PNNL-11741
UC-721

Pacific Northwest
National Laboratory

Operated by Battelle for the
U.S. Department of Energy

Development and Testing of the Cooling Coil Cleaning End Effector

K. I. Johnson
O. D. Mullen
M .R. Powell
D. S. Daly
D. W. Engel

September 30, 1997

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

DISCLAIMER

PACIFIC NORTWEST NATIONAL LABORATORY
Operated by
BATTELLE
for the
UNITED STATES Department of Energy
under Contract DE-AC06-76RL) 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. 62, Oak Ridge, TN 37831; prices available from (615) 576-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

PNNL-11741
UC-721

Development and Testing of the Cooling Coil Cleaning End Effector

K. I. Johnson
O. D. Mullen
M .R. Powell
D. S. Daly
D. W. Engel

September 30, 1997

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

EXECUTIVE SUMMARY

The Retrieval Process Development and Enhancement (RPD&E) program has developed a prototype end effector to dislodge and convey waste from the high-level liquid waste (HLLW) storage tanks at the Idaho National Engineering and Environmental Laboratory (INEEL). Cleanup of the HLLW tanks is driven by a Consent Order between the State of Idaho, the U.S. Department of Energy, and the Environmental Protection Agency that requires cleanup and closure of the tanks by the year 2009.

The HLLW tanks (15.25-m diameter and 9.75-m high) contain a maze of cooling coils covering the walls and floor at a standoff distance of 15 cm. The waste, ranging from 7.5- to 30.5-cm in depth, consists of supernate liquid covering a sedimentary layer. A black, tar-like material was also found clinging to a radio frequency probe inside one tank. The complexity of in-tank hardware, plus the waste clinging to the cooling coils and settling beneath them, provides a very challenging environment for surface cleaning and waste retrieval.

The cooling coil cleaning end effector was developed at the High-pressure Waterjet Laboratory of the University of Missouri at Rolla (UMR). This design benefits greatly from previous work by UMR in developing the confined sluicing end effector for Oak Ridge National Laboratory (ORNL). The cooling coil cleaning end effector contains high-pressure waterjets on a rotating manifold within a fixed suction shroud. The end effector is sized to fit through the 30.5-cm risers of the HLLW tanks. The prototype weighs 17-kg compared to the 11.4-kg target weight of the field-deployable unit.

Functional testing was performed at UMR before shipping the end effector to Pacific Northwest National Laboratory (PNNL). Testing in PNNL's hydraulic test bed (HTB) focused on evaluating long-duration mining strategies using waste simulants and cooling tube structures typical of the INEEL storage tanks. A multi-stage cleaning process was tested where the rotating waterjets were first used to suspend the sediment and scour the tube surfaces. In the second pass, the end effector was positioned close to the floor to remove the bulk of the particulate waste. In the third pass, the suction shroud was positioned beneath the coils to suction the remaining waste that was directly beneath the cooling coils.

The testing program showed that although the high-pressure waterjets were effective in directly removing both a fully cured roof sealing paint and a soft wax simulant from the surface of the cooling coils, they were completely ineffective in removing either of these waste simulants from the undersides of the coils. Therefore, the waterjets (at pressures up to 34.5-MPa) did not provide sufficient energy to entrain the 7.6-cm deep sand bed (the maximum estimated depth of particulate waste in the HLLW tanks) to scour the undersides of the tubes.

The end effector was also tested for bulk retrieval of sand from the tank floor beneath the cooling coils. Retrieval tests were run with the suction shroud in a flooded

condition, showing that the end effector was able to remove about 68% of the sand. Small ridges of sand remained in the corners where the cooling coils intersect with the support cross members

This task has directly supported the INEEL waste retrieval program by providing prototype testing to support the future specification of a field-deployable end effector. Completion of this task closes out the RPD&E program's development phase for retrieval end effectors to cleanup the HLLW tanks at INEEL.

The RPD&E program has developed and tested an end effector to support the waste retrieval mission at INEEL. The end effector was developed specifically to remove a sticky waste material from the cooling coils in HLLW tank. The end effector is also able to vacuum up a sediment layer that has settled beneath the cooling coils. The complexity of cooling coils inside the HLLW tanks makes for very challenging conditions for cleaning and waste retrieval.

An extensive testing program was conducted in the HTB at PNNL to evaluate the performance of the end effector under simulated in-tank conditions. A mock up of the cooling coils was installed in the test bed tank, and simulated waste materials were included to represent the sticky waste on the tubes and the particulate waste settled beneath them. The testing program focused on assessing long-duration mining strategies for cleaning the cooling coils and removing the particulate waste forms. This task has directly supported the INEEL retrieval program by providing prototype testing to support the future specification of a field-deployable end effector. Reporting the findings of this testing program marks the completion of RPD&E's support to the INEEL effort to develop waste retrieval end effectors.

The following report describes the results of the end effector testing program at PNNL. Section 2 describes the physical characteristics of the HLLW tanks, including the layout of the cooling coils, and it also describes what is known of the waste forms in the tanks. Section 3 describes the cleaning and retrieval strategy that was used in developing the end effector design. Section 4 describes the cooling coil mockup in the hydraulic test bed. Section 5 discusses the rationale used in selecting the simulants for the tarry waste and particulate waste forms. Section 6 describes the tests that were performed to evaluate cleaning of the cooling coils and retrieval of the particulate simulant. Section 7 summarizes the cleaning and retrieval tests, assesses the relative importance of cleaning the cooling coils and retrieving the particulate waste, and suggests modifications that would simplify the end effector design. An appendix is also included with the report that describes a novel method of using a hand-held scanner to map the cooling coil surface and provide a quantitative measure of cleaning effectiveness.

Contents

Figures

Tables

1.0 Introduction

The Retrieval Process Development and Enhancement (RPD&E) program has developed and tested an end effector to support the waste retrieval mission at the Idaho National Engineering and Environmental Laboratory (INEEL). The end effector was developed specifically to remove a sticky waste material from the cooling coils in the High Level Liquid Waste (HLLW) tank, and to vacuum up a sediment layer that has settled beneath the cooling coils. The complexity of cooling coils inside the HLLW tanks makes for very challenging conditions for cleaning and waste retrieval.

An extensive testing program was conducted in the hydraulic test bed (HTB) at the Pacific Northwest National Laboratory (PNNL) to evaluate the performance of the end effector under simulated in-tank conditions. A mock up of the cooling coils was installed in the test bed tank, and simulated waste materials were included to represent the sticky waste on the tubes and the particulate waste settled beneath them. The testing program focused on assessing long-duration mining strategies for cleaning the cooling coils and removing the particulate waste forms. This task has directly supported the INEEL retrieval program by providing prototype testing to support the future specification of a field-deployable end effector. Reporting the findings of this testing program marks the completion of RPD&E's support to the INEEL effort to develop waste retrieval end effectors.

This report describes the results of the end effector testing program at PNNL. Section 2 describes the physical characteristics of the HLLW tanks, including the layout of the cooling coils, and it also describes what is known of the waste forms in the tanks. Section 3 describes the cleaning and retrieval strategy that was used in developing the end effector design. Section 4 describes the cooling coil mockup in the hydraulic test bed. Section 5 discusses the rationale used in selecting the simulants for the tarry waste and particulate waste forms. Section 6 describes the tests that were performed to evaluate cleaning of the cooling coils and retrieval of the particulate simulant. Section 7 summarizes the cleaning and retrieval tests, assesses the relative importance of cleaning the cooling coils and retrieving the particulate waste, and suggests modifications that would simplify the end effector design. An appendix is also included with the report that describes a novel method of using a hand-held scanner to map the cooling coil surface and provide a quantitative measure of cleaning effectiveness.

2.0 The HLLW Tanks and their Waste Characteristics

The HLLW tanks are 15.25 m (50 ft) in diameter with a height of 9.75 m (32 ft) from the floor to the top of the dome. The dome height is 3.35 m (11 ft) and the tank capacity is 1.14 x10^6 liters (300,000 gal). The distance to the bottom of the tanks (from grade) ranges from 12.5 to 13.1 m (41 to 43 ft) for tanks WM182 through WM190, and 14.9 to 15.5 m (49 to 51 ft) for tanks WM-180 and 181. The tanks (with the exception of tanks WM-181 and 184) contain a lattice of cooling coils lining the walls and floor (Figure 1). The cooling coils are aligned in pairs spaced 65.7 cm (18 in.) apart with a standoff distance of approximately 15.2 cm (6 in.) from the tank walls and floor (see Figure 2). The cooling coils are 38-mm (1.5-in.) SCH-80 stainless steel tubing. This complexity of hardware provides many difficult surfaces for cleaning and waste retrieval.

The waste within the HLLW tanks originated from fuel reprocessing and decontamination activities, and it consists of an aqueous supernate covering a heel of particulate waste that is thought to be readily suspendable. The depth of the remaining waste ranges from 7.6 to 30.5 cm (3 to 12 in.), depending on the height of the steam jet/air lift suction line above the bottom of each individual tank. Most of the information about the HLLW mixed waste was formulated by Kaiser Engineering based on visual tank inspections and data received from limited samples taken from the waste process stream (Kaiser Engineers, 1993).

The chemical environment within the tanks is extremely acidic with high levels of sodium. The maximum acid concentration is 6 molar nitric acid with a pH level of less than 1. High levels of chloride (up to 0.031 molar) are also present. Seventy-five percent (by weight) of the particles are estimated to be larger than 45 μm with a density of 3.0 g/mL and they account for 25% of the total weight. Most of the solids are expected to be in a granular form with combined specific gravity ranging from 1.25 to 1.12. Some of the solids have specific gravity near that of the supernate and will exhibit flocculent behavior. It is estimated that the particulate waste comprises about 2.5 to 7.6 cm (1 to 3 in.) of the total 7.6 to 30.5 cm of mixed waste remaining in the tanks. The maximum total weight of solids expected for each tank is estimated at 9000 kg for a 7.6 cm (3 in.) depth of particulate waste.

There is also evidence of a sticky waste form adhering to the cooling coils and other internal tank structures. A black, tar-like material was observed clinging to a radio frequency (RF) probe during an inspection of one HLLW tank. Tank farm personnel noted that the substance "looked" like tar and that it could not be washed from the RF probe by the spray-ring waterjets (at approximately 550 KPa [80 psi] water pressure). Because this material could not be readily washed away, there is concern that it may be difficult to remove. Unfortunately, there is very little information regarding the nature of the tar-like material. In fact, aside from its being black, it is not clear whether the material actually possessed any of the physical properties typically associated with tar (e.g., sticky and highly viscous). Currently there is no information regarding how much of this material might be in the waste tanks, and the chemical composition is also unknown. The only evidence for its existence comes from the observations made during the RF probe inspection. The tank farm personnel did not attempt to touch the material, so very little can be inferred about its mechanical properties.

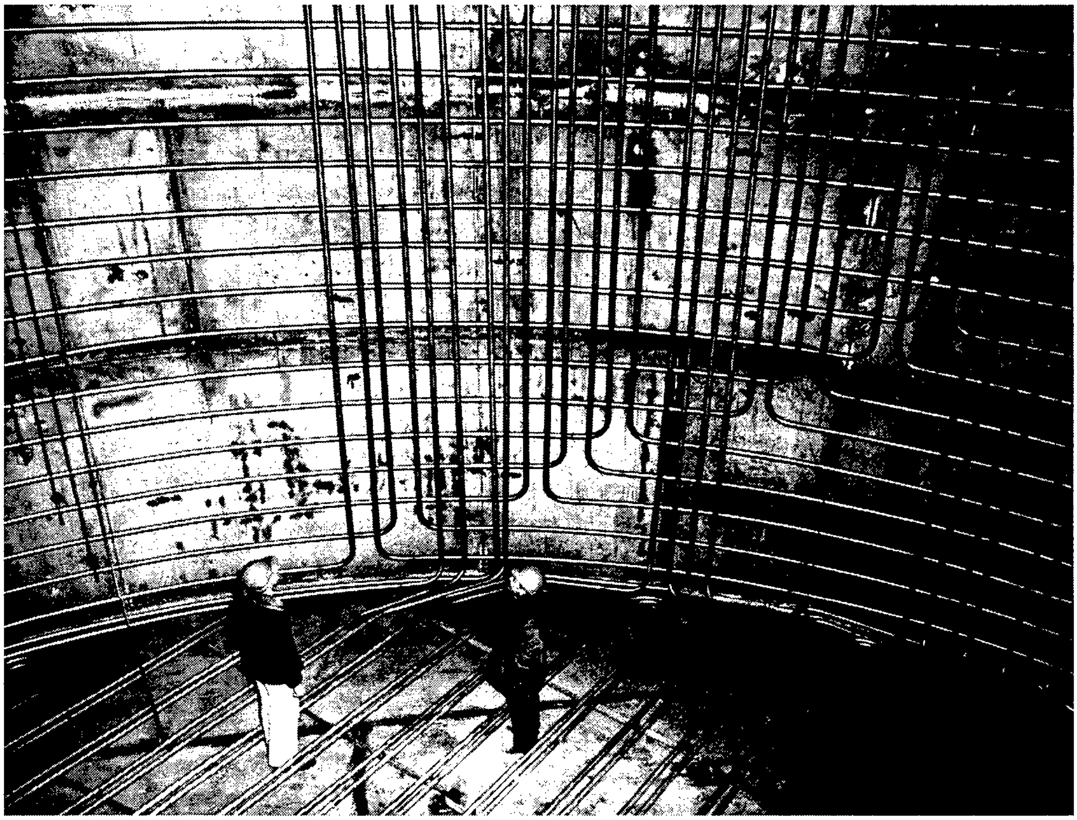

Figure 1. Cooling Tubes Lining the Walls and Floor of an HLLW Tanks at INEEL

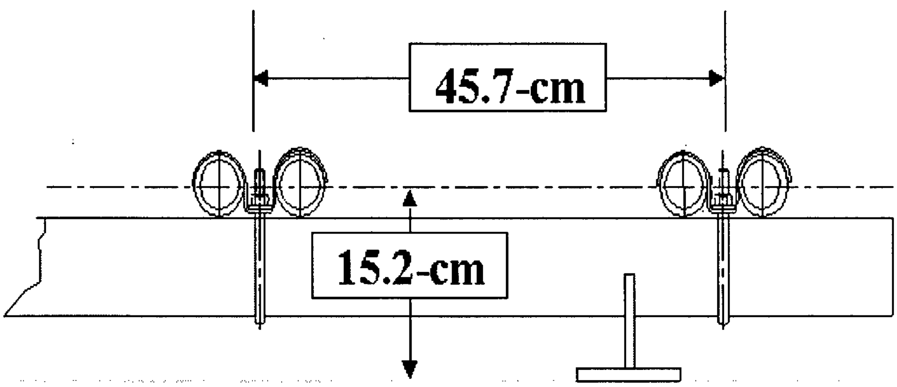

Figure 2. Sketch Showing Cooling Coil Spacing and Standoff Distance from the Tank Floor

3.0 Design Features of the Cooling Coil Cleaning End Effector

The cooling coil cleaning end effector was developed by researchers at the High-pressure Waterjet Laboratory of the University of Missouri, Rolla (UMR). The particulate and tarry waste forms combined with the complexity of cooling coils in the HLLW tanks at INEEL require a different cleaning strategy for the HLLW tanks compared to the previous strategy used in the development of the confined sluicing end effector (CSEE) for waste dislodging and retrieval at the Oak Ridge National Laboratory (ORNL). Although the cleaning strategies are different, the cooling coil cleaning end effector borrows heavily from the previous experience gained in developing the CSEE for ORNL.

A multi-pass cleaning strategy is recommended for the HLLW tanks. In the first pass, a rotating manifold of high-pressure waterjets is used to suspend the sediment and scour waste from the cooling coils and support structure. In the second pass, the end effector is passed between the cooling coils (at a low standoff distance from the floor) to remove the bulk of the particulate waste from the floor. In a third pass, the end effector traverses beneath the pairs of cooling coils to remove waste that is directly under the coils.

The end effector developed by UMR is shown in Figure 3. This design contains high-pressure waterjets on a rotating head within a fixed waste conveyance shroud (Figure 4). The nozzle arms are adjustable to allow changing the downward angle of the waterjets to optimize the cleaning performance. This end effector design represents a significant simplification compared to the ORNL CSEE that includes waterjets external to a central, rotating suction shroud. The simpler design was adopted because the end effector will initially traverse above the level of the cooling coils and the particulate waste and not contact hard waste. Large blocks of solid waste are not present that would require waterjets to cut access ahead of the suction shroud. The motor and high-pressure swivel are housed in a separate compartment above the conveyance shroud. The central, hollow shaft both rotates and supplies water to the jets. The shaft is sealed at both the top and bottom ends, and positive air pressure is supplied to the motor housing to preclude water leakage into the motor. The Kollmorgen motor, Stoneage high-pressure swivel, and the waterproof electrical connectors and cables are similar to components used in the CSEE for ORNL. These components were chosen because of their proven performance in the CSEE design.

Waste conveyance is accomplished through the two white corrugated suction hoses shown in Figure 3. The suction ports are opposed and positioned inline with the gripper interface (the attachment point to the light duty utility arm) to give maximum clearance on two sides of the shroud for sliding under the cooling coils (Figure 5). The end effector must reach approximately 10 cm (4 in.) beneath the vertical projection of the coils to fully clean the floor under the coils.

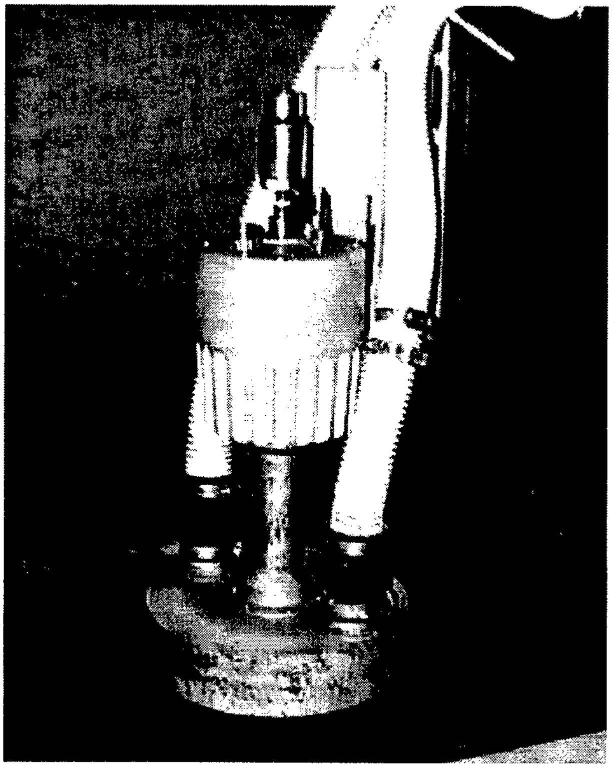

Figure 3. The Cooling Coil Cleaning End Effector Developed by UMR for Performance Testing in a Mockup of the HLLW Tank Configuration

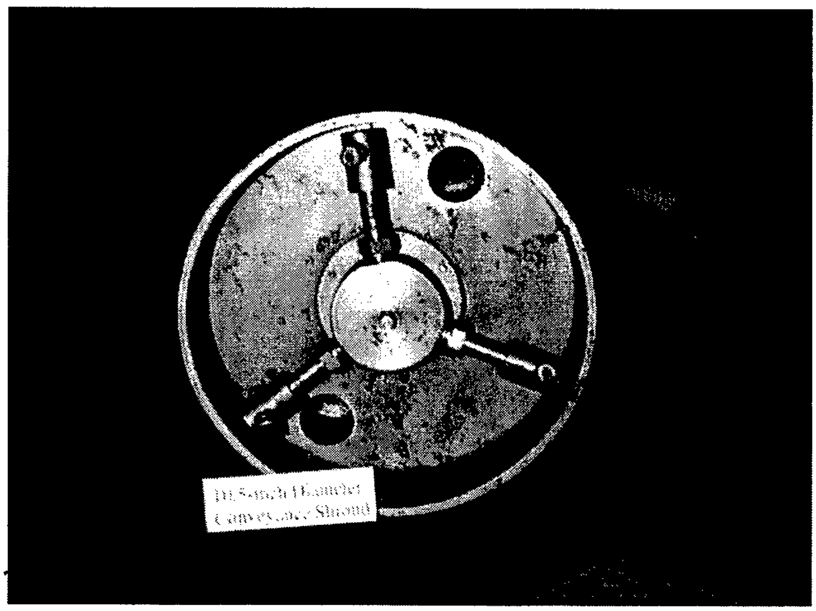

Figure 4. Bottom View of the Cooling Coil Cleaning End Effector Showing the Rotating Waterjet Manifold Beneath the Conveyance Shroud

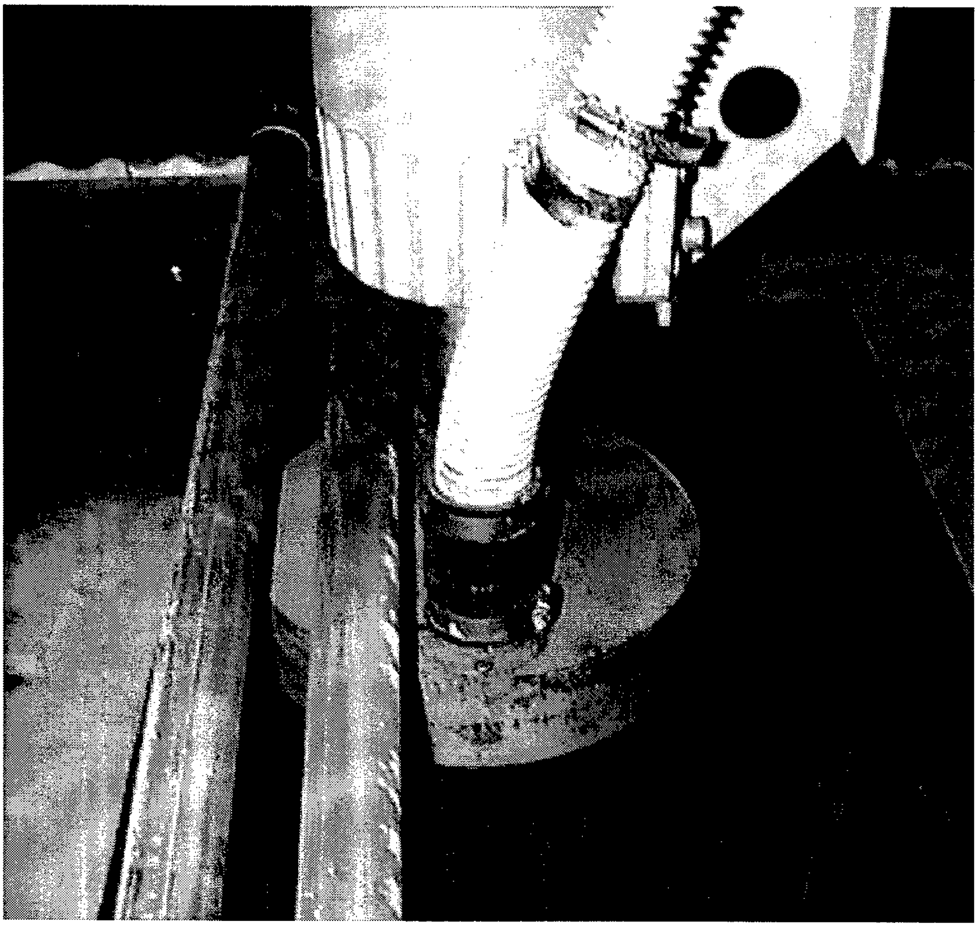

Figure 5. Photo Showing Ability of End Effector to Reach Under the Cooling Coils to Vacuum Debris from the Floor of the Tank

4.0 The HLLW Cooling Coil Mockup in the Hydraulic Test Bed

The Hydraulic Test Bed (HTB) at PNNL was used to test the cooling coil cleaning end effector under conditions similar to those in the actual HLLW tanks. The HTB contains a tank in which to perform cleaning and waste conveyance tests, a gantry robot that provides controlled motion of the end effector for testing cleaning and retrieval strategies, and the necessary support systems to safely perform the tests and record the data. The HTB support systems include a high-pressure pump, a vacuum conveyance system, a collection hopper complete with a loadcell weighing system, and computerized control and data acquisition systems. Hatchell et al. (1996) contains a detailed description of the HTB and its testing capabilities.

The HTB contains a 2.44-m (8-ft) square tank in which the mockup cooling coils were placed (Figure 6). The tank is large enough for five pairs of cooling coils spaced 45.7 cm (18 in.) apart. The cooling coil supports were spaced 137 cm (54 in.) apart (the approximate spacing in the actual waste tanks), and 1.5-m (5-ft) lengths of 44.5-mm (1.75-in.) diameter electrical conduit were used to simulate the cooling coils. The electrical conduit was readily available in 3-m (10-ft) lengths, and it was inexpensive enough that it was not reused from test to test. The cooling coil supports were constructed of bar and angle stock for easy installation and removal,0 and they reproduced the geometry of the actual supports. Standard conduit clips and J-bolts were used to attach the cooling coils to the support structure, which also made the cooling coils easy to install and remove (Figure 7).

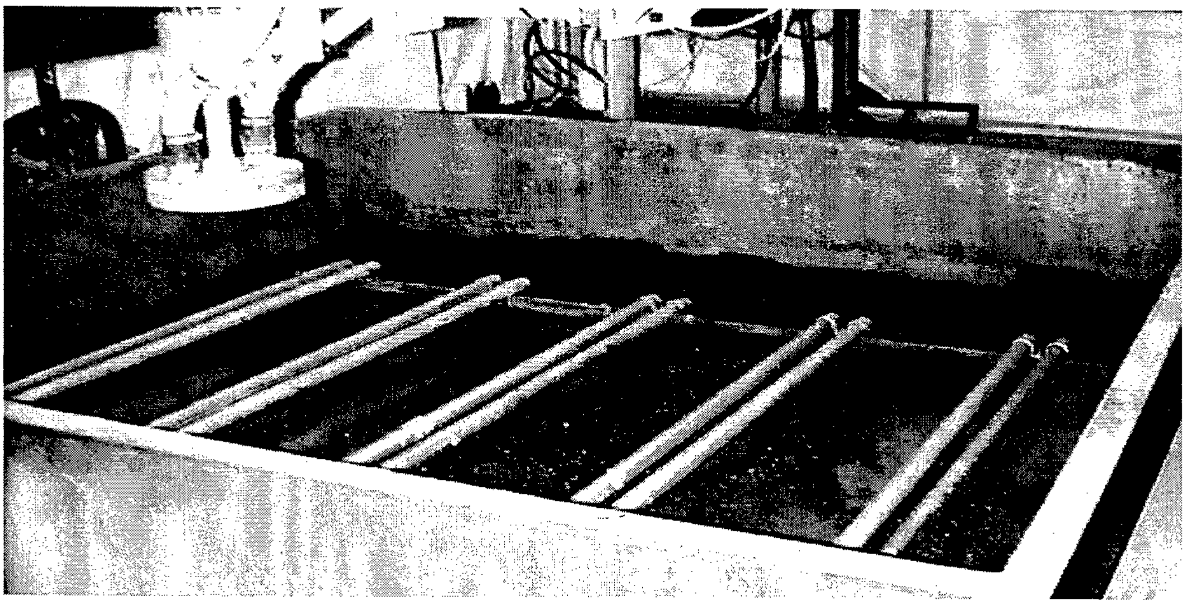

Figure 6. The Cooling Coil Mockup Shown in the HTB (The cooling cleaning end effector is shown mounted to the mast of the gantry robot to the left above the cooling coils.)

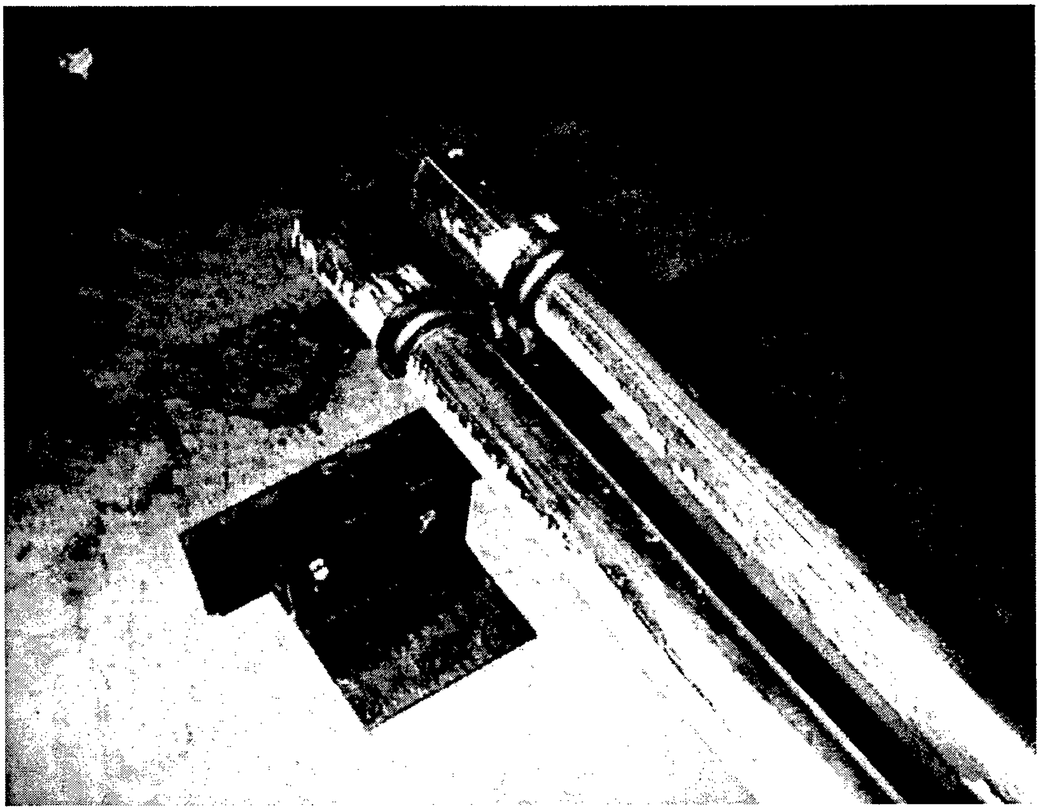

Figure 7. Close-up View of Cooling Coils and Support Structure used in the HTB

5.0 Waste Simulants for the HLLW Tanks

Waste simulants that provide realistic conditions to those in the HLLW tanks were required for the performance tests of the cooling coil cleaning end effector. The primary objectives were to identify simulants that bound: 1) the particle size distribution and abrasive characteristics of the particulate waste when agitated and suspended in the supernate liquid and 2) the strength and abrasion resistance of the tar-like waste. Simulants were chosen which fulfill these objectives, and in addition are non-hazardous and readily disposable.

5.1 Tarry Waste Simulants

The lack of physical or chemical data for the tarry waste made the development of defensible waste simulants very difficult. No clear upper bound could be inferred for the strength of the tar-like material. As a result, a "bounding" simulant would need to be extremely strong and resistant to the end effector waterjets. The drawback of choosing a simulant that is extremely resistant to the waterjets is that it may show little or no abrasion from scouring and, therefore, it would not be useful for adjusting the end effector waterjets (jet nozzle diameter, pressure, jet angles, or rotation speeds) for optimum cleaning performance. Because of these limitations, an alternate approach was used to identify potential simulants for the tarry waste. Assumptions were made about the nature of the tar-like substance and then simulants were identified that possess those assumed properties. Because this strategy includes high uncertainty, the assumptions made about the waste should be carefully reviewed as more waste characterization data become available. If future waste characterization data invalidate any of the assumptions, the results of the end effector tests must be reviewed to assess their validity.

Based on the qualitative description of the tar-like substance, it was assumed that asphalt (i.e., road tar) has analogous physical properties to the INEEL waste. Asphalt is a mixture of hydrocarbons that is solid or semi-solid with a very high viscosity at room temperature. Asphalt is not water soluble and it adheres well to a variety of materials including steel. Unfortunately, safety and regulatory concerns did not permit using asphalt as a simulant for the tar-like material during testing of the cooling coil cleaning end effector at either UMR or at PNNL.

Two different types of materials were used to simulate the tar-like substance. The first was a latex-based roof patching and flashing sealant, sold by the Master's Choice Company under the brand name Patchworks™. Patchworks is an aqueous acrylic/urethane latex similar to water-based house paint. As the Patchworks cures, it forms a water-tight barrier of synthetic rubber. The curing of Patchworks is primarily driven by the loss of water, so factors such as relative humidity, temperature, and air circulation all affect the curing rate. Patchworks was chosen because 1) in the partially cured state it is qualitatively similar to a tar-like substance, 2) it is not hazardous, and 3) it can be applied in a thin layer.

Two wax-based simulants were also used after it was discovered that the Patchworks paint gave inconsistent, non-repeatable results when used in a partially cured state. Wax was chosen because it is stable when submerged in water and because it could be melted and applied easily with a brush. Beeswax was first used, and found to be very difficult to remove, even with direct impact of the high-pressure waterjets (13.8-MPa [2000-psi] jet pressure). A soft, petroleum-based wax was then tried and found to be more satisfactory. The details of the tests using these wax-based simulants are described in a later section.

5.2 Particulate Waste Simulants

The simulated calcine solids include washed sand, ground calcium carbonate, and granular gypsum. These solids were selected because their abrasive properties are expected to bound those of the calcine solids known to be inside the waste tanks at INEEL, and because they are non-hazardous and non-regulated. Water solutions in contact with these solids have a pH near 7.0 and a dissolved salt concentration less than about 0.3 wt% (calcium sulfate [gypsum] is the only soluble component).

A sample of the granular calcine produced at the waste calcining facility at INEEL was analyzed for comparison with the physical properties of the candidate simulants. Table 1 lists the physical properties of the calcine granules plus similar properties of the three simulants. Particle densities were measured using a helium pycnometer. The particle crush strength (given in grams) was measured by crushing single particles between parallel stainless steel plates. This measurement correlates with mechanical strength which, in turn, correlates roughly to hardness. Thus, the crushing strength provides an indication of the expected strength contribution to abrasiveness. However, it does not address particle shape and size as factors in determining abrasiveness. By matching crushing strength, particle size/shape, and particle density, it is assumed that a simulant can be identified with similar abrasiveness. The particle size distributions in Table 1 were measured by sifting the sample through progressively finer sieves.

Table 1. Physical Properties of Calcine and the Candidates for Particulate Waste Simulants

Physical Property	Calcine	Calcium Carbonate $CaCO_3$	Gypsum $CaSO_4$	Fine Sand
Solids Density, g/cm^3	3.01	2.72	2.39	----
Bulk Particle Density, g/cm^3	1.61	2.72	1.04	2.8
Bulk Density, g/cm^3	0.92	1.55	0.59	----
Crushing Strength, grams to crush single particle	740	2420	850	----
Weight Percent finer than given size (mm)	wt% finer than	Wt% finer than	wt% finer than	wt% finer than
4.75	100	100	100	100
2.38	100	100	100	84
2.00	100	100	100	-----
1.00	83	53	43.1	51.7
0.841	58	30	27.2	----
0.600	20	6	16	40.8
0.425	3.6	1.2	13.1	----
0.300	-----	----	----	12.3
0.212	0	0.4	8.9	----
0.15	0	0.3	0	3.0

6.0 The End Effector Testing Program

The test objectives for the cooling coil cleaning end effector were to optimize performance of the high-pressure waterjets in removing the tarry waste simulants from the cooling coils and to test long duration mining strategies for removing the waste from the HLLW tanks. The performance of the end effector was evaluated based on its ability to: 1) remove the tarry simulant from the cooling coils, 2) retrieve the bulk of the particulate waste from the tank floor, and 3) perform a final floor-cleaning pass. This section describes the results of the cooling coil cleaning tests and the particulate waste removal tests. Data that was collected during the testing program is used to estimate the cleaning efficiency of the end effector, the rate of tube cleaning and waste removable that is achievable, and the water addition required in these processes.

6.1 The Cooling Coil Cleaning Tests

The performance of the end effector in cleaning the tarry waste simulants from the cooling coils was tested using both the Patchworks and wax-based simulants. The simulants were tested to determine their resistance to both a low-pressure water jet (qualitatively similar to the decontamination spray ring used in the HLLW tanks) and the high-pressure waterjets of the cooling coil cleaning end effector. A method for quantitatively measuring the level of surface cleaning was also developed to aid in comparing the end effector performance under a range of parameters. The measurement technique uses a handheld optical scanner to map the surface of the cooling coil. Statistical methods are then used to interpret the data and calculate the level of cleaning over the surface. The appendix included at the end of this report provides a full description of this technique. This system was intended to provide information to differentiate subtle differences in cleaning performance given a well-controlled waste simulant and different combinations of waterjet pressures and settings. However, the cleaning tests described in the following sections did not exhibit the subtle differences that were anticipated, and therefore the optical scanning method was not needed to interpret the results. The system is described, nonetheless, because of its applicability to other evaluations of cleaning effectiveness.

6.1.1 Patchworks Sealant as the Tarry Waste Simulant

A series of initial tube cleaning tests was performed to determine an approximate coating thickness and cure time that would yield consistent Patchworks properties and give sufficient resistance so as not to be washed off completely by the range of waterjet pressures, rotation speeds, and jet angles to be tested. The tubes were scrubbed with a 3M Scotch-Brite pad and detergent and allowed to fully dry before being coated with the Patchworks sealant.

6.1.1.1 Resistance to an 550 KPa (80 psi) Waterjet

The first tests used a single 550-KPa (80-psi) waterjet to approximate the conditions of the decontamination spray ring that was unable to remove the tarry waste from the radio frequency probe. A single, coherent waterjet was produced by a brass cleaning nozzle (with a 5-mm [0.2-in.] diameter orifice) attached to a hose. A length of the 44.5-mm diameter conduit was cleaned and small sections were coated with Patchworks every 5 minutes for a total of 45 minutes. This was done for "thin" and "thick" coatings. The thin coating just covered the surface uniformly, while the thick coating was what remained after a heavy coat was applied and allowed to drip off. An additional 20 minutes was added before testing, giving total cure times from 20 to 65 minutes.

The waterjet was traversed over the top of the pipe (moving axially) at about 5 cm/s (2 in./s). Each patch was about 5 cm (2 in.) wide, so the jet was on each for about 1 second total time. A standoff distance of about 1 m (3.3 ft) was maintained. The thin coats showed no Patchworks removal from the initial 1 second exposure to the jet. The test was then repeated with an exposure time of about 3 seconds aimed at the center of the patch. Only the tenth patch (20 minutes cure time) developed perceivable Patchworks removal.

The thick coating responded quite differently when exposed to the waterjet traversing at 5 cm/s. The patches that had cured for 50 minutes and longer showed no response. It was estimated by eye that about 50% of the Patchworks was removed from the 45 minute patch.. The 40-minute patch had about 80% removed; the 30 and 35 minute patches had about 90+% removed, and the 20 and 25 minutes patches had essentially complete removal. Based on the thick layer tests, a 50-minute cure time would be required to reproduce the qualitative behavior of the tarry substance that was not removed by the 550 KPa (80 psi) spray ring.

6.1.1.2 Resistance to the End Effector Waterjets

A second series of tests used a range of cure times to test the resistance of Patchworks to the end effector waterjets. The goal was to determine a cure time for evaluating the end effector's high-pressure waterjets for both direct cleaning of the tops of the coils and indirectly cleaning the bottoms of the coils through scouring with the slurry of particulate waste simulant in water. The 1.5-m (5-ft) lengths of conduit were coated with Patchworks. These mock cooling coils were painted and allowed to cure on a rotating rack to help achieve a uniform coating (Figure 8). The Patchworks was applied in a thick coating with a short-napped paint roller. The Patchworks was applied in a spiral pattern by moving the roller slowly in the axial direction against the rotating conduit. The net weight of Patchworks applied to each length of conduit was recorded for future correlation with the cleaning test results. Table 2 lists the Patchworks weights and cure times for the first ten tubes in the test matrix. Table 2 shows that even when care was taken to apply uniform, even coats, there was as much as 13 grams difference in the amount of Patchworks applied to the tubes. It should also be noted that the tubes were coated in quick succession and, therefore, the tube-to-tube differences in cure time (ranging from 5 to 10 minutes) represent the range of application times. A minimum 5-minute application time is significant when trying to prepare five or ten tubes for a test run of the end effector.

The tubes listed in Table 2 were installed in the HTB tank and cleaning tests were performed with the end effector. The waterjet pressure was 13.8 MPa (2,000 psi) and the rotation speed was set to 150 rpm for these tests. The traverse velocity of the gantry robot was 2.5 cm/s (1in./s). In addition, the tank was filled with fine sand to a depth of 7.6 cm (3 in.), the maximum expected depth of particulate waste in the HLLW tanks. Water was also added to give a total depth of 20.3 cm (8 in.), which completely covered the cooling coils. These simulated waste conditions were expected to give the most aggressive scouring action for cleaning the undersides of the cooling coils. Figure 9 shows the cleaning results for the coils with curing times from 18 to 41 minutes, and Figure 10 shows the coils with curing times from 48 to 80 minutes. These photos show the tubes rotated so that the side of each tube (the 3:00 or 9:00 position on the tubes) is facing the camera. That is, the top surface that was directly exposed to the waterjets is shown on the left, and the bottom of the coil (that was not exposed to direct jet impingement) is on the right. The black lines marked on each coil (above the curing times) are the 3:00 or 9:00 position on the coils.

Table 2. Weights and Cure Times for the Patchwork Cure Tests at 13.8-MPa (2,000-psi) Waterjet Pressure

Tube Number	Patchworks Weight (grams)	Variance from Mean (grams)	Cure Time (minutes)
04	31.7	-3.58	80
33	32.8	-2.48	72
25	30.5	-4.78	62
31	30.2	-5.08	54
30	38.1	2.82	48
24	32.7	-2.58	41
07	43.5	8.22	35
05	42.1	6.82	29
19	35.9	0.62	23
20	35.3	0.02	18
Average wt.	35.28		

Figure 9 shows that a substantial amount of the Patchworks sealant was removed from the undersides of the coils with the 18, 23, and 29-minute cure times. At cure times of 35 minutes and above (Figures 9 and 10), the Patchworks remains in a continuous coating on the bottom surfaces. It is interesting to note that at the 3:00 position on these coils, the Patchworks has been loosened and pealed back rather than being abraded and scoured from the surface. All Patchworks was removed from the top surface of the coils, regardless of the cure time. A second set of coils was prepared to reproduce the Patchworks curing tests at the maximum waterjet pressure achievable by the HTB system, 42.8 Mpa (6,200 psi). The sand was releveled in the tank before installing the cooling coils. Table 3 lists the Patchworks weights and cure times for these cooling coils. This time, a different person applied the Patchworks and again tried to maintain a constant weight of material applied to each coil. Table 3 shows a rather wide range of Patchworks weights (33.1 to 59.6 grams) which reflects the difficulty of applying this sealant material in a consistent, uniform coating.

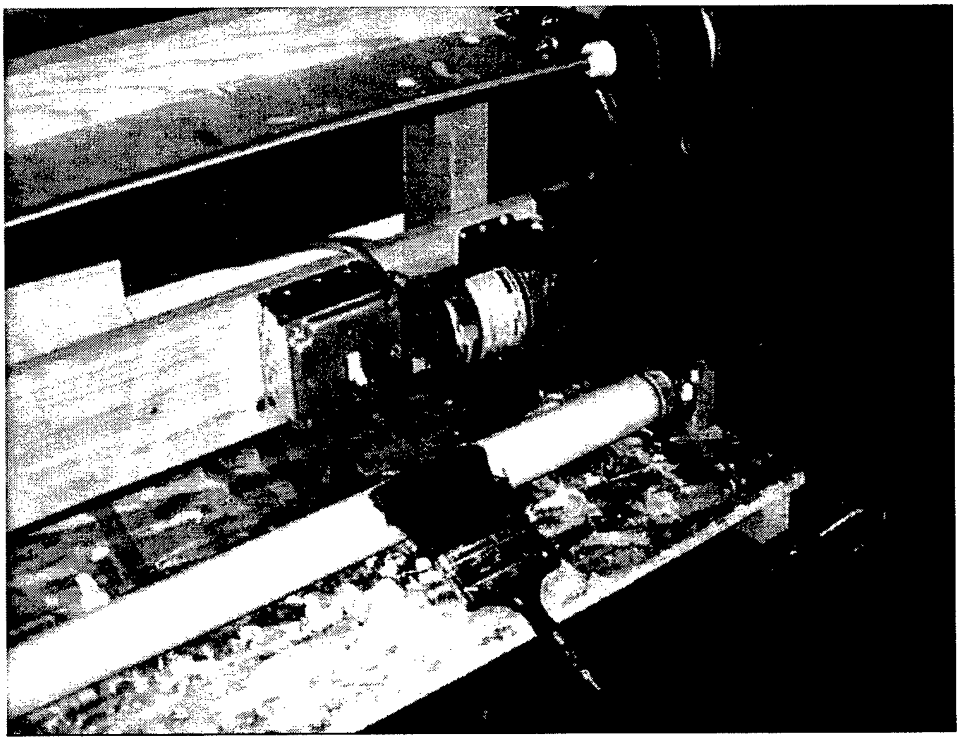

Figure 8. Rotating Rack for Painting and Drying the Mock Cooling Coils

Table 3. Weights and Cure Times for the Patchwork Cure Tests at 42.8-Mpa Waterjet Pressure

Tube Number	Patchworks Weight (grams)	Variance from Mean (grams)	Cure Time (minutes)
10	44.2	2.86	87
14	44.1	2.76	79
26	59.6	18.26	72
02	45.1	3.76	66
16	45.3	3.96	50
18	33.3	-8.04	44
09	36.5	-4.84	34
15	33.1	-8.24	29
03	36.6	-4.74	24
13	35.6	-5.74	16
Average wt.	41.34		

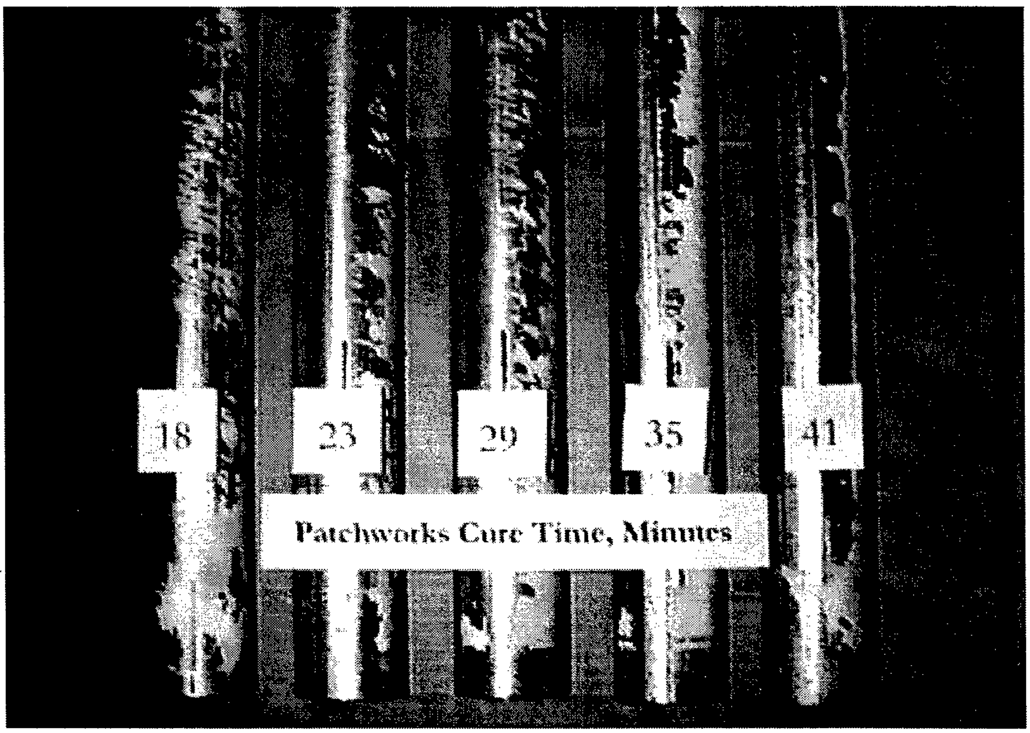

Figure 9. Patchworks Cleaning Results for Cure Times in Air of 18 to 41 minutes [Waterjet Pressure = 13.8 Mpa (2,000 psi), Rotation Speed = 150 rpm, Traverse Velocity = 2.5 cm/s (1in./s)]

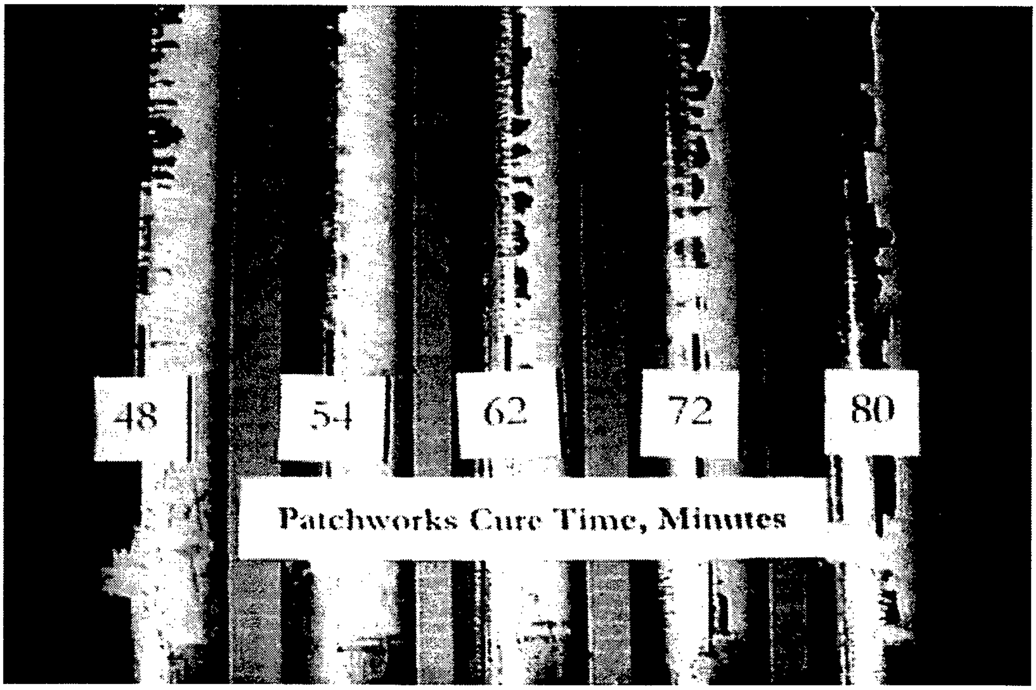

Figure 10. Patchworks cleaning results for cure times in air of 48 to 80 minutes (Waterjet Pressure = 13.8 Mpa (2,000 psi), Rotation Speed = 150 rpm, Traverse Velocity = 2.5 cm/s (1 in./s)]

Figures 11 and 12 show the cleaning effectiveness of the rotating waterjets at 42.8 Mpa (6,200 psi). Virtually all of the Patchworks was removed from the top surfaces of the tubes regardless of the cure time. Figure 11 shows that most of the Patchworks was also removed from the bottom surfaces of the tubes with curing times below 34 minutes. This is essentially the same conclusion as was drawn in the previous tests at 13.8 Mpa (2,000 psi). Although the cure times above 34 minutes generally show little or no removal of the Patchworks from the under surfaces, the 72-minute cure time (tube number 26) in Figure 12 substantially breaks this trend. Reviewing Table 3 shows that considerably more Patchworks was applied to this tube. In this case, the extra heavy coating slowed the curing process and significantly reduced the bond between the sealant layer and the surface of the conduit. This dramatically shows the sensitivity of the tube cleaning results to the tube-specific cure conditions of the partially cured Patchworks.

In the third series of Patchworks tests, an attempt was made to hold the cure time constant by submerging the tubes in water after a 35-minute cure time in air. Some parallel experiments had indicated that the Patchworks curing process could be suspended by immersing in water. This set of cooling coil tests varied the rotation speed of the waterjet manifold from 50 to 300 rpm to find the threshold where complete coverage was achieved with a traverse speed of 2.5 cm/s (1 in./s). Table 4 shows the Patchworks weights and cure times for the five cooling coils that were tested.

Table 4. Patchworks Curing Data for the Tests with Varying Rotation Speeds and a Constant Waterjet Pressure of 13.8 Mpa (2,000 psi)

Tube Number	Patchworks Weight (grams)	Cure Time in Air (min.)	Immersion Time in Water (min.)	Waterjet Rotation Speed, rpm
27	34.3	35	0	50
12	35.7	35	7	100
28	36.1	35	14	150
17	34.0	30	24	200
11	31.7	37	24	300

Figure 13 shows the tops of the tubes after cleaning with the various rotation speeds. A rotation speed of 150 rpm is the lowest speed that resulted in full coverage of the cooling coil surface. Figure 14 shows the bottom surfaces of the same tubes. The tube tested at 200 rpm is the only one with any sign of Patchworks removed from the bottom surface. This tube also had the lowest cure time in air and one of the longest immersion times in the water. The spiraled pattern of clean areas on the underside of this tube actually corresponds to the overlapping roller marks from the painting process. Therefore, local inconsistencies in the Patchworks coating thickness can cause variable cleaning performance along each cooling coil.

It was also discovered, after leaving several partially cured tubes in water overnight, that long immersion times in water dramatically softened the partially cured Patchworks layer. After being submerged for approximately 12 hours, much of the Patchworks had loosened from the tube surfaces and was found lying on the sand under the tubes. Therefore, submersion could not be used to suspend the curing process while additional tubes were prepared for a test run.

Different methods of applying the Patchworks sealant were also tried in an attempt to overcome these curing inconsistencies. Several cooling tubes were dipped in a long tray of Patchworks that had been thinned slightly with water. These tubes were allowed to drip for a short while and then they were placed in the rotating rack for curing. The coating initially appeared very even and consistent; however, as they cured, the surface skin that had formed began to crack, leaving a very mottled finish. The cracked areas cured to a very thin, tough layer while the uncracked areas were much thicker and did not cure through to the surface of the conduit even after more than an hour.

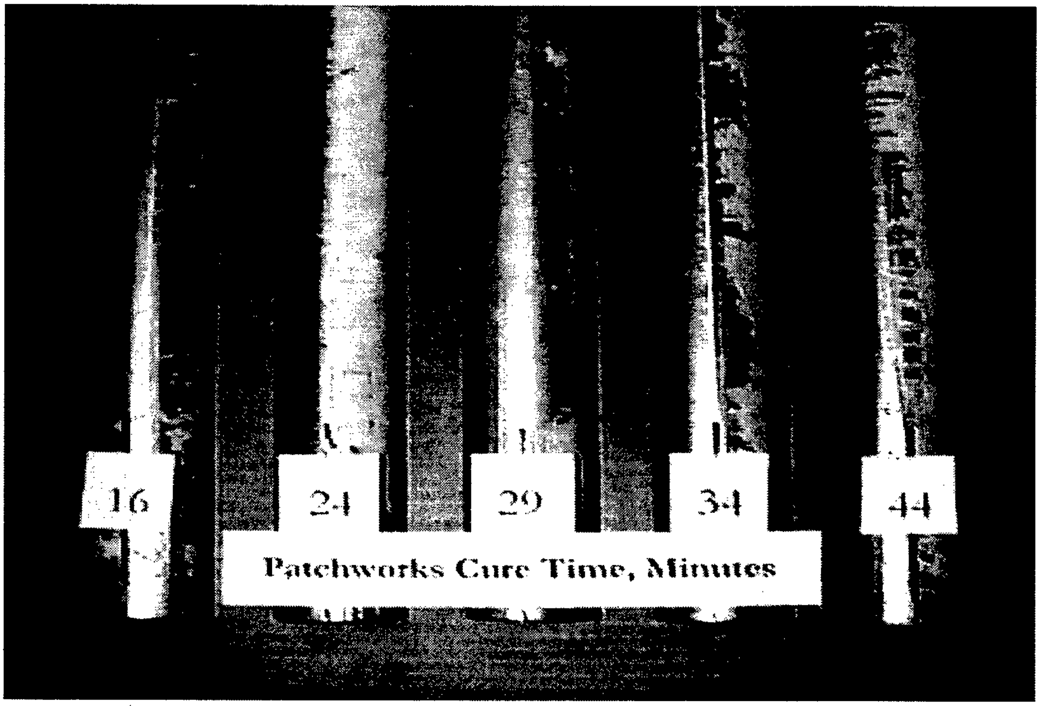

Figure 11. Patchworks Cleaning Results For Cure Times in Air of 16 to 44 Minutes [Waterjet Pressure = 42.8 Mpa (6,200 psi), Rotation Speed = 150 rpm, Traverse Velocity = 2.5 cm/s (1 in./s)]

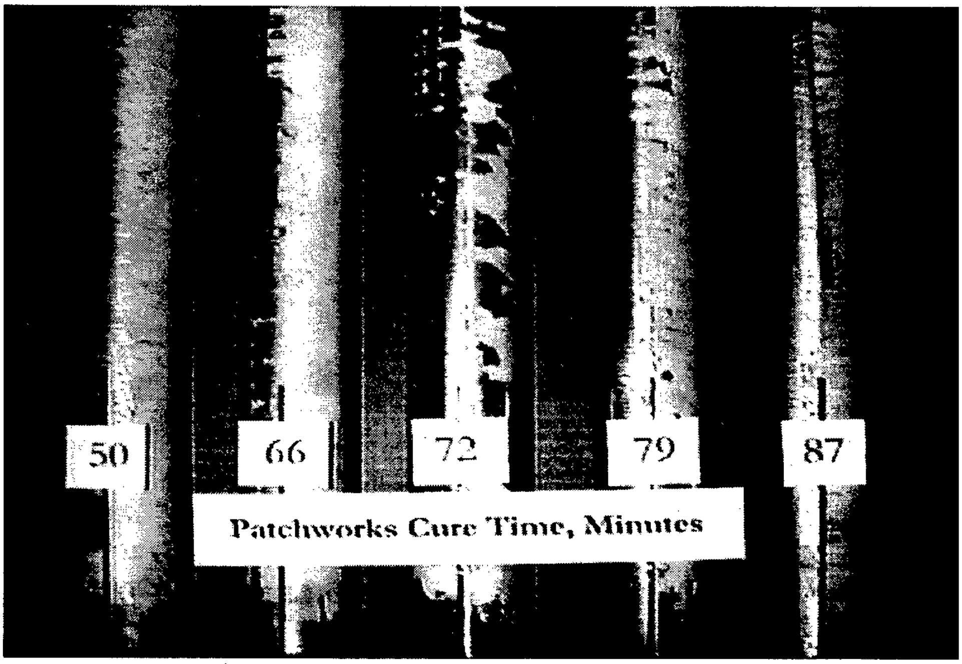

Figure 12. Patchworks Cleaning Results For Cure Times in Air of 50 to 87 Minutes [Waterjet Pressure = 42.8 Mpa (6,200 psi), Rotation Speed = 150 rpm, Traverse Velocity = 2.5 cm/s (1 in./s)]

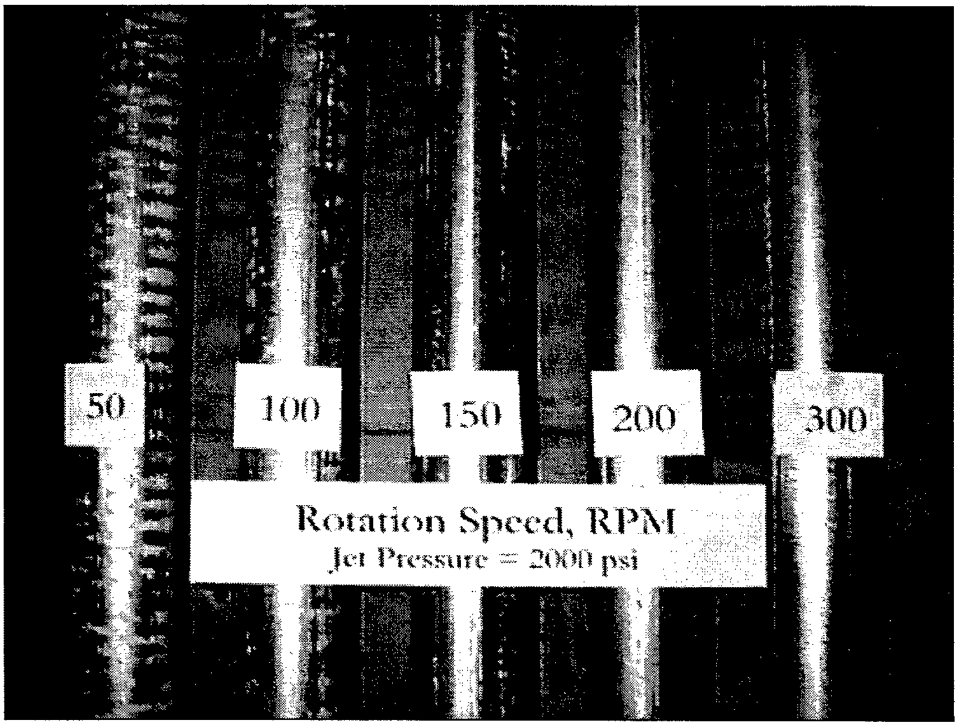

Figure 13. The Effect of Rotation Speed on the Cleaning Performance of End Effector [Tops of cooling coils shown. Approximate Patchworks Cure Time = 35 minutes, Jet Pressure = 13.8 Mpa (2,000 psi), Traverse Speed = 2.5 cm/s (1in./s)]

At this point, the decision was made to discontinue using Patchworks as a simulant for the tarry waste. The tube-to-tube inconsistencies in applying the Patchworks, the excessive application time, and the inability to suspend curing made it impossible to obtain consistent abrasion resistance using Patchworks.

6.1.2 Cleaning Tests Using the Wax-Based Simulants

Two wax-based simulants were then used to overcome the problems with the water-based Patchworks sealant. First, a length of conduit was coated with melted beeswax that was applied with a brush. The tube was allowed to cool and a cleaning test was run at 13.8-KPa (2,000-psi) waterjet pressure and 150-rpm rotation speed. For comparison, a tube coated with fully cured Patchworks sealant was also tested along side. The waterjets removed some of the beeswax from the top surface of the tube, while nearly all of the fully cured Patchworks was removed from the other. Neither tube had noticeable scouring on the bottom surfaces. This test had also used the maximum expected particulate depth of 7.6 cm (3 in.). The tube covered with beeswax was then rerun at 34.5-MPa (5,000-psi) jet pressure along with another tube that was covered with the fully cured Patchworks. The higher pressure was successful in removing all of the beeswax and Patchworks from the top surfaces of the tubes. Again, no scouring was observed on the bottom sides of the tubes coated with beeswax or Patchworks.

The second tarry simulant consisted of a soft, petroleum-based wax that is sold as a wax sealing ring for mounting plumbing fixtures to a floor drain. The wax was again melted and applied with a brush. Because the wax was nearly clear, a red primer spray-paint was applied over the wax layer to increase the contrast between the clean and coated surfaces. This wax was so soft that great care had to be taken not to smudge the tube surfaces when mounting the cooling coils in the HTB tank.

A tube coated with the soft wax simulant was first tested with the 550-KPa (80-psi) waterjet before performing cleaning tests with the end effector. The waterjet was passed along the length of the tube at about 5 cm/s (2 in./s). Figure 15 shows that the 550-KPa (80-psi) waterjet removed the soft wax down to the metal surface in a path that was approximately four times the diameter of the jet. Therefore, this simulant is estimated to have much lower strength than the actual tarry waste that was observed in the HLLW tanks.

Additional tubes were coated with the soft wax and mounted in the HTB tank for testing with the high-pressure waterjets. As in the previous tests, a 7.6-cm (3-in.) sand bed was used and water was added to completely cover the tubes. Figure 16 shows the top, side, and bottom views of three tubes that were cleaned using 34.5-MPa (5,000-psi) waterjets and a cleaning head speed of 300 rpm. As expected, the top surfaces of the tubes (that were directly exposed to the waterjets) were cleaned to bare metal, as in the test using the 550-KPa (80-psi) waterjet. Remarkably, the bottom surface of the tubes showed absolutely no removal of the primer paint that covered the soft wax. Even the brush strokes (from applying the melted wax to the rotating tube) were distinct and showed no sign of scouring. Therefore, the high-pressure waterjets did not impart enough energy to mobilize the sand to scour the paint and soft wax from the bottom sides of the tubes. Since it is expected that the soft wax will be easier to remove than the actual tarry waste, the high-pressure waterjets cannot be relied on to remove the tarry waste from the undersides of the cooling coils.

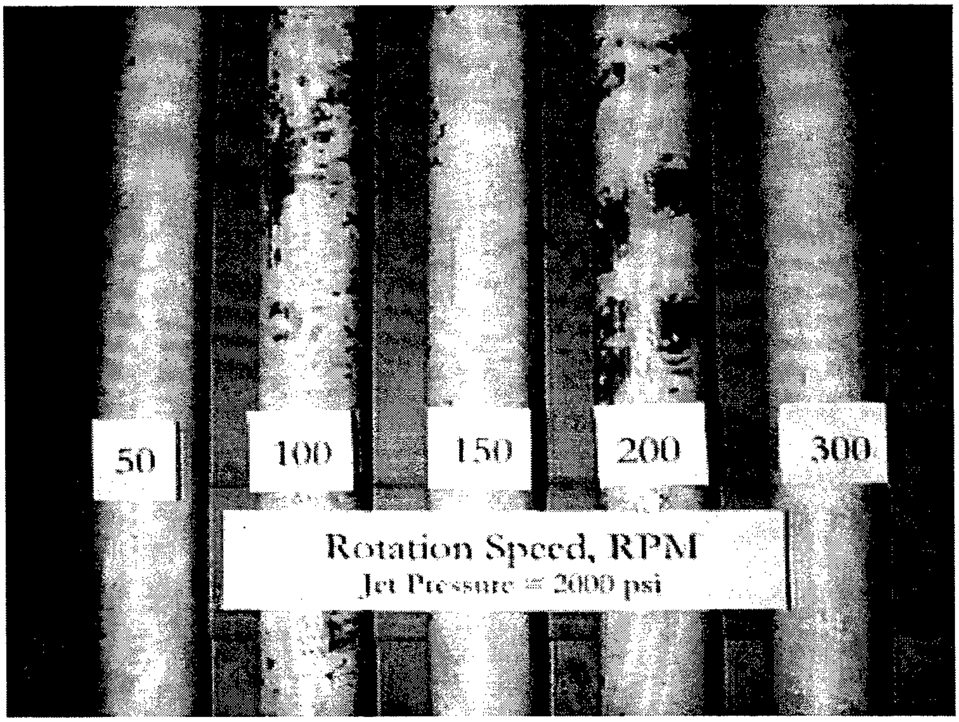

Figure 14. Bottom Surfaces of Cooling Coils Cleaned with a Range of Rotation Speeds Spiraled [Cleaning pattern shown on coil cleaned at 200 rpm (second from right) corresponds to overlapping brush strokes with thicker coating]

Additional tests were run showing that a 13.8-MPa (2,000-psi) waterjet pressure combined with a 300-rpm head rotation speed and 5-cm/s (2-in./s) traverse speed provided equal cleaning performance (for both cured Patchworks and the soft wax simulant) to the 34.5-Mpa (5,000-psi) jet pressure at 150-rpm rotation speed and 2.5-cm/s (1-in./s) traverse speed. This is an important finding because equal tube cleaning performance was achieved with lower waterjet flow rates (26 lpm at 13.8 MPa [6.7 gpm at 2,000 psi] versus 41 lpm at 34.5 Mpa [10.5 gpm at 5,000 psi]) and twice the traverse speed. If one used these cleaning parameters and assumed 100% overlapping coverage, the cooling coils in a 15.25-m (50-ft) diameter HLLW tank could be cleaned in about 9 hours. Water addition during this process would be approximately 13,660 liters (3,500 gal). Although still lower jet pressures would more than likely give equal tube cleaning, they would also give reduced mixing of the particulate and liquid wastes. Time constraints did not allow performing the matrix of tests required to further optimize the end effector performance.

6.2 Particulate Waste Retrieval Tests

The end effector was tested to evaluate its performance in retrieving the particulate waste simulant from the floor of the tank. First, bulk retrieval tests were performed to retrieve the largest portion of the particulate waste from the floor between two pairs of cooling coils. Next, final floor cleaning tests were performed to estimate the level of cleanliness that is achievable with this tool in the final pass. The water and sand retrieved during these tests were captured in the hopper and weighed to provide a basis for estimating the retrieval rate of the end effector.

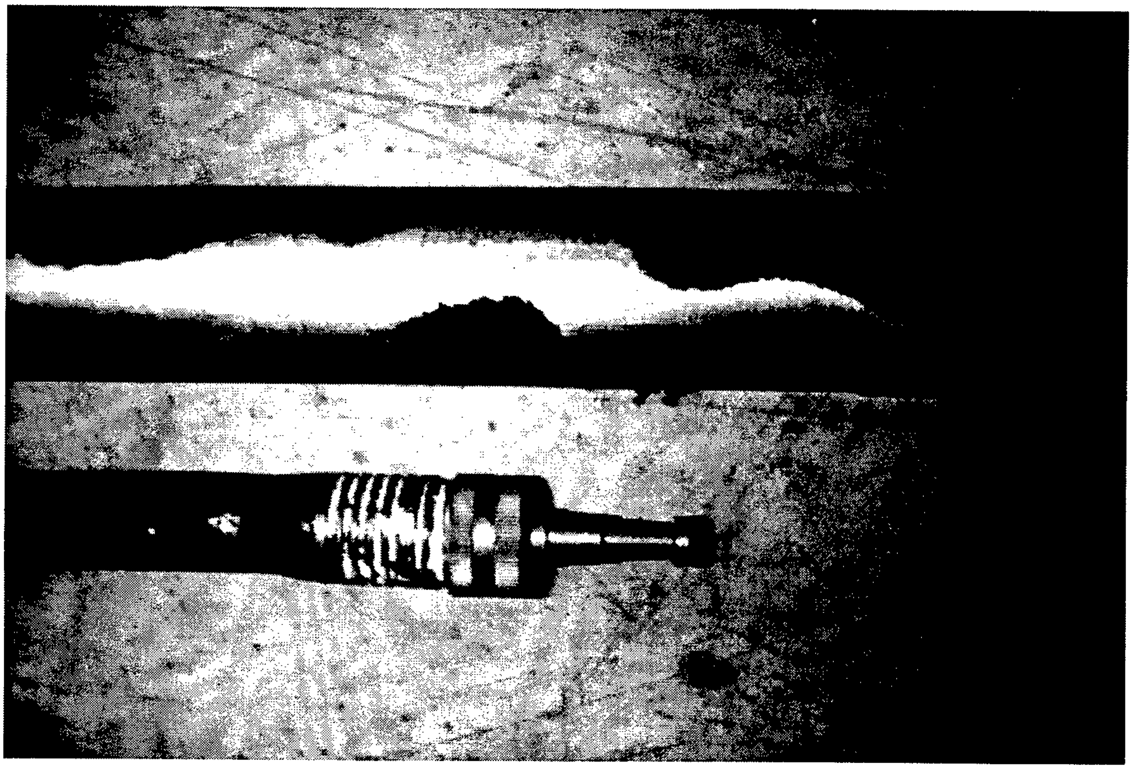

Figure 15. Soft Wax Simulant Removed using the 550 Kpa (80 psi) Waterjet

6.2.1 Bulk Retrieval Tests

The bulk retrieval tests used a simple mining strategy where the end effector was centered between two pairs of cooling coils and it traversed up and back the distance between the two support cross members. A 7.6-cm (3-in.) deep sand bed was used as the initial condition, and sufficient water was added before testing was initiated so that the suction shroud remained flooded throughout the entire test. The flooded shroud represents near-optimum retrieval conditions. The high fluid momentum effectively entrains the sand and carries it into the conveyance lines. In the first pass, the end effector was positioned at a standoff distance of 5 cm (2 in.) from the tank floor. The jet pump was turned on and the end effector traversed the distance between the cooling coil supports at a velocity of 2.5 cm/s (1 in./s). At the end of the first pass, the standoff distance was reduced to 2.5 cm (1 in.) and the end effector traversed back to the starting position. The end effector was then raised above the cooling coils and moved to center over the next cell in the lattice of cooling coils. The up and back mining strategy was then repeated in the second lattice cell. Table 5 contains the retrieval data for this test.

Table 5. Bulk Retrieval Test Data

Retrieval Data	Value	
Initial Sand in Two Lattice Cells	98 liter	25 gal
Sand Retrieved	37 liter	9.5 gal
Percent Sand Retrieved	38 %	
Water Retrieved	1,187 liter	305 gal
Elapsed time	286 seconds	
Jet Pump Flow Rate	40.85 lpm	10.5 gpm
Jet Pump, Total Water added	195 liter	50 gal
Ratio of Sand to Water Volumes Retrieved	1 : 32	
Ratio of Sand Volume Retrieved to Water added by Jet Pump	1 : 5	
Ratio of Water plus Sand Volume Retrieved to Water added by Jet Pump	6.3 : 1	

Table 5 shows that 38% of the sand was removed in the bulk retrieval pass and, along with it, 32 times as much water as sand. The data shows that the jet pump was effective in retrieving more than six times the volume of water that it added to the system. However, considering retrieval of sand alone shows that the volume of sand retrieved was about one-fifth the volume of water added by the jet pump. Although the overall retrieval rate of 6.3:1 for the jet pump is comparable to what we have seen in tests of other end effector designs, the small amount of sand that was retrieved is considerably lower than our previous tests have shown. This is most likely due to inefficiencies in the shroud design, which contains abrupt transitions from the large volume beneath the shroud to the two small conveyance lines. This causes dead spots in the flow field that allow the sand to drop out of suspension. The bulk retrieval test cleaned an area equal to 1.25 m^2 (13.5 ft^2) in 286 seconds. Scaling this up to the floor area of the tank gives an approximate cleaning time of 8 hours. This does not account for lost time in positioning the end effector within each cell to be cleaned. Manually positioning the end effector could easily double the cleaning time to 16 hours.

6.2.2 Floor Cleaning Tests

Floor cleaning tests were performed with a more detailed mining strategy. The gantry robot was programmed to position the end effector under the side of the cooling coils (as shown in Figure 5) and traverse the length of the coils to retrieve the particulate waste simulant located beneath them. A traverse velocity of 2.5 cm/s was used with a standoff distance of 13 mm (0.5

in.) from the tank floor. The sand remaining from the bulk retrieval test was used as the initial condition for the floor cleaning test. Additional water was added, but the sand was not releveled. The floor cleaning tests were again run with the suction shroud in a flooded condition. (As a note, floor cleaning in a later test was also tried with the shroud in the unflooded condition and the waterjets operating at low pressure [3.5 Mpa, 500 psi] and low rotation speed [60 rpm]. However, so little sand was retrieved that these tests were not pursued further.) Table 6 lists the retrieval data from the floor cleaning test.

Table 6 also shows that 49% of the sand remaining from the bulk retrieval test was removed during the floor cleaning pass. Figure 17 shows that the central area within each cooling coil lattice cell is cleaned to the bare floor. Figure 18 shows a close up of the sand piles surrounding one of the lattice cells where cleaning tests were conducted. The sand that remained in the tank was in ridges beneath the cooling coils and at the intersections of the cooling coils and the support structure. Additional piles of sand were located where the end effector had been raised to move into the next lattice cell. The floor cleaning test required 316 seconds to clean the same 1.25-m^2 (13.5-ft^2) area of the bulk retrieval test. Scaling this up to the full tank floor gives a cleaning time of about 13 hours. Again, the time required to position the end effector to start the cleaning program in each cell could easily double this time to 26 hours.

Table 6. Floor Cleaning Retrieval Test Data

Retrieval Data	Value	
Sand Remaining from the Bulk Retrieval Test	61 liter	15.5 gal
Sand Retrieved	30 liter	7.5 gal
Percent Sand Retrieved	**49 %**	
Water Retrieved	1,358 liter	349 gal
Elapsed time	316 seconds	
Jet Pump Flow Rate	40.85 lpm	10.5 gpm
Jet Pump, Water added	215 liter	55 gal
Ratio of Sand to Water Retrieved	1 : 45	
Ratio of Sand Retrieved to Water added by Jet Pump	1 : 7	
Ratio of Water plus Sand Volume Retrieved to Water added by Jet Pump	6.5 : 1	

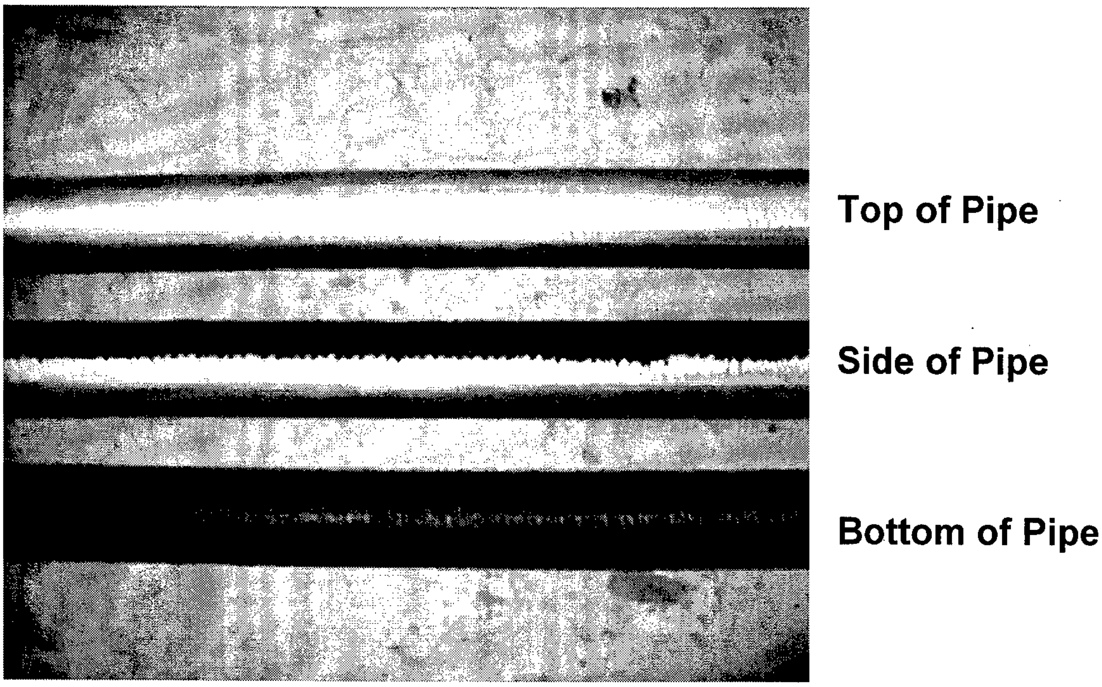

Figure 16. Top, Side, and Bottom Views after Cleaning of Tubes Covered with the Soft Wax Simulant

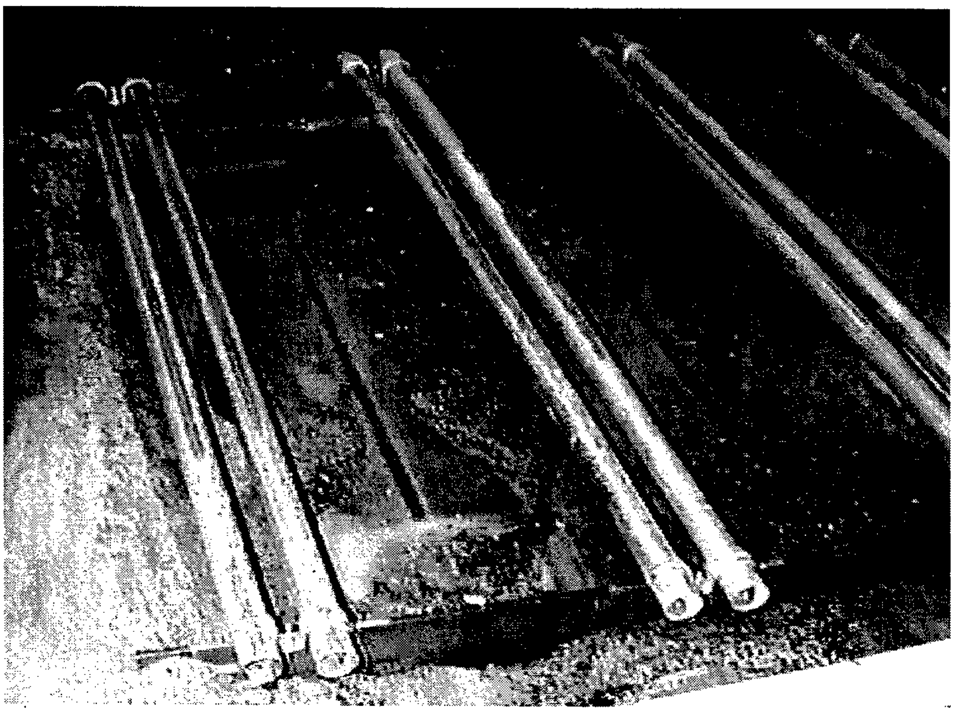

Figure 17. Final Cleanliness Achieved After Bulk Retrieval and Floor Cleaning Tests

Figure 18. Close-up of Sand Piles Remaining After the Floor Cleaning Test [The remaining sand is close to the original 7.6 cm (3 in.) depth outside the lattice cell between pairs of cooling coils. The tank is cleaned to the bare floor within the cell.]

7.0 Summary of the End Effector Performance Testing

The Retrieval Process Development and Enhancement (RPD&E) program has developed a prototype end effector to dislodge and convey waste from the HLLW storage tanks at INEEL. This work has directly supported the INEEL waste retrieval program by providing prototype testing to support the future specification of a field-deployable end effector.

The cooling coil cleaning tests showed that the waterjets were very effective in directly cleaning the surfaces of the cooling coils, but that they were completely ineffective in mobilizing the sand to scour even the soft wax simulant from the undersides of the coils. Therefore, based on the current end effector design, a 50% cleaning effectiveness is estimated for the removal of tarry waste from the cooling coils in the HLLW tanks. A cleaning head could be developed to clean more of the coil circumference by adding a manifold of waterjets that are below the cooling coils and pointed upward to clean the underside of the coils. In addition to cleaning the tube surfaces, the waterjets provided sufficient scouring action to effectively remove a heavy layer of rust from the bottom of the test tank. The waterjets were positioned about 20 cm (8 in.) above the tank floor during the cooling coil cleaning tests. It is estimated that the entire tank bottom could be cleaned with the high-pressure waterjets in about 9 hours. This assumes a 5-cm/s (2-in./s) traverse speed and 100% overlap.

A novel system was developed to provide a quantitative measurement of the level of surface cleaning. This new method replaces the previous method of "eyeballing" the percent cleaning of the cooling coils. The appendix at the end of this report describes the handheld scanner that was used to map the surface of the cooling coil and the statistical software that was developed to calculate the percent cleaning achieved in the tests. This represents a unique application of readily available computer hardware to provide an accurate assessment of cleaning performance. The system could be easily applied to other cleaning performance tests as well.

The mining strategies for bulk retrieval and floor cleaning removed about 68% of the sand simulant. These tests were performed under near-optimal conditions with the suction shroud flooded to maintain high fluid momentum to entrain the sand and carry it into the conveyance lines. Maintaining a flooded shroud condition throughout the waste retrieval process could be accomplished by filtering and recycling the liquid waste back to the tank. Additional liquid waste could be pumped from another tank in the event that the level is to low to support the retrieval operation.

Piles of sand were left at the base of the cooling coil supports and at the corners formed by the intersection of the cooling coils and the support members. Additional piles of sand were left when the end effector was raised (i.e., increasing the stand-off distance from the floor). This was especially true when the end effector was moved above the water level to clear the cooling coils while moving to the next lattice cell.

One can estimate the expected volumes of both the tarry waste and particulate waste forms remaining in the tank to evaluate the relative importance of cleaning the cooling coil surfaces versus removing the particulate waste from the tank. If one assumes that the entire floor and the walls are covered to a height of 9 m (30 ft) with the cooling coil pairs spaced 0.46-m (18 in.) apart, then each tank would contain about 2700 m (8,860 ft) of the coils. If the surfaces of the coils were uniformly coated with a 2-mm (0.078-in.) thickness, then there would be a total of about 0.75 m^3 (26.5 ft^3) of the tarry substance. About 0.38 m^3 (13.25 ft^3) would remain on the coils if a 50% cleaning efficiency was achieved. In comparison, a 7.6-cm (3-in.) depth of particulate waste covering the entire tank floor yields about 14.2 m^3 (500 ft^3) of the particulate waste. If a 68% cleaning efficiency is realized, then about 4.5 m^3 (160 ft^3) would be left in the tank. Comparing the estimated amounts of remaining waste suggests that the particulate waste volume would be about twelve times the amount of the remaining tarry waste. These simple calculations, assuming they are valid, suggest that it would be more worthwhile to concentrate on removing the particulate waste than to concentrate on removing more of the tarry waste.

It is important to note here that the end effector may actually perform better in the real waste conditions, because the particulate and liquid waste forms are estimated to have nearly equal specific gravities. The sand used in the current testing program had a specific gravity of about 2.7 compared to water (used as the liquid waste simulant) which has a specific gravity of 1.0. Once agitated by the rotating waterjets, the actual particulate waste should stay suspended longer, and it should be more easily entrained by the liquid waste flowing into the suction shroud. Although time and money did not allow repeating the particulate waste retrieval tests with a simulant material that had a specific gravity near 1.0, this argument suggests that a 68% particulate removal rate may be a low estimate.

Sand retrieval could also be improved by optimizing the conveyance shroud design. The current shroud contains abrupt transitions in the flow cross section that cause dead spots where the sand can drop out of suspension. Streamlining the flow paths in the shroud will improve the sand retrieval rate.

During the end effector testing program, the waterjet manifold was observed to freewheel. The waterjets were installed at an angle of about 10° from vertical in the tangential direction and the thrust of the three jets caused a moment that turned the rotating head without the aid of the motor and controller. This suggests that future end effector designs may not require the added weight and complexity of a motor and speed controller. It may be possible to design a very simple cleaning tool that uses angled waterjets to provide the necessary rotation for cleaning the tops of the tubes and agitating the particulate waste. This concept would be even more promising if the end effector only required rotation when operating in air above the cooling tubes. Eliminating the motor and controller would save more than 50% of the total weight of the end effector, and it would eliminate all electrical components and cabling from the harsh environment of the waste tank. It should be noted that this concept was considered during the development of the CSEE for ORNL, but motor and controller was used to make rotation speed independent of the waterjet pressure. However, the cleaning and retrieval strategies that were tested in the current program did not require tight control of rotation speed, as long as a minimum speed was maintained.

8.0 References

ICF Kaiser Engineering. 1994. ICPP Heel Removal and Handling Study. May 20, 1994.

Hatchell, B. K., J. T. Smalley, J. C. Tucker. 1995. Retrieval Process Development and Enhancements, Hydraulic Test Bed Integrated Testing, Fiscal Year 1995 Technology Development Summary Report. PNNL-11105, UC-2030. Pacific Northwest National Laboratory, Richland, WA.

Appendix – Tube Cleaning Effectiveness

A method for quantification and analysis of results was developed by David Engel, Don Daly, and Dennis Mullen of Pacific Northwest National Laboratory.

1.0 Summary

An innovative method was developed for accurately taking quantitative measurements of the fraction of tube surface cleaned by the INEEL End Effector. The established alternative method was to "eyeball" the fraction of surface cleaned in each quadrant of the pipe. This practice is known by statisticians to be unreliable even when carefully structured, i.e., using optimized scoring methods and trained unbiased operators. The new method virtually eliminates subjective evaluation and provides statistically significant information if a sufficient number of samples are measured.

2.0 Data Acquisition Method

Figure 1

A photocopied paper index tape about 19 mm wide is secured to the pipe at randomly pre-determined locations [1] with a rubber band (Figure 1). The index tape is marked with transverse lines spaced to correspond to equal angular divisions of the pipe surface The long transverse mark on the index tape is aligned with the top dead center mark (referencing the orientation of the pipe in the testbed) on the pipe. The pipe is mounted in the last drying bay of the coating fixture and rotated at about 6 rpm.

An inexpensive handheld document scanner (Logitech Scanman Color 2000) is used to capture a grey scale bitmap image of a swath about 4 inches wide, centered on the index tape. The scanner is held stationary on the fixture with the scanner indexing roller bearing on the rubber band. This prevents damage to the optical window, which minimizes speed and exposure variation due to irregularities in the surface. Two revolutions of the pipe are scanned. The operator must hold the scanner so the window and scanner bar are parallel to the axis of the subject tube, and keep the scanner from moving tangentially to the tube. In proof-of-principle work, the operator was able to accomplish this by hand, resting the butt of the scanner on part of the fixture and guiding it by hand. For experimental work it would be worthwhile to add a simple guide fixture.

[1] The N locations are determined by the formula R_1L/N, $R_2L/N+L/N$, $R_3L/N+2L/N$, … , where R_m is a unique random number: $0<R_m<1$, and L is the effective length of tested pipe.

The scanner data is captured using Adobe PhotoDeluxe software (bundled with the scanner) running on a laptop personal computer. The scanned image (Figure 2) is displayed in near real time on screen as it is captured. The scanner speed relative to the pipe surface is important; the scanner software displays a speed indicator for guidance. A speed of 6 rpm for the 2-in. conduit test pieces turns out to be within the acceptable speed range for 256-grey scale scanning but too fast for optimal color scans. The operator can review the scan for quality (uniformity of exposure, tracking, streaking, contrast) before saving the file.

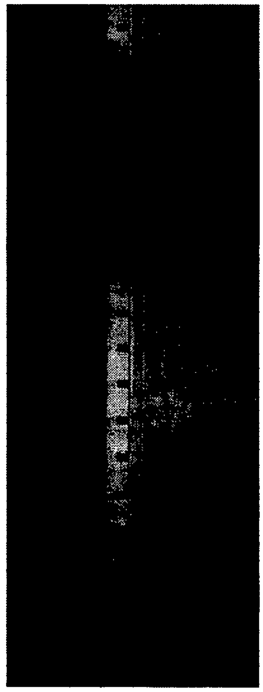

Figure 2

The scan data file is converted from the Adobe file format to *.tif* format by PhotoDeluxe for post-processing. The bitmap file is processed to extract the data, which can be represented graphically and compiled into a database for statistical analysis of test process parameters.

3.0 Data Analysis

The scan bitmap image is cropped to one pipe circumference (Figure 3) using either PhotoDeluxe or any other bitmap editor (Paintshop Pro was used for the experimental work).

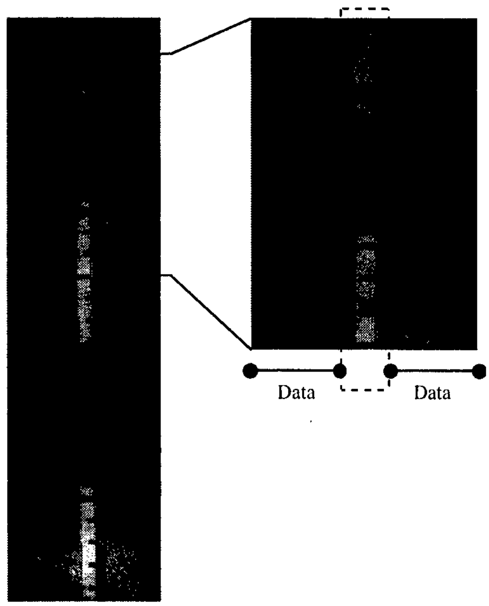

Figure 3

The numerical values for each pixel of the bitmap correlate to the brightness of the grey scale image. The pixel values can be handled as an array of data. The vectors containing the index tape and rubber band can be segregated by the analysis program and used for scaling and position data. The top-dead-center index mark is identifiable by length.

Each row of pixel values in the scan data array can be treated as a vector and the values plotted in a histogram (Figure 4). If the scanner is distinguishing between the bare metal and the simulant, the values will exhibit a clearly bimodal distribution.

The bimodally distributed pixel alues can be mapped to binary values responding to display colors and the resulting array presented graphically for illustrative purposes (Figure 5) and further analyzed. The discriminant between "clean" and "not cleaned" can be set to any arbitrary value, manually or by software, on the basis of the actual pixel values. Color scans may be used if necessary to distinguish between metal and simulant (file size and processing time will increase).

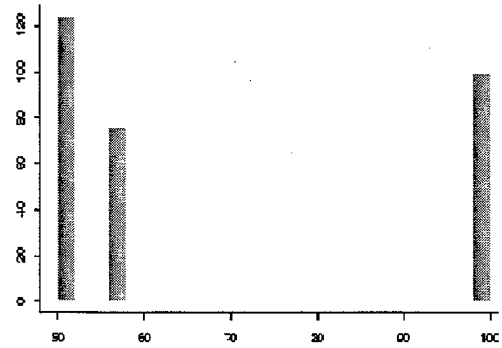

Figure 4

The pixel values can be sorted for each vector corresponding to an angular position on the pipe, and the fraction having the binary value for "simulant remaining" plotted against angular position in cartesian (Figure 6) or polar (Figure 7) formats depending on the purposes of the visualization.

Figure 5

The results of several scans for a given pipe or test can be averaged, the degree of variation evaluated, and correlation with process and simulant parameters tested statistically.

The scans analyzed have shown good repeatability between repetitions of coverage by a single scan and nambiguous interpretation of the presence/absence of white pigmented simulant (Patchworks).

Further quality assurance tests (repeatability of scans, accuracy of calibration) should be done to fully qualify the procedure for scientific/engineering use. Development was halted by other factors in the end effector test program.

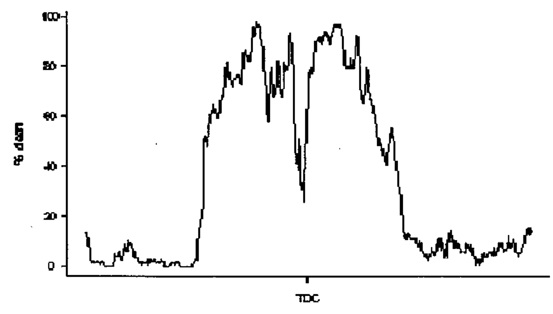

Figure 6

The data acquisition scanner and software are inexpensive and operate on a Microsoft Windows95 platform, requiring only modest resources. In the test setup, a Pentium 120 laptop with 64Mb of RAM was used. Post processing code could be portable and run on the acquisition computer, but the file sizes can become quite large.

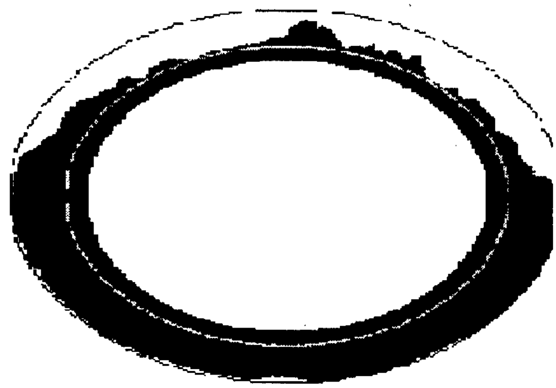

Figure 7

Distribution

No. of
Copies

Offsite

6 **DOE/Office of Scientific and Technical Information & Information Release**

1 **DOE Headquarters**

David W Geiser, Manager
Tanks Focus Area
Cloverleaf Building, EM-50
19901 Germantown Road
Germantown, MD 20874-12901

1 **University of Missouri, Rolla**

David Summers
Rock Mechanics and Explosive Research Center
High Pressure Waterjet Laboratory
University of Missouri-Rolla
Rolla, MO 65401

1 **Idaho National Engineering Environmental Laboratory**

Cal Christensen
P.O. Box 1625, MSIN 3710
Idaho Falls, ID 83415

No. Of
Copies

Onsite

6 **DOE Richland Operations Office**

VF Fitzpatrick, H6-12
JA Frey, K8-50
MJ Glasper, K8-50
JP Hanson, K8-50
LS Mamiya, K8-50
BM Mauss, K8-50

4 **Project Hanford Management Contract**

JA Frey, K8-50
PW Gibbons, H6-12
LB Mc Daniel, H6-12
DC Ramsower, H6-12

30 **Pacific Northwest National Laboratory**

KM Airhart (10), K5-22
JA Bamberger, K7-15
WF Bonner, K9-14
JL Buelt, K2-14
BA Carteret, K9-91
FF Erian, K7-15
JA Fort, K7-15
BK Hatchell, K5-22
KL Johnson (3), K5-26
EV Morrey, P7-28
OD Mullen, K5-22
MR Powell, P7-43
RK Quinn, K9-69
MW Rinker (2), K5-22
BF Saffell, K5-02
TJ Samuel, K5-22
TL Stewart, K9-69
JA Yount, K5-22

Report Number (14) PNNL--11741

Publ. Date (11) 19970930

Sponsor Code (18) DOE/DP, XF

UC Category (19) UC-721, DOE/ER

DOE