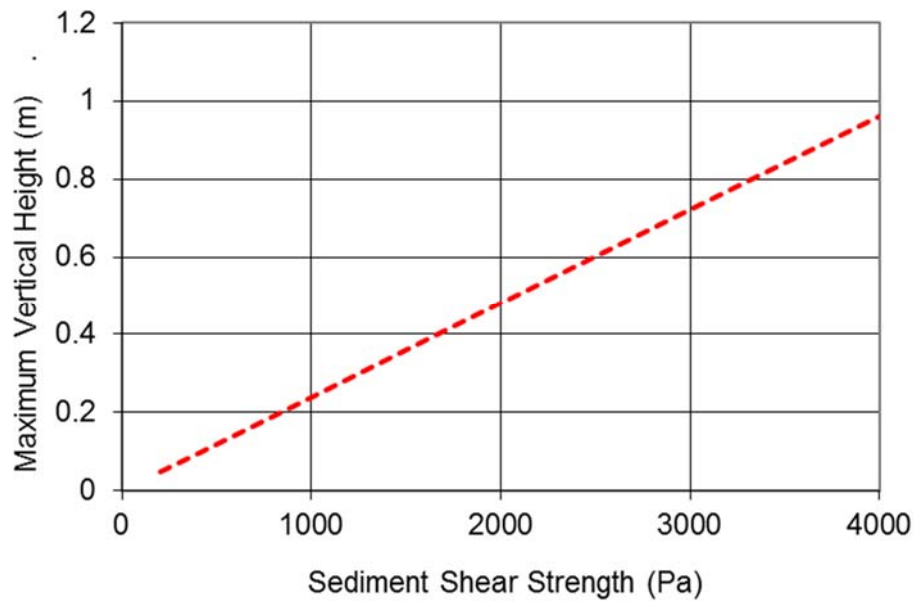


Figure 4.26. Calculated Approximate Mound Vertical Extent as a Function of Waste Shear Strength

4.4.4.4 Selected Representative Simulant Targets

Simulant targets that are representative of the A-106 waste as described in the previous sections are specified for layered waste and topographical features for Phase II testing of the HWEE.

Layered Waste Simulant Target

As described in Section 4.4.4, the layer waste simulant target is based on the A-106 waste shear strength with depth. Note, following the Phase I approach, waste strength used for erosion characteristic metric. From Figure 4.17, the A-106 waste sediment is indicated to have higher shear strength material at the top and bottom surrounding a lower shear strength middle layer. Starting at the bottom of the sediment, the shear strength is shown to nominally linearly decrease to a minimum and then nominally linearly increase.

The 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 (Section 4.4.4.2). 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 4.27, 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 break-through 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 break-through may be “lost” in the lower shear strength middle layer until the HWEE is interacting directly with that layer.

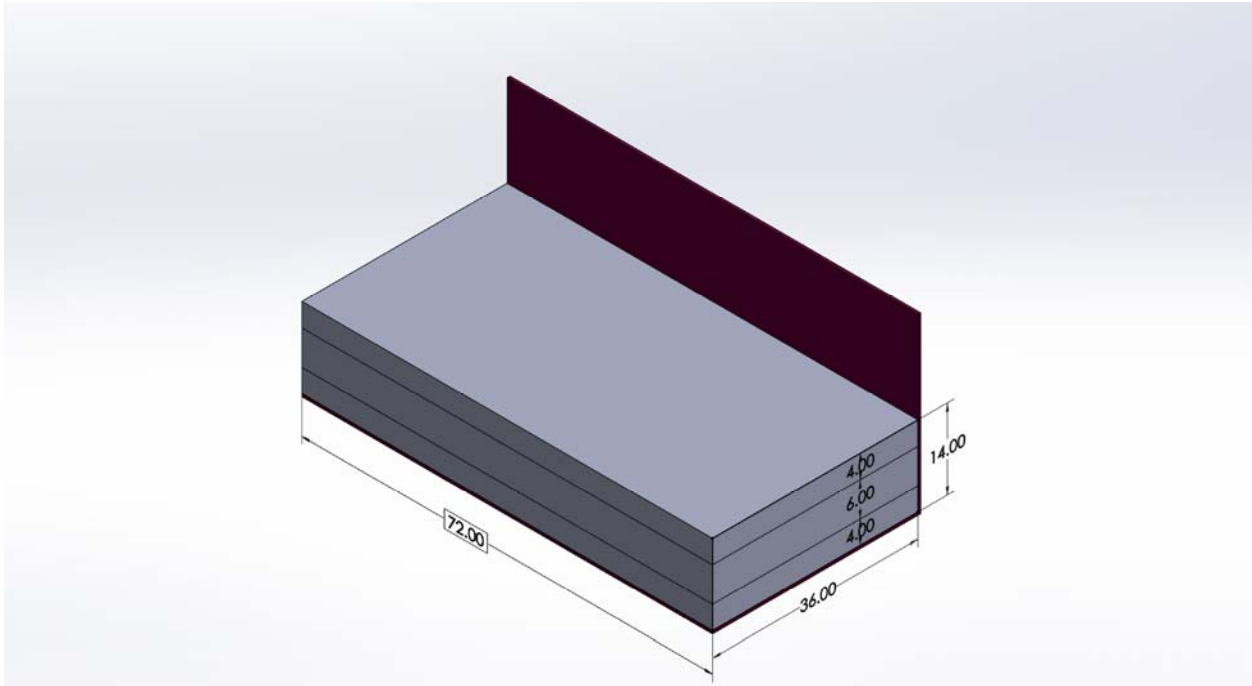


Figure 4.27. Simulant Configuration for Waste Layering Test

Waste Topography Simulant Target

The A-106 topographical features described in Section 4.4.4.3 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 4.28. 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 4.28, 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.

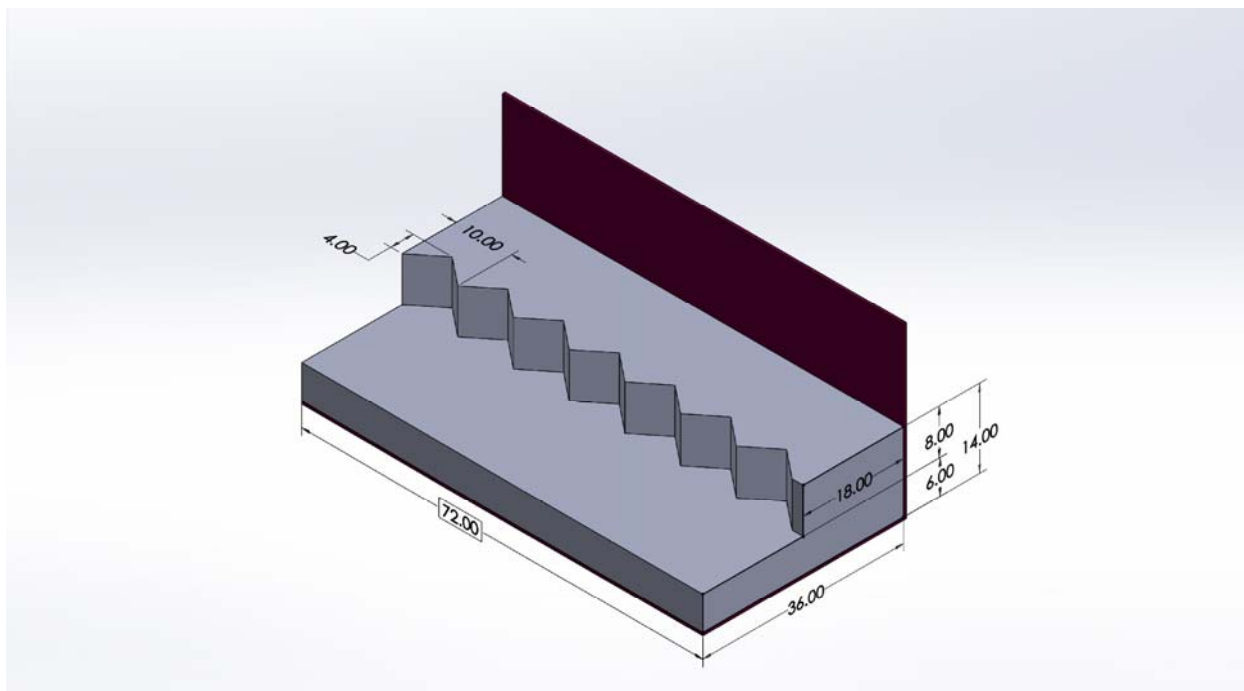


Figure 4.28. Simulant Configuration for Waste Topography Test

4.4.5 Simulant Preparation

The simulant for the HWEE Phase II testing was specified by WRPS to be based on the materials selected for the Phase I tests (Berglin et al. 2017). For the described shear strength targets, the kaolin clay simulant, with adjusted composition, is selected. Bench-scale simulant samples will be prepared and characterized for shear strength. The simulant compositions and target shear strengths are listed in Table 4.1.

Table 4.1. Phase I HWEE Simulants

Simulant	Shear Strength
Kaolin (Strong): ~64 wt.% EPK Pulverized Kaolin Clay made up in Richland City Water	~ 3,375 Pa
Kaolin (Weak): ~51 wt.% EPK Pulverized Kaolin Clay made up in Richland City Water	~ 284 Pa

All simulant characterization performed by the PNNL HWEE test team will be done using PNNL standard procedures and calibrated equipment as applicable.

4.4.5.1 Simulant Preparation, Kaolin

Supplier: EPK Pulverized kaolin clay can be obtained from Feldspar Corporation (Edgar, Florida).

~284 Pa Simulant Preparation: The simulant will be prepared in approximately 6-gallon batches to obtain a homogenized clay slurry. An Eibenstock 23/1.3R handheld mixer mounted on a portable mixing stand and a 9.25" diameter mixing paddle (Model MG 235) will be used to blend and homogenize the kaolin slurry. Kaolin powder will be added slowly to the required amount of water to avoid dust production and ensure complete mixing. Once the slurry has been made, it will be aged for a minimum of 2 days before being used. The target shear strength will be measured after a 12- to 16-hour gelling period, which will enable the layered bed to be prepared the day before testing is scheduled.

~3.5 kPa Simulant Preparation: The simulant will be prepared in 11-gallon batches. Due to the high strength of this simulant, mechanical mixers are not suitable. The required water will be added to a 30-gallon drum and the kaolin powder will be added quickly (inside a walk-in fume hood to mitigate dust). The drum will be sealed and rolled several times and then left to age. The drum will be rolled periodically over a 2-week period. Gravity and diffusion ensure that the resultant clay mixture is homogeneous.

Properties: The 284 Pa kaolin slurry will dewater slightly and will need to be mixed before use. The slurry can be readily poured into the test vessel with the aid of a spatula. The 3.5 kPa (0.51 psi) kaolin paste is very sticky and will need to be removed from the mixing drum with the aid of a shovel. For comparison, creamy peanut butter has a shear strength of about 2.0 kPa (0.3 psi).

The physical properties of the mixed kaolin clay are largely independent of temperature over the range of 15° to 80°C (59° to 176°F), but freezing temperatures must be avoided, and care must be taken to prevent evaporation.

4.4.5.2 Test Bed Preparation

Layered Waste Simulant: The simulant bed will be prepared 12 to 16 hours prior to testing following the layered profile outlined in Figure 4.27. The 3.5 kPa kaolin paste will be added manually to the bottom of the test vessel and flattened by hand; the 284 Pa kaolin slurry will be poured over the top. The final, 3.5 kPa kaolin paste layer will be prepared in 2" thick sheets of a manageable size (approximately 18" by 24", limiting the weight of the paste to ~ 23 kg). The sheets will be hand formed on a support media, a piece of Teflon™ that has been pre-wetted with water (to aid with the removal of the kaolin paste); the kaolin will be removed from the support media with the aid of wire cutter and gently placed on top of the 284 Pa kaolin slurry. This will be repeated to obtain a final layer thickness of 4" using a middle/edge approach whereby the middle of the second kaolin paste sheet will be placed over the edges of the lower layer to minimize weak areas. The sheets will be compressed together to form a single layer; this step is facilitated by the cohesive nature of the kaolin paste. Once the test bed has been built, it will be covered and should remain covered until testing. It is recommended that the simulant bed be prepared onsite to avoid disturbing the layers.

Waste Topography Simulant: The simulant used for this test consists solely of the 3.5 kPa kaolin paste and will be added by hand to the test vessel. The first layer will be 6" deep, and a second layer will be added with the aid of a mold to ensure the "saw-tooth" front face, as shown in Figure 4.28, is well defined and of the desired dimensions. Once the simulant has been prepared, it will be covered and should remain covered until testing. This test bed can be prepared 1 to 2 days in advance.

5.0 Test Instructions

This section includes the test phases and individual test instructions. Changes to this test plan will be documented on the “work place” record copy and approved by the program manager as indicated by initial and date. Revisions to this test plan can be used to incorporate changes. Table 5.1 describes the various tests that will be undertaken.

Table 5.1. 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

5.1 Instrument Verification and Cross-check

Table 2 describes the performance tests that will be conducted to cross-check and validate the instrument measurements. The tests are intended to verify that the sensors are wired to the data acquisition correctly, are powered appropriately, and are responding in a reasonable manner.

Table 5.2. Instrument Field Checks

Instrument	Method of Measurement Cross-Check or Performance Check
Force/torque sensor	Apply a force/torque load to the HWEE and note a response of the calibrated force/torque sensor.
Tank load cells	Apply a load (i.e., adding weight) to the HWEE simulant and retrieval tanks and note a response of the calibrated load cells.
High-pressure sensor	With the high-pressure pump pressure-reducing valve in the open position, compare the output pressure of the high-pressure pump visual gauge with the downstream visual gauge on the PRM as applicable.
Controls	Verify operation of the HWEE gantry E-stop, high-pressure control valves, and pump on/off as applicable.
Level sensor	Verify operation of level by filling a tank with changes in water level.
	Verify temperature by submerging in ice water bath and/or boiling water.
Temperature sensor	Verify operation of length or position sensors (e.g., calipers, string pots, etc.) with fixed length scale.
Position sensor	

5.2 HWEE Component Testing

HWEE component testing is done prior to retrieval demonstrations to determine or verify the performance of various components of the HWEE system with water. HWEE components using high-pressure water jets for operation (HWEE jets, HWEE flush, and jet pump) are tested to measure water usage over a range of pressures so that their individual water contribution can be correlated during retrieval demonstrations. In addition, the jet pump retrieval rate of water with flooded suction at various pressures is determined as a baseline for jet pump vertical lift tests in Section 5.4 of this test plan. For the retrieval tank, a measurement of the water volume in the tank has been added in Phase II that will be correlated by measurement of the fluid surface using a level sensor.

Table 5.3 describes the flow data needed to determine water flows, water retrieval rates, and water volume to tank level. Component flow testing previously done during Phase I testing described in PNNL-26856 (Berglin et al. 2017) can be used to meet the following requirements if applicable; however, a

performance check should be done to verify previous test data. Record key physical parameters related to the HWEE component testing, including jet pump suction and discharge vertical height to applicable reference points, inlet hose/pipe size/length and inlet features, discharge pipe size/length and outlet features, etc.

Table 5.3. Water Testing Summary

Component	Method of Measurement or Performance Check
HWEE components using high-pressure water flow • HWEE rotary jets • HWEE internal flush * • Jet pump	Allow the various combinations of HWEE jets and the jet pump water to accumulate in the tanks for a known amount of time (target > 1 minutes) at various pressures. Component water usage flow rate will be derived from the load cell measurements. * Note: HWEE internal flush with jet size change will require screen clearing demonstration prior to being accepted for retrieval testing.
HWEE and jet pump flooded suction water retrieval	Configure HWEE and jet pump to Phase II operation conditions (i.e. suction lift only). Allow jet pump water to accumulate in the tanks for a known amount of time (target > 1 minutes) at various pressures. Jet pump water retrieval flow rate with flooded suction will be derived from the load cell measurements.
HWEE retrieval tank volume *	Determine the correlation of tank fluid level to tank fluid volume. Add incremental volume / weight of water to the retrieval tank and measure water surface level with level sensor. Level sensor and retrieval tank should to be installed in field location and configuration that will be used for retrieval testing. *See additional details following for these components.

If the HWEE internal flush uses a different jet size than Phase I, the following testing will be required prior to water testing described in this section:

1. Demonstration of screen cleaning that was done in Phase I and detailed in Phase I the PNNL-26856 test report (Berglin et al. 2017), Section 5.3.4.
2. Water retrieval testing with flooded suction over the full HWEE pressure operating range from 1,000 to 10,000 psi that was done in Phase I testing and detailed in Phase I the PNNL-26856 test report (Berglin et al. 2017), Section 5.1.2.1.

The HWEE retrieval tank in Phase I was 400 gallons when filled to full height of 35 inches (11.4 gallons/inch); however, typical utilization of the tank during retrieval operations was a 10- to 20-inch fill height before retrieval tank pump down and refilling. A suggest measurement method would be to fill the tank in set volume increments and record fluid level and net water weight at each increment. Five fills of 55-gallon volumes get to near 25-inch fill height and near the maximum operating level in the tank. Level sensor and retrieval tank should be installed in field location and configured in the way that will be used for retrieval testing.

5.3 HWEE Retrieval Tests

Retrieval tests will focus on measuring the HWEE performance during simulated mining of kaolin (sludge) in more complex configurations as described below:

- Layered waste - Kaolin of two different shear strengths (strong and weak) with increased depth
- Waste topography – Kaolin of strong shear strength in a stepped/profile configuration

The following procedures are a general guide for retrieval testing and may be adjusted in the field as necessary to achieve HWEE retrieval performance objectives and changing field conditions. Operational sequencing steps for this testing are defined in general terms to portray how HWEE equipment is set up and operated during the retrieval process. The order of these retrieval tests can be varied as necessary.

5.3.1 Pre-test Procedure

The pre-test procedure below is a general framework for pre-test startup.

1. Check that cleanup equipment is available.
2. Verify that any additional products used to lubricate or maintain equipment have an approved Material Safety Data Sheet in the WRPS Level 1 Work Package for executing the test.
3. Record key physical parameters related to the HWEE retrieval testing that would include jet pump suction and discharge vertical height to applicable reference points, inlet hose/pipe size/length and inlet features, discharge pipe size/length and outlet features, etc.
4. Check that inlet water pressure is on.
5. Clear the HWEE gantry workspace area and secure electrical interlock.
6. Initiate ancillary equipment, including cameras, data acquisition, and motor control. Ensure the data acquisition and cameras are recording data.
7. Perform high-pressure pump pre-start checks and then start pump. Check for leaks in high-pressure lines. Check that high-pressure dump water is being collected and not dumped to the ground.
8. Adjust the pump output pressure to the desired pressure. Pump maximum allowable operating pressure is 10,000 psi. The pump is protected by a rupture disk will fail at a pressure just above 10,000 psi.

5.3.2 Test Procedure

Retrieval testing will test the performance and operating characteristics of the HWEE to retrieve the waste simulant kaolin (sludge) in a mining operation under two configurations described earlier (i.e., layered and topography). Retrieval information obtained from Phase I testing (Berglin 2017) has been used to set the initial HWEE retrieval operating parameters for this testing (see below). The goal of this testing is not to optimize retrieval parameters of the HWEE but to demonstrate the effectiveness of the HWEE to retrieve this waste simulant in both a layered and topography configuration for using and optimizing the HWEE in any follow-on retrieval operations.

The initial retrieval target* equipment parameters are:

Kaolin:	Rotation Speed	300 RPM
(Sludge)	Traverse Speed	300 inches/minute
	Waterjet pressure	1000 psi
	HWEE vertical stepping	1 inch

For these retrieval tests, portions or all of the mining paths may be predetermined based on knowledge gained from Phase I testing and Phase II simulant setup testing. Phase I test setup had limited motion of the gantry's x and y axis that limited programmable motions to a serpentine path starting along the x-axis only or full manual control. For Phase II, the HWEE now has added head tilt around the x-axis and possibly more flexibility in the gantry's x and y axis motions over Phase I limitations may be available.

Setting the HWEE component pressures may now use a small tank next to the simulant tank to eliminate water to the simulant bed during this pretest operation. In Phase I, the void ends of the simulant tank were used for this function.

The following HWEE retrieval operation steps are "general" to meet retrieval testing intent. These steps may be updated, modified, or reordered as needed to meet final equipment configuration, retrieval mining strategy, etc.

Pre-test Operation of HWEE System

1. Prior to start of retrieval testing, demonstrate the operation of the HWEE system to achieve the full range of initial retrieval target parameters described above at the simulant tank bed location; mining path operation may also be demonstrated. Demonstrate that the HWEE can access the small capture tank for water pressure setup. These demonstrations can be simulated prior to the simulant tank and capture tank in place.

Simulant Tank Fill with Simulant Sampling/Characterization

2. Fill the simulant tank with simulant in the configuration for specific test (i.e., layered or topography). Simulant target volume in the simulant tank is 14 inches deep (maximum for topography configuration), 3 feet wide, and 6 feet long. Take samples of the simulant during preparation and/or in the field as appropriate. Collect sample in a way to prevent evaporation and send the samples to the PNNL simulant lab for characterization.

Simulant Tank/Capture Tank Configuration and Operations

3. Ensure the simulant tank is configured for retrieval/ operations and load cells are operational. Final location of simulant tank is on the simulant tank pallet and likely a separate small capture tank located on one end. This simulant tank pallet is located on top of the simulant loads cell pallet that is centered under the gantry system for full mining access of the HWEE in the simulant tank and adjacent smaller access of the HWEE to the small tank for setting initial HWEE operating parameters (i.e., HWEE jet and flush pressure, rotation of the HWEE jet head, etc.) as needed.
4. During retrieval operations, the HWEE jet pump is used to collect and transport the simulant mined in the simulant tank to the retrieval tank.

5. During non-retrieval operations (e.g., configuring the HWEE components water pressures). Alternate means to minimize non-retrieval water deposited in the simulant tank shall be used. A small capture tank located past one end of the simulant tank can be used for these operations and will collect weight data because it resides on the simulant tank load cell pallet.

Retrieval Tank Configuration and Operations

6. Conduct pre-test meeting to discuss roles and responsibilities during testing. Designate a test director who will orchestrate all test activities. Ensure required safety signs and safety barriers are in place.
7. Ensure the retrieval tank is configured to accept retrieved simulant and load cells, level sensor, and temperature sensor are operational. Depending on time and fluid volume of retrieval operations, the retrieval tank may need to be periodically emptied. If emptying is required during a retrieval operation, the retrieval operations should be placed in a holding condition. During tank fluid pump down operations, the beginning and end tank weight, fluid level, and temperature is recorded. At the end of each retrieval operation, a tally of total weight retrieved is determined. The residual simulant material collected should be assessed as applicable, and then disposed into the CTF slurry receipt pit.

HWEE Retrieval Pre-Test Operations in Simulant Tank

8. Configure the HWEE on the gantry for start of retrieval mining operations. Using the gantry system 3D motions, set the HWEE skirt height off the surface of the simulant field to a stand-off of approximately 0.25 inches (± 0.25 inch) over the area to be mined. Check the HWEE motions over the simulant bed including verifying transverse speeds, motion limits, and mining paths as needed and applicable.
9. Locate the HWEE to the location where mining start and note x,y,z-axis and head tilt position for starting reference.
10. Position the HWEE to a location for setting HWEE component pressures independent of the simulant tank (e.g., small capture tank).
11. Start with all manual control valves associated with the jet pump, PRM, HWEE jets, and HWEE flush closed.
12. Open manual control valves downstream of the foot pedal diverter that supply water to the jet pump, PRM, and any HWEE manual control valve(s) downstream of PRM that are upstream of any remote operated valves.
13. Turn on the high-pressure pump. Adjust the pump outlet pressure to desired pump pressure.
14. Activate foot pedal diverter valve from the pump to supply full pump water pressure to the jet pump and PRM.
15. Check acceptable jet pump operation by observing desired water pressure obtained and water from jet pump is filling retrieval tank.
16. Deactivate foot pedal diverter valve and observe jet pump water shutoff to retrieval tank.
17. Set the retrieval test water pressure to the HWEE components (jets and flush) at the PRM by activating the foot pedal diverter valve and then adjusting pressure using both the pressure regulator and associated pressure gauge. Deactivate foot pedal diverter valve when completed.

18. Check operation of the HWEE jets and flush. Activate foot pedal diverter valve and open valve(s) sequence to control each of these operations and observe for acceptable test operation and pressure.
19. With HWEE jets operating, activate the hydraulic power unit and verify/adjust HWEE rotational speed. When completed, stop the HWEE rotation.
20. Deactivate foot pedal diverter valve to shut off water supply to jet pump and PRM.

Start Retrieval Mining Operations

21. Ensure that the HWEE mining path is defined, tested, and set for retrieval operation being performed. Typically, mining path is defined by layer because vertical adjustment is manual. For Phase II retrieval, it is expected that each layer will have slightly different mining parameters due to simulant condition and obstructions at the end of each mining layer. For Phase II, the HWEE head tilt along the x-axis is new and may lead to some unforeseen mining strategy changes once mining is initiated because there will be no prior pre-test operational experience. In addition, the use of a diverter valve between the HWEE jet and flush function is new for Phase II, and expected operation is to run the flush whenever HWEE mining is not being done, assuming the water flow rate of the flush is less than the jets. For extended mining stops, the foot pedal can be deactivated to shut off all water to the HWEE jets, flush, and jet pump.
22. Ensure the above “HWEE Retrieval Pre-Test Operations in Simulant Tank” has been successfully completed and end of pre-test conditions are met (i.e., pump is on, manual valves are correctly configured, pressures are set, foot pedal is off, and valving is set up for HWEE jet operation). Note: If continuing directly from the Pre-Test sequence above, the pre-test conditions should be met.
23. Position the HWEE to the safe retrieval starting reference position (see Step 8) over the simulant bed.
24. Activate jet pump and HWEE jet operation by depressing foot pedal diverter valve.
25. Activate the hydraulic power unit and verify/adjust HWEE rotational speed. Note: Hydraulic power unit requires water flow to HWEE jets or flush for cooling. HWEE rotation should be stopped when these water flows are not running. Operation of HWEE rotation without water flow may damage the seal because of excessive heating. Past HWEE rotation without water flow has been done, but time was limited to around 15–30 seconds.
26. After steady state conditions are reached, initiate the mining path. Operate the HWEE flush system(s) using the configuration and frequency determined in mining strategy. If retrieval rate drops appreciably during mining operations, increase the flushing time or frequency of flushing. Alternate flushing methods may be employed to determine if additional flushing is required, such as stopping retrieval operations periodically to look at debris buildup on the HWEE screen and then activating flush to clear the screen.
27. When a horizontal layer of mining is complete, deactivate foot pedal diverter valve to turn off water flow to the HWEE jets/flush and jet pump. Dewatering of the mined layer can be done by moving the HWEE to a location where water has accumulated, configuring system to only activate the jet pump, and then moving the HWEE head to the water pool for suction removal. This dewatering operation may be useful to observe the mining results of each retrieved layer and to assess mining results of the strategy.

28. If another layer of mining is desired, move the HWEE horizontally and vertically to the next mining starting point as done in Step 22 and repeat the operations to this step. When moving the HWEE down into simulant material, the HWEE jets should be activated to bore into the simulant.
29. If retrieval mining is complete, all remaining water in the simulant tank assessable by the HWEE is removed using the jet pump suction only. At the end of water removal, a small amount of flush water in conjunction with jet pump suction may be used to flush the HWEE screen of simulant as well as the conveyance line to the jet pump inlet. Raise the HWEE at least 6 inches above the waste (or alternately, a separate capture tank) and allow jet pump to operate for a period of time (e.g. 1–2 minutes) as necessary to flush the line of simulant material. Deactivate the foot pedal diverter valve when complete.
30. Turn off the high-pressure pump.
31. Store and archive the data acquisition and cameras data files.
32. Configure HWEE system to safe condition and positions for post-test work such as HWEE observation of HWEE inlet screen for residual simulant, removal/replacement of simulant tank, etc. (as applicable)
33. Repeat steps 1–32, as applicable, for next retrieval test.

5.3.3 Post-test Procedure

1. Empty retrieval tank(s) with retrieved simulant into the CTF slurry receipt pit or other approved designated area.
2. Empty simulant tanks of any remaining simulant and fluids into the CTF slurry receipt pit unless simulant is being used for jet pump vertical lift tests (Section 5.4). In that case, this operation will be done after the completion of that testing.
3. Place simulant tank or other container under HWEE end effector when not in use to catch fluid leaks as applicable.
4. When testing is complete, demobilize from the CTF as directed by client.

5.4 Jet Pump Vertical Lift Tests

Jet pump vertical lift tests will focus on demonstrating the vertical conveyance abilities of the AquaDyne jet pump configured for HWEE Phase I and II operations up to pressures of 10,000 psi. Minimum lift height is 35 feet, including both suction lift and discharge lift of the jet pump. The jet pump will be oriented in a vertical configuration instead of the horizontal configuration used for both Phase I and II HWEE retrieval testing with only suction lift. On the suction side of the jet pump, the line length, suction height, and HWEE screen inlet will be close to retrieval testing conditions so that the jet pump flooded suction data from Phase I and II component testing can be integrated with this testing.

The following procedures are a general guide for jet pump vertical lift testing and may be adjusted in the field as necessary to achieve lift objectives and changing field conditions. Operational sequencing steps for this test are defined in general terms to portray how HWEE equipment is set up and operated during

the jet pump vertical lift process. Water and Phase II simulants (kaolin clays) will be used for vertical lift demonstration baseline but may not be limited to these simulants.

For this test, the high-pressure pump is planned to be relocated to a location where the existing high-pressure lines of 150 feet with foot pedal diverter valve can reach the inlet water connection on the jet pump that is suspended from the CTF platform structure near the elevator. High-pressure water operations are similar to retrieval testing; however, there is no PRM or HWEE associated with this test. The simulant and retrieval tank systems used for this test will be the same as HWEE retrieval tests except that the retrieval tank will be replaced with a carboy tank (e.g., 330-gallon poly container) and level and temperature measurements are optional.

5.4.1 Pre-test Procedure

The pre-test procedure below is a general framework for pre-test startup.

1. Check that cleanup equipment is available.
2. Verify that any additional products used to lubricate or maintain equipment have an approved Material Safety Data Sheet in the WRPS Level 1 Work Package for executing the test.
3. Record key physical parameters related to the jet pump vertical lift testing, including jet pump suction and discharge vertical height to applicable reference points, inlet hose/pipe size/length and inlet features, discharge pipe size/length and outlet features, etc.
4. Check that inlet water pressure is on.
5. Initiate ancillary equipment, including data acquisition. Ensure that data acquisition is recording data.
6. Perform high-pressure pump pre-start checks and then start pump. Check for leaks in high-pressure lines. Verify that high-pressure dump water is being collected and not dumped to the ground.
7. Adjust the pump output pressure to the desired pressure. Pump maximum allowable operating pressure is 10,000 psi. The pump is protected by a rupture disk that will fail at a pressure just above 10,000 psi.

5.4.2 Test Procedure

Jet pump vertical lift test demonstrates the performance and operating characteristics of the jet pump to lift water and waste simulants (e.g., kaolin high-strength formulation) at least 35 feet in simulated retrieval conditions that includes phased flow (i.e., single- to three-phase flow). The goal of this testing is not to optimize vertical lift parameters of the jet pump but to demonstrate the effectiveness of the current jet pump configuration, used in HWEE Phase I and II retrieval testing, to lift water/simulant vertically higher to obtain information for using and optimizing the jet pump in any follow-on, more challenging retrieval operations.

Jet pump testing will proceed in steps with increasing complexity of fluid flow and materials transported as follows:

1. Single phase gas (air) – Demonstrate the ability of the jet pump to deposit its motivation water into the retrieval tank at elevation.

2. Single phase liquid (water) transport – With the HWEE inlet screen submerged in water (flooded inlet condition), demonstrate the ability of the jet pump to transport water from the simulant tank to the retrieval tank at elevation; this will be similar to the HWEE component testing done with flooded HWEE suction (see Section 5.2).
3. Two-phase gas (air) and liquid (water) transport – A combination of the two tests above where the jet pump inlet hose with attached HWEE screen is moved in and out of the liquid to simulant; this is a more typical HWEE retrieval operation scenario.
4. Three-phase gas (air), liquid (water), and solids (kaolin simulant) transport—this is similar to the test above but simulant is now in the tank along with water.

5.4.3 General Procedures for all Jet Pump Vertical Lift Testing

The following operation steps are “general” to meet jet pump vertical lift intent. These steps may be updated, modified, or reordered as needed to meet final equipment configuration and vertical lift parameters that may include jet pump pressure, mix of simulant, and mix of flow from single-phase water lift to three-phase gas, water, and waste simulant materials, etc.

1. Water and simulant materials used during testing operations are disposed into the CTF slurry receipt pit unless other project arrangements are made. Various tanks/containers can be used to retain water and simulant materials during setup or testing prior to disposal.
2. Ensure that the retrieval tank is configured to accept retrieved materials and that load cells are operational. Transported materials from the simulant tank and jet pump motivation water is collected and weighed in the retrieval tank. Prior to the start of testing, the retrieval tank is typically empty and initial system “tare” weight recorded. When testing is complete or retrieval tank is filled/full, the jet pump is shut off and the material in transport lines is allowed to gravity drain, primary to the simulant tank located at ground level. As applicable, the retrieval tank contents are bulk characterized (i.e., weight, volume, bulk fluid temperature, aliquot sample, etc.) prior to draining.
3. Ensure that the simulant tank is configured for testing operations and load cells are operational. The HWEE jet pump is used to collect, transport, and lift the materials out of the simulant tank and deposit these materials into the retrieval tank.
4. Open the jet pump control valve.
5. Turn on the pump. Adjust the pump outlet pressure to desired pump pressure. Initial testing will be done at the highest pump pressure (typically 9,000 – 10,000 psi range) where maximum transport is expected to be achieved. If adequate jet pump transport is demonstrated at highest pressure, subsequent step-down in pressure may be used to define performance and transport limits of the jet pump as schedule and budget permits.
6. Locate the jet pump inlet hose with attached inlet screen inside the simulant tank (positioned and secured to allow safe draining of conveyance line contents back to the simulant tank).
 - a. For Test A, single-phase gas (air) testing, the location of inlet is not critical.
 - b. For Test B, single-phase liquid (water) transport, the location of inlet should be at the bottom of the simulant tank. Simulant tank should be filled to an adequate level with water to allow adequate time for test data to be collected prior to emptying water contents to the point where

HWEE inlet unsubmerged (i.e., drawing air). Suggested water level is slightly less than full (e.g., $\frac{3}{4}$ full) to allow room for water drain back in the transport line that could include additional jet pump motivation water.

- c. For Test C, two-phase gas (air) and liquid (water) transport, the location of the inlet is variable to simulate HWEE retrieval two-phase retrieval conditions (i.e., air, air with water, and water) as the HWEE head moves in and out of the fluid. For this testing, the inlet hose (with HWEE inlet screen attached) is physically moved in and out of the water to mimic HWEE retrieval and dewatering operations.
 - d. For Test D, three-phase gas (air), liquid (water), and solids (kaolin simulant) transport, the location of the inlet is variable to simulate HWEE retrieval three-phase retrieval conditions (i.e., air, air with water/simulant, and water/simulant) as the HWEE head moves in and out of the simulant mix. For this testing, the inlet hose (with HWEE inlet screen attached) is physically moved in and out of the simulant mix to mimic HWEE retrieval and dewatering operations. Solid simulant clay materials are not expected to be retrieved by the jet pump suction (i.e., no HWEE mining being done) so physical motivation of the simulant is likely required to allow exposure of the simulant to the jet pump inlet. If jet pump inlet screen becomes clogged with simulant, then the screen may have to be manually cleaned or removed to perform testing.
7. Start the jet pump via high-pressure pump foot pedal (or equivalent method).
 8. Continue jet pump operations until testing period and adequate data is complete or retrieval tank is full. Testing periods on the order of several minutes or less should be adequate to collect data at each test condition. Depending on retrieval tank fill, several test conditions may be done before tank needs to be drained.
 9. Stop the jet pump via high-pressure pump foot pedal (or equivalent method) at the end of each test condition and record bulk test conditions (i.e., weight, volume, bulk fluid temperature, aliquot sample, etc.) as applicable.
 10. Optional: Repeat steps 1-9 for different solid/simulant materials/particles as schedule and budget permits.
 11. Turn off the high-pressure pump.
 12. Close the jet pump control valve.
 13. Store and archive the data acquisition and cameras data files as applicable.

5.4.4 Post-test Procedure

1. Empty retrieval tank(s) with retrieved simulant into the CTF slurry receipt pit or other approved designated area.
2. Empty simulant tank(s) of any remaining simulant and fluids into the CTF slurry receipt pit.
3. Place jet pump inlet in simulant tank when not in use to catch fluid leaks as applicable.
4. When testing is complete, demobilize from the CTF as directed by client.

6.0 Data Evaluation

All data records, calculations, and analyses reported from this test will be documented sufficiently to be traceable from the primary data and the methods and equipment used, through the assumptions and/or interpretations made, to the corresponding reported results. This section outlines planned analysis and a preferred system of units for reported values.

6.1 Planned Analyses

The first step in the data evaluation process will be to convert the raw data to engineering units for graphical display. Where applicable, instantaneous data and average results will be analyzed and compared. Analyses of test data will be conducted to obtain data requirements listed in Table 2.2 that must be derived from test data as follows:

- Water usage of HWEE components
- Retrieval rates and slurry dilution rates versus simulant type during retrieval operations
- HWEE force loads experienced during retrieval operations
- Pumping rates, water usage, and retrieval rates associated with jet pump vertical lift operations

6.2 Water Usage of HWEE

Water usage of the various HWEE water jetting components is derived by using a cash and weigh system for collected water out of the HWEE device water jet(s) operating at steady state conditions for a collection time; typically at least 1 minute. Data will be collected at a range of operating pressures, typically from 1000 to 10,000 psi.

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

Water usage is collected dynamically from HWEE load cells under the simulant and retrieval tanks. Prior to data collection, the weight of the tank is typically zeroed and the weight in the tank increases as the device runs.

6.3 Retrieval Rates and Slurry Dilution Rates – Retrieval Tests

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

$$\text{WSR} = \frac{\frac{1}{\rho_H} - \frac{1}{\rho_R}}{\frac{1}{\rho_H} - \frac{1}{\rho_S}} \quad (6.1)$$

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

$$\rho_R = \frac{MR}{VR} \quad (6.2)$$

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

$$\rho_H = 999.85308 + 6.32693E-2 \times T - 8.523829E-3 \times T^2 + 6.943248E-5 \times T^3 - 3.821216E-7 \times T^4 \quad (6.3)$$

where T is the measured temperature in Celsius (Jones 1992). Equation (6.3) 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

$$MSR = MR \times WSR \quad (6.4)$$

and the retrieval rate, RR, is thus

$$RR = \frac{\frac{MSR}{\rho_S}}{t} \quad (6.5)$$

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

$$DR = \frac{RR \times t}{\frac{MH}{\rho_H}} \quad (6.6)$$

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

$$MHR = MR \times (1 - WSR) \quad (6.7)$$

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

$$MHS = MS1 - (MS0 - MSR) \quad (6.8)$$

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.

6.4 Pumping Rate, Water Usage, and Retrieval Rates – Jet Pump Vertical Lift Test

The pumping rate of the jet pump for all tests is derived by using a cash and weigh system for collected material transferred out of the simulant tank into the retrieval tank by the jet pump operating at steady state conditions for a collection time, typically at least 1 minute. Data will be collected at highest operating pressure (typically 9,500 to 10,000 psi) used by the jet pump during HWEE Phase I and II retrieval testing. Data at lower pressures may be taken to determine limitations of jet pump operation.

The following formula/definitions are used for these calculations:

WTI_{cRT} – Tare weight of retrieval tank system (start of test)

WTF_{cRT} – Final weight of retrieval tank system (end of test)

W_{cRT} – Weight of material collected in retrieval tank (during test) = $WTF_{cRT} - WTI_{cRT}$

LI_{cRT} – Initial level of fluid collected in retrieval tank (start of test, typically zero)

LF_{cRT} – Final level of fluid collected in retrieval tank (end of test)

L_{cRT} – Level of fluid collected in retrieval tank (during test) = $LF_{cRT} - LI_{cRT}$

V_{unitRT} – Volume per unit of level change in retrieval tank [*optional*] (determined prior to testing)

V_{cRT} – Volume of material collected in retrieval tank [*optional*] = $L_{cRT} \times V_{unitRT}$

T_{cRT} – Bulk temperature of material fluid collected in retrieval tank [*optional*]

D_{calRT} – Calculated density of material collected in retrieval tank

D_{sampRT} – Density of material collected in retrieval tank from sample [*optional*]

WTI_{cST} – Tare weight of simulant tank system (start of test)

WTF_{cST} – Final weight of simulant tank system (end of test)

W_{cST} – Weight of material change in simulant tank (during testing) = $WTF_{cST} - WTI_{cST}$

T_{cST} – Bulk temperature of fluid material in simulant tank [*optional*] (end of test)

t_c – Collection time

F_{jp} – Flow rate of jet pump at pressure

For test A, no liquid or simulant material is pumped from the simulant tanks. Pumping rate percent ($PR_{gas\%jp}$) only determines how much of the jet pump motivation fluid is transferred to the retrieval tank at specified vertical height verses how much drains to the simulant tank at a specific pressure.

$$PR_{gas\%jp} \text{ (at set pressure and vertical height)} = [W_{cRT} / (W_{cRT} + W_{cST})] \times 100$$

Jet pump water usage (WU_{jp}) at pressure is calculated and should compare to previous jet pump component testing data done in this Phase II testing.

$$WU_{jp} = (W_{cRT} + W_{cST}) / t_c$$

For test B, water in the simulant tank is pumped to the retrieval tank at a vertical height using a submerged inlet (i.e., flooded suction), which receives both the simulant tank water and jet pump motivation fluid. Pumping rate ($PR_{waterjp}$) at a specific pressure is determined by net water transferred from the simulant tank to the retrieval tank at submerged suction conditions.

$$PR_{waterjp} \text{ (at set pressure and vertical height)} = (W_{cST} / t_c) - F_{jp}$$

For test C, water in the simulant tank is pumped to the retrieval tank at a vertical height using an inlet and is moved in and out of the water to mimic retrieval operations. Because of the variable nature of the inlet movement, a net pumping rate ($PR_{waterTestCjp}$) can be calculated but no comparison is valid unless a set frequency of inlet submerging (not a planned activity) can be set or determined (e.g., video record). This test instead will be an observation of retrieval performance and to see the extent of vertical lifting to the elevated retrieval tank with water and any drain back of water to the simulant with the variable inlet conditions of three phase flow.

$$PR_{waterTestCjp} \text{ (at set pressure and vertical height)} = (W_{cST} / t_c) - F_{jp}$$

Test D is the same as test C but now with simulant in the tank. Like test C, because of the variable nature of the inlet movement, a net pumping rate ($PR_{waterTestCjp}$) can be calculated but no comparison is valid unless a set frequency of inlet submerging (not a planned activity) can be set or determined (e.g., video record). This test instead will be an observation of retrieval performance and to see the extent of vertical lifting to the elevated retrieval tank with more dense material (water and simulant mix) and any drain back of this material to the simulant with the variable inlet conditions of three phase flow.

$$PR_{waterTestDjp} \text{ (at set pressure and vertical height)} = (W_{cST} / t_c) - F_{jp}$$

For test D, the density of the material retrieved by the simulant tank will be determined by calculation (D_{calRT}) and/or measured from sample (D_{sampRT}). If retrieval rates are calculated, the calculation methods would follow those used in Section 6.1.2 for HWEE retrieval testing.

For all the above testing, dynamic calculations may be presented to show results during the testing sequence. This likely would apply mostly to tests C and D.

Data collected from the 35-foot lift test, relevant data from HWEE Phase I testing, and consultations with the jet pump vendor shall be used to extrapolate jet pump performance at 60 assuming a linear extrapolation. Note that there was no data found to support a linear extrapolation.

6.4.1.1 HWEE End Effector Force Loads—Retrieval Testing

HWEE end effector force loads are derived from reviewing collected force data over the testing period of interest. Force load data collected during the Phase I retrieval of kaolin will provide a useful comparison.

7.0 Project Record System

This section describes how testing data and results will be documented and maintained.

7.1 Software and Control

The majority of the data will be collected with the computer data acquisition equipment and saved to hard disk. Portions of this data will be converted to Microsoft Excel spreadsheet format for data manipulation and display. Other data, such as observed test conditions, will be taken manually and collected in an electronic repository or notebook.

A test summary database will be maintained to capture the essential aspects of each test. This database will, at a minimum, record the following information:

- Date
- Start Time
- End Time
- Test Description (including test parameters if part of a test matrix)
- Reference Test Instruction of Procedure
- Excel Data File Name(s)
- Excel Data File Archive Name and Location
- Raw Data File Name(s)
- Raw Data File Archive Name and Location
- Notes / Associated Records

Data files will be archived to optical disk. Copies of the archive disks will be stored in remote locations. Test data archives will be included in the project Record Inventory and Disposition Schedule as set forth in PNNL's "Plan for Managing Project Records" workflow in the How Do I? system.

7.2 Engineering Records

All laboratory data, general observations, and details of the activities performed per this test plan will be documented electronically. Hardcopy documents, datasheets, observations, etc. will be scanned as applicable for data retention. For each test, the following minimum information will be recorded: date, time, procedure number, procedure parameters, data file, and observations.

7.3 Calibration Records

Quality Assurance Engineering will review the M&TE list before test initiation. Calibration records of instruments used to generate reported data will be maintained in the project files. The M&TE list is provided in Appendix A. As shown in Appendix A, certain instruments will be calibrated by an ISO 17025 Accredited Calibration Laboratory. Instrumentation that has not been calibrated within the approved interval will be recalibrated before testing. Instrumentation that is added in response to unforeseen circumstances (e.g., sensor failure) that is not calibrated can be post-calibrated with the

condition that no issues were found at the time of the calibration, and calibration information will be submitted to WRPS Quality Assurance for review. Other instruments that are not calibrated but will be used to supplement or provide context for reported information will be designated as FIO.

The M&TE list in Appendix A includes the planned field checks as described in Section 5.1. Use of standard off-the-shelf metal tapes or scales may be used for length measurement. Standard off-the-shelf containers may be used for volume measurements.

7.4 Quality Assurance

This test program shall follow the guidelines of DOE Order 5700.6C implemented through the Quality Management System Description within PNNL's How Do I? system. All requirements are implemented through manuals, work controls, and workflow procedures. Quality Assurance personnel shall assist in data verification, calibration, inspection, and other activities as required. Staff from the WRPS contract team are invited to witness all aspects of testing.

8.0 Facility and Safety Considerations

The HWEE will be installed in the PNNL test bed, located at WRPS's CTF. This section provides an overview of the CTF systems that will be used in the tests and reviews safety and personnel training considerations.

8.1 Electrical Supply

The HWEE does not require any electrical power. However, electrical power will be required for the following:

- HWEE and jet pump hydraulic power unit(s) and the high-pressure pump(s) may require facility electrical power if an electric motor is used (gasoline or diesel generation is expected)
- PNNL test bed gantry system
- Control and data acquisition trailer located nearby
- Ancillary equipment like overhead lighting

A service request will be submitted to connect these pieces of equipment before operation as applicable.

8.2 Water

Water will be required for the following:

- Supply for the high-pressure pump(s)
- A hose for wash-down

All water used in the facility must be confined and controlled. Cleanup equipment for excess water cleanup will be available.

8.3 Compressed Air

The diaphragm pump and pressure regulator require compressed air at a minimum 80 psi, 20 CFM for operation. For Phase II, the new pneumatically operated air valve requires a minimum 100 psi, 2 CFM flow for operation. Maximum air pressure to these valves will be limited to 120 psi by a local pressure relieve valve.

8.4 Safety Precautions

How Do I (HDI) system workflows and work controls provide the minimum requirements for routine operations. This system, along with consultation with PNNL Industrial Safety and Health Representatives, was used to compile the Job Hazards Assessment shown in Table 8.1. This table is consistent with the WPRS Job Hazard Analysis Checklist and the PNNL Off-site Risk Management Plan that has been approved for this activity.

The most serious hazards associated with test bed operations are listed in Table 8.1.

- There is a serious hazard to personnel involved with the motion of the gantry in the PNNL test bed. Personnel cannot be allowed into the working envelope of the gantry during operation except under the very controlled conditions described in ANSI 15.06 American National Safety Standard for Industrial Robots and Robot Systems (ANSI/RIA 1992).
- There is a serious hazard to personnel from high-pressure waterjets due to their ability to penetrate and damage human skin. This hazard will be managed by preventing personnel from entering the tent containment during pump operation.

Table 8.1. Job Hazards Assessment

Sequence of Basic Job Steps or Work Activity	Hazards Present	How to Eliminate Hazards
Operation of low-pressure water system	Water leakage	Isolate water sources when not in use. Monitor water and discontinue operation if significant uncontrolled water is generated.
Material transfer operations (e.g., diaphragm transfer pump, tank draining, etc.)	Fluid leakage	Monitor transfer operations and discontinue operation if significant uncontrolled fluid leaks are observed.
	Possible high noise levels during operation (>85 dBA)	Diaphragm pump may generate high noise levels if not shielded for sound. Hearing protection and warning signs may be based on field evaluation.
Testing and operation of high-pressure water system	Hazardous energy (air, steam, fluid, pressurized)	Operators will establish clear communication signals (e.g., voice, hand signals) for high-pressure water operations. See related HWEE operations.
		Continuous burst-shielded hose from valves at high-pressure water source to test bed.
		Whip checks to secure quick disconnect fittings. Piping protected by rupture disk discharging into safe area.
		End effector nozzles will be operated within personnel barrier/shield (e.g., tent)
	High noise levels during operation (>85 dBA)	Hearing protection for personnel exposed to greater than 85 decibels. Warning signs. Strobe light indicates system operation with time delay.
	Heat stress due to localized heat source or special personal protection equipment use	Apply heat stress mitigation checklist
Assembly and operation of compressed air hoses	Hazardous Energy (air, steam, fluid, pressurized)	Secure hoses at appropriate points and intervals. Compressed air is not to be used for housekeeping.

Sequence of Basic Job Steps or Work Activity	Hazards Present	How to Eliminate Hazards
HWEE gantry	Rotating, Moving Equipment or Pinch Points	Work zone to be established and interior cleared of personnel prior to operation. Personnel barrier (e.g., tent enclosure) with interlock to E-stop control will prevent access to the work space of the gantry. Warning signs will be placed on the personnel barrier to warn personnel of the hazard of entering the working envelope. Mechanical stops on the gantry have been provided by the vendor to define the gantry operating envelope. In addition, software limits the travel of the individual degrees of freedom. Operators will be instructed on the proper use of gantry and location of E-stops. A list of personnel qualified to operate the system will be posted at the system control station. Emergency stops (or E-stops) for the gantry are provided at the drive cabinet. When this switch is activated, all brakes are applied, power is cut to the gantry drive, and the system is disarmed. While the gantry is operating, one person will be designated system operator. The system operator will be the only person to command the gantry to move. The operator must be within arm's reach of an E-stop button and will be responsible for activating the E-stop if it is deemed necessary.
Simulant equipment cleaning	Hazardous energy (air, steam, fluid, pressurized)	Wear rubber gloves, boots, overalls or rain suit, eye and face protection as applicable for test.
Simulant preparation	Inhalation of nuisance dusts	Use dust mitigation procedure to reduce dust, such as HEPA vacuum. Wear respirators when handling dry materials. Wear eye protection, gloves, and coveralls when handling simulant materials. Respirators will include HEPA cartridges with pre-filters.
	Manual lifting	Use proper lifting procedures and material handling equipment.
Simulant disposal	Vehicular traffic, equipment, and/or forklift	Post observer as required to guide forklift or truck operator and keep personnel clear.
Overhead work (applies to CTF tank platform – jet pump vertical testing)	Falling material from above	Where elevated platforms with workers above or equipment operating pose a risk of falling material (e.g., tools, debris, fluids) to personnel below, the personnel shall wear appropriate personal protection equipment such as hard hat or similar at a minimum as specified by safety organizations.

Sequence of Basic Job Steps or Work Activity	Hazards Present	How to Eliminate Hazards
HWEE operation	Rotating, moving equipment, or pinch points	Pre-job briefing. Hydraulic motor to be deactivated prior to personnel working on HWEE.
	High-pressure water spray	Pre-job briefing. Water spray from jets activated only when HWEE positioned to contain the high-pressure water spray in a tank/container (excludes splashing). Personnel to be located behind perimeter barriers during high-pressure water spray operations. Water pressure to be deactivated prior to personnel working on HWEE.

8.5 Training and Qualification Requirements

Personnel training for the operation of test equipment will be done using a combination of briefings, equipment walk-throughs, site hazard orientation, and on-the-job training in accordance with the Identify, Schedule, and Complete Training workflow (see <https://hdi.pnl.gov/hdi>). Briefings of operational and test procedures will be conducted by the author of the procedure being discussed. Equipment walk-through and on-the-job training shall be conducted by experienced operations personnel. Attendance for all training activities will be documented using training attendance forms. Training on equipment use will be based on vendor-supplied documentation.

8.6 Waste Simulant Minimization and Management

Waste disposal procedures have been developed with the cooperation of the PNNL Environment, Health, Safety and Security organization for all materials that will be used in this test program. Simulants will be deposited into the CTF slurry receipt pit. Waste simulant disposal must also be in accordance with the Hanford Waste End-Effector Cold Test Facility Memorandum of Understanding Section 5.5.

9.0 References

ANSI/RIA R15.06-1992. 1992. American National Standard for Industrial Robots and Robot Systems.

ASME B31.3-2014. 2014. *ASME Code for Process Piping*. The American Society of Mechanical Engineering. New York, New York.

ASTM C1750-1. *Standard Guide for Development, Verification, Validation, and Documentation of Simulated High-Level Waste*. ASTM International, West Conshohocken, Pennsylvania.

Berglin EJ, CA Burns, BK Hatchell, JC Mount, KJ Neill, and BE Wells. 2017. *Hanford Waste End Effector Phase I Test Report*. PNNL-26856 Rev 1. Pacific Northwest National Laboratory, Richland, WA.

Gauglitz, P.A, B.E. Wells, E.J. Berglin, and L.A. Mahoney. 2017. *Evaluation of A-105 Waste Properties and Potential Simulants for Confined Sluicing Testing*. PNNL-26206, Pacific Northwest Laboratory, Richland, Washington.

Gauglitz PA and JT Aikin. 1997. *Waste Behavior during Horizontal Extrusion: Effect of Waste Strength for Bentonite and Kaolin/Ludox Simulants and Strength Estimates for Wastes from Hanford Waste Tanks 241-SY-103, AW-101, AN-103, and S-102*. PNNL-11706, Pacific Northwest National Laboratory, Richland, Washington.

Gauglitz PA, BE Wells, JA Fort, and PA Meyer. 2009. *An Approach to Understanding Cohesive Slurry Settling, Mobilization, and Hydrogen Gas Retention in Pulsed Jet Mixed Vessels*. PNNL-17707 (WTP-RPT-177 Rev. 0), Pacific Northwest National Laboratory, Richland, Washington.

Gauglitz PA, BE Wells, JA Bamberger, JA Fort, J Chun, and JJ Jenks. 2010. *The Role of Cohesive Particle Interactions on Solids Uniformity and Mobilization during Jet Mixing: Testing Recommendations*. PNNL-19245. Pacific Northwest National Laboratory, Richland, WA.

Hatchell, B.K. 2018. *HWEF Modification Recommendations for Phase 2 (letter report)*, Pacific Northwest Laboratory, Richland, Washington 99352

Hatchell, B.K., E.J. Berglin, M.W. Rinker, and K.M. Airhart. 2016. *Alternate Retrieval A-105 Application Assessment Report*. PNNL-26037, Pacific Northwest Laboratory, Richland, Washington 99352.

Higley BA and DE Place. 2004. *Hanford Defined Waste Model – Revision 5*. RPP-19822, CH2M Hill Hanford Group, Inc., Richland, Washington.

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

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

Rassat SD, LA Mahoney, BE Wells, DP Mendoza, and DD Caldwell. 2003. *Assessment of Physical Properties of Transuranic Waste in Hanford Single-Shell Tanks*. PNNL-14221, Pacific Northwest National Laboratory, Richland, Washington.

Rogers CA. 1993. *Data Transmittal Package for 241-A-106 Waste Tank Characterization*. WHC-SD-RE-TI-200 Rev. 0.

Sturman GA. 2016. *Derivation of Best-Basis Inventory for Tank 241-A-106 as of April 1, 2016*. RPP-RPT-59283 Rev. 0. Washington River Protection Solutions, LLC, Richland, Washington.

Wells BE, DE Kurath, LA Mahoney, Y Onishi, JL Huckaby, SK Cooley, CA Burns, EC Buck, JM Tingey, RC Daniel, and KK Anderson. 2011. *Hanford Waste Physical and Rheological Properties: Data and Gaps*. PNNL-20646. Pacific Northwest National Laboratory, Richland Washington.

Wooley, T.A. 2018. Statement of Work for Alternate Retrieval Technology Concept Testing Definition Hanford Waste End Effector Phase II, Revision 1. Washington River Protection Solutions, Richland, WA 99352.

Yarbrough RJ. 2013. *Methodology and Calculations for the Assignment of Waste Groups for the Large Underground Waste Storage Tanks at the Hanford Site*. RPP-10006, Rev. 11. Washington River Protection Solutions, LLC, Richland, Washington.

Appendix A

M&TE Calibration

Measured Parameter	Range, Units	Tag #	Sensor / Control Element	Signal Conditioning	Calibrated	FOI	Calibration Date	Calibration Due
Valve, Process Water Control	On, Off	V1	None	None				
Level, Water Tank on Pump	Empty - Full	YS5000	Sight glass	None				
Pressure, HWEE Waterjet Supply	0-10,000 psi	PE 5000	Pressure Gauge	None	X		Prior to test	
Valve, Pressure Reducing Bypass, HWEE Waterjet Supply	0-10,000 psi	PR5000	NA	NA				
Valve, On-Off with Bypass, HWEE Waterjet Supply	0-10,000 psi	VD1	NA	NA				
Valve Position of VD1	On, Off	IO 5001	Limit Switch	None				
Valve, Jet Pump Control	On, Off	V3	NA	NA				
Valve, PRM 1st Isolation	On, Off	V4	NA	NA				
Valve, PRM 2ns Isolation	On, Off	V5	NA	NA				
Pressure, HWEE Flush & HWEE Jets	0-10,000 psi	PE 5001	Pressure Gauge	None	X		7/28/2017	7/27/2018
Valve, Pressure Reducing Bypass, HWEE Flush & HWEE Jets	0-10,000 psi	PR5001	NA	NA				
Valve, HWEE Flush Control/Isolation	On, Off	V6	NA	NA				
Valve, HWEE Jets Control/Isolation	On, Off	V7	NA	NA				
Level, Water Tank on HPU	Empty - Full	YS5001	Sight glass	None				
Valve, HPU Control/Isolation	On, Off	V9	NA	NA				

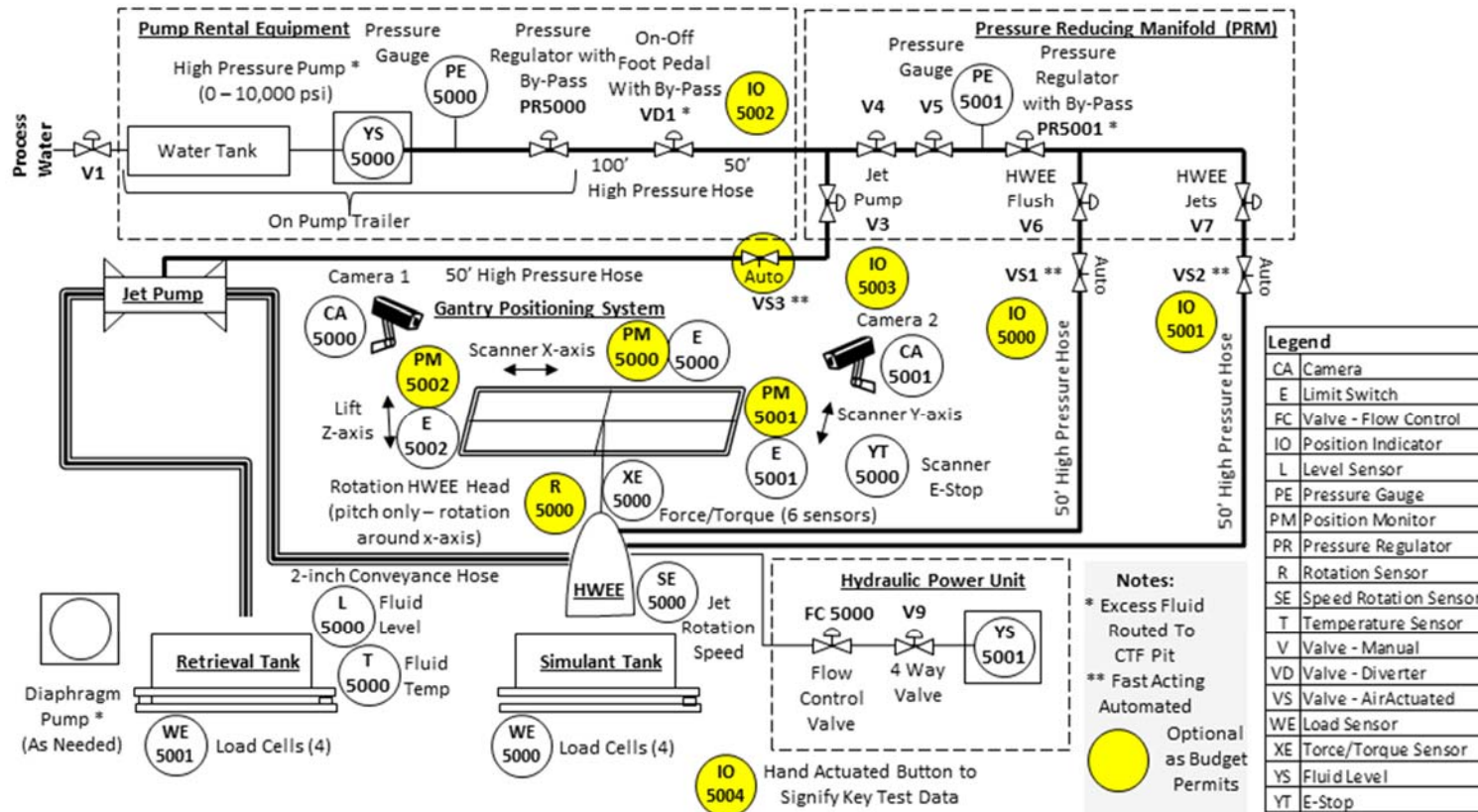
Measured Parameter	Range, Units	Tag #	Sensor / Control Element	Signal Conditioning	Calibrated	FOI	Calibration Date	Calibration Due
Valve, HPU Flow Control	On, Off	FC5000	NA	NA				
Flow Control, HPU	0-3 gpm	FC 5000	Flow Gauge	None				
Force/Torque Sensor (forces and torques in three directions)	Fx, Fy: +/-300 lbf	XE-5000	9105-T-OMEGA160-IP65	ATI F/T Controller	X ¹		5/22/2017	5/21/2018
	Fz: +/-875 lbf		US-300-1800					
	Tx, Ty, Tz: +/-1800 in-lbf							
Angle, HWEE Head Rotation	45 to -45 degrees (Actuator Linear Position)	R5000	SP1-25 String Pot	None		X		
Position, Scanner X-axis	0 - 100 inches	PM5000	HX-PA-100-S10-N1S-1BC String Pot	None		X		
Position, Scanner Y-axis	0 - 50 inches	PM5001	SP2-50 String Pot	None		X		
Position, Scanner Z-axis	0-50 inches	PM 5002	SP2-50 String Pot	None		X		
	0-80 inches	None	Tape Measure	None				
E-Stop, Scanner	On, Off	YT 5000	Circuit Loop	None				
Camera 1, Overview	Video, Time	CA 5000	None	None				
Camera 2, Close-up	Video, Time	CA 5001	None	None				
HWEE Rotation	0-1000 RPM	SE 5000	MCS-655M Optical Receiver	None				
Weight, Simulant Tank & Contents	0-10000 lbs	WE 5000	SPWE-SR-2.5K	IPE50	X		Prior to test	
Weight, Retrieval Tank & Contents	0-10000 lbs	WE 5001	SPWE-SR-2.5K	IPE50	X		Prior to test	
Level, Retrieval Tank Fluid	0 - 50 inches	L5000	Endress+Hauser FMU40-ANB2A4	None	X		Prior to test	

Measured Parameter	Range, Units	Tag #	Sensor / Control Element	Signal Conditioning	Calibrated	FOI	Calibration Date	Calibration Due
Temperature, Retrieval Tank Fluid	0 - 100° C	T5000	OM-2628-C6	None	X		Prior to test	
Data Button	On, Off	IO5004	Limit Switch	None				
Field Time Measurements	DAS	DAS	None	None				
	Camera 1	CA 5000	None	None				
	Camera 2	CA 5001	None	None				
Field Length Measurements	0-6 inches	DC 5000	None	None				
	Tape Measure	None	None	None				
Simulant Strength	0-5.25 kg(f)/cm2	POCKP EN-1000	S-170 Pocket Penetrometer			X	8/18/2017	8/17/2018

1 – Will not be calibrated by an accredited laboratory. Will submit waiver through PNNL QA department. If not approved by PNNL, sensor will be FOI.

Appendix B

Piping and Instrumentation Diagram





Pacific Northwest
NATIONAL LABORATORY

*Proudly Operated by **Battelle** Since 1965*

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)

U.S. DEPARTMENT OF
ENERGY

www.pnnl.gov