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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Borehole Miner - Extendible Nozzle Development for Radioactive Waste Dislodging and Retrieval from Underground Storage Tanks

J.A. Bamberger
D.G. Alberts
C.W. Enderlin
M. White

September 1998

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

This work is funded by the Office of Science and Technology, within the Department of Energy's Office of Environmental Management, under the Tanks Focus Area Program

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Acknowledgments

The following individuals were instrumental in the successful completion of extendible-nozzle testing at Pacific Northwest National Laboratory. Bill Combs operated the prototype extendible-nozzle system during the experimental activities including the coefficient of discharge determination, the integrated dislodging experiments, and the horizontal tank tests. He also was instrumental in construction of the test fixtures, piping systems, and implementation of the instrumentation. Mike Powell developed simulants for the extendible-nozzle tests of Savannah River Site Tank 19 zeolite and Oak Ridge National Laboratory Old Hydrofracture Facility sludge. Chuck Hymas provided direction and timely support for simulant preparation and waste disposal. Catherine O'Campo provided assistance with video production and record keeping.

Summary

This report summarizes development of borehole-miner extendible-nozzle water-jetting technology for dislodging and retrieving salt cake, sludge, and supernate to remediate underground storage tanks full of radioactive waste. The extendible-nozzle development was based on commercial borehole-miner technology.

- In fiscal year 1995, the borehole miner was identified as a potential addition to the suite of remediation technologies.
- In fiscal year 1996, the technology was identified for deployment in Savannah River Site Tank 19. In late fiscal year 1996, this deployment was postponed; a deployment at the Oak Ridge National Laboratory Old Hydrofracture Tanks was identified.
- In fiscal year 1997, an extendible-nozzle system was designed, constructed, and delivered to the Oak Ridge National Laboratory's Old Hydrofracture Facility to remediate waste stored in five horizontal underground storage tanks. The tanks contained up to 18 in. of sludge covered by supernate. The 42,000 gal of low level liquid waste were estimated to contain 30,000 Ci with 97% of this total located in the sludge.
- In fiscal year 1998, over a period of less than 3 weeks from June 29 through July 19, the borehole-miner extendible-nozzle system was deployed to remediate these five tanks. The remediation was successful. At the completion of the remediation, the State of Tennessee Department of Environment and Conservation agreed that *the tanks were cleaned to the maximum extent practicable using pumping technology.*

The borehole-miner activities are part of the Retrieval Process Development and Enhancements (RPD&E) project under direction of the US Department of Energy's EM-50 Tanks Focus Area. This development and deployment is being conducted as a partnership between RPD&E and the Oak Ridge National Laboratory's US DOE EM-40 Old Hydrofracture Facility remediation project team. The purpose of Retrieval Process Development and Enhancements is to understand retrieval processes including ongoing and existing technologies, gather data on these technologies, and relate the data to specific tank problems such that end users have requisite technical bases to make retrieval and closure decisions.

The extendible-nozzle system, delivered to Oak Ridge National Laboratory, represented completion of a formal system design including 50% and 90% completion reviews and acceptance testing prior to delivery in 1997. Additional extendible-nozzle system components, including the high-pressure pump skid, containment, and valving and instrumentation to complete the extendible-nozzle system were provided to Oak Ridge National Laboratory in fiscal year 1998. Also Sandia National Laboratory teamed with Pacific Northwest National Laboratory to develop a visualization system, an operator aid to provide a real-time image of the extendible nozzle operating inside the tank being remediated.

To support extendible-nozzle development and deployment, experiments were conducted and correlations developed:

- Experiments were conducted to evaluate the nozzle coefficient of discharge.

- Single-nozzle tests were conducted to evaluate the effects of stand-off distance, jet pressure, and diameter on the ability to dislodge saltcake and sludge simulants. The jet performed at stand-off-distances up to 50 ft.

- Integrated-nozzle tests using simulants were conducted to evaluate the effect of traverse rate on waste dislodging. The integrated nozzle tests were conducted using hard sludge and saltcake simulants exposed to air.

- Horizontal-tank tests were conducted to evaluate the effect of a supernate layer and balanced or unbalanced dislodging and retrieval flow rates on dislodging of sludge type waste simulants.

Data from the successful hot-deployment of the borehole-miner extendible-nozzle system is being compiled and will be analyzed and reported in fiscal year 1999 to define system overall performance.

The borehole-miner extendible-nozzle system design for Old Hydrofracture Tank remediation was for curved-bottom, horizontally-oriented underground storage tanks. The system can also be deployed for remediation of flat-bottom, vertically-oriented underground storage tanks.

- In fiscal year 1996, an extendible-nozzle system design was developed for deployment in an 85-ft-diameter vertical underground storage tank, Tank 19 at Savannah River Site. This design is also applicable for the large diameter tanks at Hanford and West Valley.

- The 100% system design developed for Oak Ridge is also appropriate for system deployment in horizontal underground storage tanks at Bethel Valley at Oak Ridge and in the horizontal underground V-Tanks at Idaho National Engineering and Environmental Laboratory.

Nomenclature

A_e	nozzle cross-sectional area at the exit of the nozzle
A_i	nozzle cross-sectional area at the inlet of the nozzle
C_D	coefficient of discharge
d	nozzle diameter
DOE	US Department of Energy
gpm	gallons per minute
hp	horsepower
HS	hard sludge simulant
LLLW	low level liquid waste
m_{dot}	mass flow rate through nozzle
MVST	Melton Valley Storage Tanks
OHF	Old Hydrofracture Facility
ORNL	Oak Ridge National Laboratory
P	jet pressure
P_e	pressure at the exit of the nozzle
P_i	pressure at the inlet of the nozzle
PNNL	Pacific Northwest National Laboratory
Q	nozzle volume flow rate
Re	Reynolds number
rpm	revolutions per minute
SS	sludge simulant
T	thrust
V_e	fluid velocity at the exit of the nozzle
V_i	fluid velocity at the inlet of the nozzle

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1.0 Introduction

A borehole-miner, extendible-nozzle water-jetting system was designed, constructed and deployed to remediate five horizontal underground storage tanks containing sludge and supernate at the Oak Ridge National Laboratory (ORNL) Old Hydrofracture Facility (OHF) site. The borehole-miner extendible-nozzle technology was identified in 1995 for potential US Department of Energy (DOE) tank retrieval applications. The waste from the OHF tanks was retrieved over a period of less than 3 weeks in June and July 1998. The OHF tanks ranged in diameter from 8 to 10.5 ft and length from 23 to 45 ft. The tanks were submerged at depths up to 4 ft below grade. The tanks contained up to 18 in. of sludge covered by supernate. The 42,000 gal of low level liquid waste were estimated to contain 30,000 Ci with 97% of this total located in the sludge. The retrieval was successful. At the completion of the remediation the State of Tennessee Department of Environment and Conservation agreed that *the tanks were cleaned to the maximum extent practicable using pumping technology.*

This work was completed as part of the Retrieval Process Development and Enhancements (RPD&E) project under direction of the US Department of Energy's EM-50 Tanks Focus Area. The purpose of Retrieval Process Development and Enhancements is to understand retrieval processes including ongoing and existing technologies, gather data on these technologies, and relate the data to specific tank problems such that end users have requisite technical bases to make retrieval and closure decisions. This work is being conducted as a partnership between RPD&E and the Oak Ridge National Laboratory's US DOE EM-40 Old Hydrofracture Facility remediation project team.

The extendible-nozzle system is based on commercial borehole-miner technology developed in the 1970s and 1980s. Waterjet Technology, Inc.[a] has exclusive rights to this technology for environmental cleanup applications. The borehole-miner technology has been identified as a means of acquiring low cost tank waste dislodging and conveyance capabilities. It consists of a semi-flexible, extendible, and erectable arm, which supports a payload at some distance away from the entry point in the tank for dislodging.[b] An integral jet pump system is used for conveyance. The arm and launching mechanism can be lowered through a relatively small opening for deployment. Once inside a tank, the arm can be remotely extended or retracted horizontally and raised or lowered.

1.1 Background

In fiscal year 1995, the borehole-miner, extendible-nozzle system was identified as a potential commercial technology that could be deployed to dislodge and retrieve waste from underground storage tanks. In fiscal year 1996, Savannah River Site Tank 19 was identified as a potential initial application for the extendible-nozzle demonstration. The extendible-nozzle would be deployed to break up and mix the hard zeolite heel remaining at the bottom of the tank. Based on this need, an extendible-nozzle system was designed for deployment in Tank 19. The design was completed through the 90% design. At that point,

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a) Waterjet Technology, Inc., Kent, Washington.

b) Extendible arm links range from 2 in. to 12 in. in cross section. These links have been designed to support large payloads. For example, an 8-in. cross-section system can support an 800 lbm payload at an extension of 20 ft.

Savannah River Site priorities were reordered to push deployment back. Also, a sample of the top of the zeolite sludge surface was taken in Tank 19 that indicated that at least the surface was soft, thus eliminating the need for a 3000 psi retrieval system. Therefore, another site at Oak Ridge National Laboratory was selected for extendible-nozzle deployment in fiscal year 1998. In fiscal year 1997, design of the extendible-nozzle system for deployment in a tank farm of horizontal underground storage tanks was initiated.

This report describes the extendible-nozzle development and design and construction activities that have occurred since fiscal year 1995 to support extendible-nozzle deployment.

1.2 Objectives

The objectives of the borehole-miner activities are to:

- Understand the physics of the borehole miner as a retrieval process so that systems can be readily designed to operate over a range of waste conditions and tank sizes
- Design a system configuration that can be successfully deployed to remediate the Old Hydrofracture Facility tanks at Oak Ridge and may be applicable for deployment at other DOE sites
- Work with the Oak Ridge EM40 remediation team to provide an integrated operable extendible-nozzle system
- Analyze operating data from the cold and hot operations to quantify system performance for waste dislodging and retrieval.

1.3 Scope

The work scope covers four areas: 1) laboratory and scaled testing of the extendible-nozzle system (Sections 4, 5, 6, 7) to establish its operating regime; 2) extendible-nozzle design, construction, and acceptance testing (Sections 8 and 9); 3) extendible-nozzle integrated system design and procurement (Section 10); and 4) analysis of operating data to quantify system performance.

1.3.1 Extendible-Nozzle Testing

Experiments have been completed to define the extendible-nozzle range of performance. The nozzle coefficient of discharge (C_D) was evaluated. This data enhances understanding of the performance of the extendible nozzle and enhances the ability to design the extendible nozzle by providing information about the reaction force from the nozzle onto the arm.

Stationary-jet experiments have been completed to determine extendible-nozzle performance over a range of stand-off distances, nozzle diameters, and nozzle pressures. Integrated-dislodging experiments have been completed to determine the efficiency of the nozzle for dislodging simulants with a range of physical properties from soft sludge wastes to hard saltcake waste. Integrated dislodging and retrieval experiments in a scale-model of a horizontal tank were conducted to provide design and operational guidance for deployment at Oak Ridge.

1.3.2 Extendible-Nozzle Design, Construction, and Acceptance Testing

Pacific Northwest National Laboratory (PNNL) subcontracted Waterjet Technology, Inc. to design, construct and acceptance test the extendible-nozzle for tank remediation. Waterjet Technology, Inc. possesses exclusive rights to market the extendible-nozzle technology for nuclear applications. To further this activity, two extendible-nozzle designs have been developed: 1) a 90% design for deployment via bridge mount for an 85-ft-diameter vertical underground storage tank at the Savannah River Site, and 2) a 100% design, construction, acceptance test and delivery of a tank-mounted system for deployment in the horizontal underground storage tanks at Oak Ridge. These two designs cover aspects pertinent to underground storage tanks at Hanford (Washington), Idaho, West Valley (New York), as well as Oak Ridge (Tennessee) and Savannah River Site (Georgia).

1.3.3 Balance-of-Plant Integration and Performance Analysis

Pacific Northwest National Laboratory is working with Oak Ridge National Laboratory and ORNL's subcontractor to provide the balance-of-plant items necessary for extendible-nozzle deployment. These items include a high-pressure pump to power the extendible nozzle, and the pump skid, instrumentation, and valving required to support system operation. In fiscal year 1999, the system operating data will be analyzed and reported.

2.0 Conclusions and Recommendations

2.1 Conclusions

An extendible-nozzle water-jetting system, shown in Figure 2.1, was designed, constructed, and delivered to Oak Ridge National Laboratory to remediate five horizontal underground storage tanks containing sludge and supernate at the ORNL Old Hydrofracture Facility site. The tanks were remediated in fiscal year 1998 to remove >95% of the waste. The tanks contained up to 18 in. of sludge covered by supernate. The 42,000 gal of low level liquid waste were estimated to contain 30,000 Ci with 97% of this total located in the sludge. The retrieval was successful. At the completion of the remediation, the State of Tennessee Department of Environment and Conservation agreed that *the tanks were cleaned to the maximum extent practicable using pumping technology.* This deployment was the first radioactive demonstration of the borehole-miner extendible-nozzle water-jetting system. The extendible nozzle is based on existing borehole-miner technology used to fracture and dislodge ore deposits in mines. Typically borehole-miner technology includes both dislodging and retrieval capabilities. Both dislodging, using the extendible-nozzle water-jetting system, and retrieval using a jet pump located at the base of the mast are deployed as an integrated system through one borehole or riser. Note that the extendible-nozzle system for Oak Ridge remediation only incorporated the dislodging capability; the retrieval pump was deployed through a separate riser.

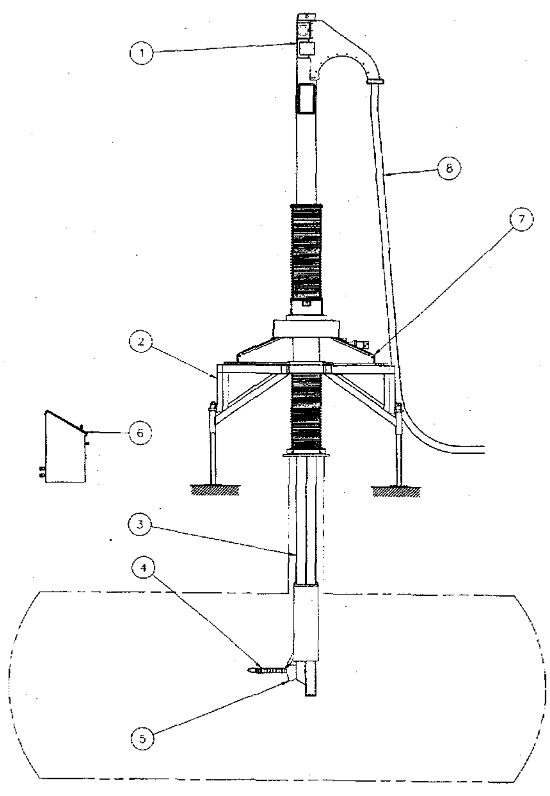

Figure 2.1 Extendible-Nozzle System for Deployment at ORNL OHF

The extendible-nozzle arm extends up to 10 ft from the center of the mast, extends downward at angles from the horizontal to nearly vertical, and rotates 360 degrees about the mast. The extendible nozzle can operate at water pressures up to 3000 psi; however, for deployment at Oak Ridge, the maximum operating pressure was limited by the high-pressure pump to ~1500 psi. The extendible-nozzle design was improved during the design phase. The design moved the arm actuator from beneath the elbow to above the elbow, thereby shortening the lower mast length by ~2.5 ft. The new design simplifies construction and operation considerably. The current nozzle design 1) covers the entire area beneath the nozzle from vertically downward to horizontal and eliminates the need for separate spray nozzles to clean beneath the mast, 2) eliminates an additional line from the pump to the extendible-nozzle and valves and controls associated with operation of these separate spray nozzles, and 3) allows the nozzle to operate along the horizontal tank centerline. The extendible-nozzle, as configured during the acceptance tests, is shown in Figure 2.2.

Pacific Northwest National Laboratory supplied ORNL a complete extendible-nozzle system; ORNL provided the balance-of-plant equipment to support the tank remediation. The extendible-nozzle operating system includes the high-pressure pump and pump skid to power the nozzle, the valving and instrumentation and control system to monitor pump performance, the hydraulic power unit to control the extendible-nozzle motion, and extendible nozzle including the mast and support platform. These components were integrated by PNNL and provided to support extendible-nozzle operation. In addition, a visualization system developed by PNNL and Sandia to track nozzle location in the tank in real-time during operation was also supplied.

The extendible-nozzle visualization system, shown in Figure 2.3, is an operator aid to be used during extendible-nozzle in-tank operation. In the tank, the operator cannot view the nozzle position; in-tank cameras may cloud from mist generated during extendible-nozzle operation. The extendible-nozzle visualization system provides the operator guidance on nozzle position relative to the tank. The visualization system provides a 3-dimensional animated model of the extendible-nozzle and the tank in which it is deployed. Position and orientation information from the extendible-nozzle is fed to the software via the input/output model so that the 3-dimensional model accurately depicts where the extendible-nozzle and its spray stream are in relation to the tank. The software can also warn of impending collisions between the nozzle and the tank infrastructure or any in-tank hardware that are modeled and included in the tank model.

Figure 2.2 Extendible-Nozzle During Acceptance Test

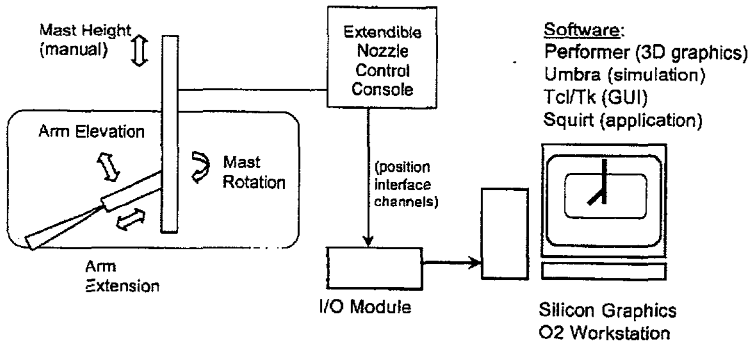

Figure 2.3 Extendible-Nozzle Visualization System Components

Experiments were conducted to evaluate the performance of components essential to the extendible-nozzle deployment at Oak Ridge.

- The nozzle coefficient of discharge was evaluated experimentally. This data affects the system design and provides a means to better estimate system performance and operating limitations.

- Integrated extendible-nozzle dislodging and retrieval experiments were conducted in a full-diameter, half-length model of a horizontal tank at Pacific Northwest National Laboratory to define the ability of the extendible-nozzle system to dislodge wastes similar to and more challenging than those at ORNL OHF. The extendible-nozzle was able to readily dislodge simulants that matched the shear strength of ORNL OHF tank wastes; simulants with shear strengths up to 60 times larger (with shear strengths up to 150 kPa) were also successfully dislodged. Extendible-nozzle operation was integrated with the tank retrieval system to determine suitable nozzle motion, pressure, and stand-off distance to most effectively remove waste from the tank. Tests were conducted with and without supernate layers. Supernate layers up to 18-in. deep were evaluated. Also single- and multiple-riser extendible-nozzle deployment was modeled.

- Extendible-nozzle dislodging tests conducted with hard saltcake simulants challenged the range of extendible-nozzle operation and deployment. Pressures up to 2700 psi were tested during experiments with these saltcake simulants. Dislodging rates were identified based on simulant type, stand-off distance and pressure. The saltcake simulants were successfully dislodged both by erosion and dissolution.

2.2 Benefits

The extendible-nozzle system provides DOE with a commercially developed, demonstrated technology that has been successfully applied to hazardous waste tank remediation needs. Current sluicing methods employ high-volume, low-pressure jets to erode solids. The potential of current methods to erode tough materials is minimal, and based on previous sluicing operations, layers of heel material remain at the bottom of the tank. The borehole-miner, extendible-nozzle system fills this void.

The extendible-nozzle operates at increased jet pressure, significantly reduced flow rate (when compared to conventional sluicing) and stand-off distance, and can be positioned to impinge directly upon the area to erode, significantly improving system performance. The extendible-nozzle technology may significantly improve retrieval by dislodging sludge heels, fracturing saltcake, and decreasing the time and water required to provide safe transport of the variety of materials in the waste storage tanks.

Specific benefits of the extendible-nozzle are as follows:

- Enhanced sluicing capabilities resulting from high-pressure, low-volume waterjet at small stand-off distances.
- Designed to operate with either water or recycled slurry as the jet dislodging fluid.
- High-pressure waterjet provides increased waste removal volume per unit volume of water.
- Extreme simplicity of design and operation directly relates to a lower cost system and lower operating costs compared with conventional rotary joint robotics arms.
- Can be used to deploy end effectors or manage cable/hose systems.
- Complete retraction into a compact tool housing for installation and storage through a relatively small hole.
- Demonstrated performance for radioactive sludge remediation.

2.3 Recommendations

Based on the successful laboratory testing evaluating 1) dislodging of challenging simulants, 2) single and multiple-riser deployment, 3) integrated dislodging and retrieval, and 4) field deployment demonstrating multiple-riser deployment, an integrated single-riser borehole-miner extendible-nozzle tank remediation should be conducted. The extendible-nozzle has potential in this application in terms of simple deployment, ease of adjustment for multiple riser applications (the borehole-miner system deployed at ORNL was operated in four tanks over a period of 2½ weeks), and the capability to rapidly dislodge and retrieve waste.

3.0 Borehole-Miner Extendible-Nozzle System

In the 1970s and 1980s, Quest Integrated, Inc. (now Waterjet Technology, Inc.) developed an extendible-nozzle system for excavation of minerals through small boreholes. The system configuration, shown in Figure 3.1, is based on the successful development of a patented borehole-miner technology (1993 U.S. Patent No. 5,197,783) that Quest Integrated, Inc. conducted for ESSO Resources Ltd., Canada, for hydraulic borehole mining of subterranean tar sands deposits through a drilled borehole.[a] Waterjet Technology, Inc.[b] has exclusive rights to this technology for environmental cleanup applications. This development grew from nearly 15 years of experience at Quest Integrated, Inc. designing machinery for borehole mining of uranium sandstone, coal, phosphates as well as tar sands.

The extendible-nozzle system consists of a semi-flexible, extendible, and erectable arm, which supports a payload at some radial distance away from the entry point in the tank for dislodging.[c] An integral jet pump system is used for conveyance. The arm and launching mechanism can be lowered through a relatively small opening for deployment. Once inside a tank, the arm can be remotely extended or retracted horizontally and raised or lowered azimuthally.

The existing demonstration prototype extendible-nozzle at Waterjet Technology, Inc. has a 2-in.-square arm cross section that holds a high horsepower waterjet nozzle extended up to 10 feet radially from the launching mechanism. This unit, shown in Figure 3.2, can pass through a 12-in.-diameter opening. Many factors that affect scaling up of this design have been determined.[d]

The extendible-nozzle system from Waterjet Technology, Inc. provides DOE with a commercially developed technology that can be modified and applied to hazardous waste tank remediation needs. Current sluicing methods employ high-volume, low-pressure jets to erode solids. The potential of current methods to erode tough materials is minimal, and based on previous sluicing operations, such layers of heel material remain at the bottom of the tank.

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a) This borehole miner was deployed underground to centrally mine an 80-ft diameter cavity at a depth of 300 ft. The miner nozzle operated at 300- psi water pressure with a flow rate of 500 gal/min. This configuration was used to mine uranium deposits in Wyoming, phosphates in Florida, and tar sands in Canada.

b) Waterjet Technology, Inc., Kent, Washington.

c) Extendible arm links range from 2 in. to 12 in. in cross section. These links have been designed to support large payloads. For example, an 8-in. cross section system can support an 800 lbm payload at an extension of 20 ft.

d) Factors that affect tool scaling include arm length, payload and dynamic loads, standoff, mining costs versus system size, and jet pump performance parameters.

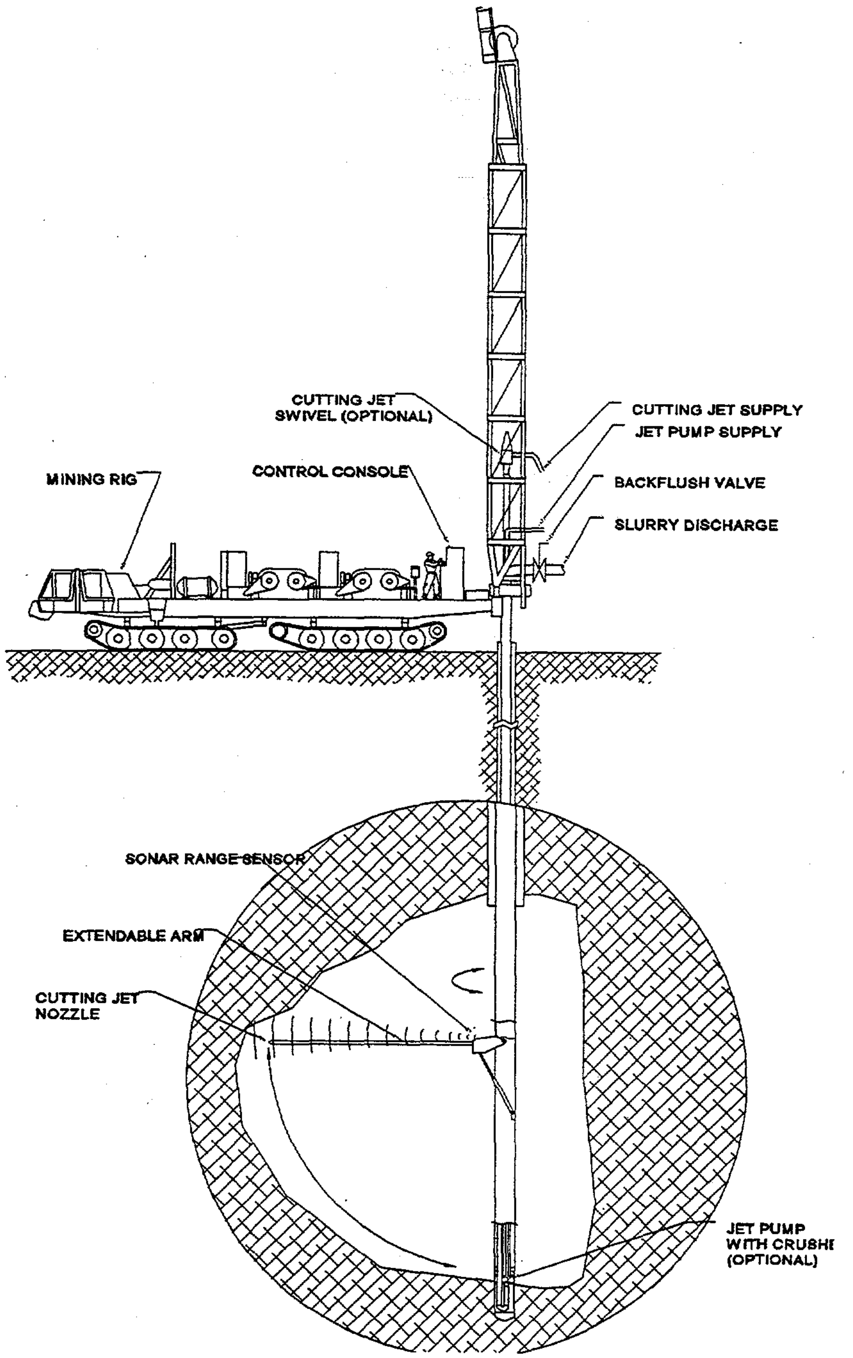

Figure 3.1 The Borehole-Miner Tool Incorporates an Integral Jet Pump Conveyance System and Sonar-Range Stand-Off Sensor

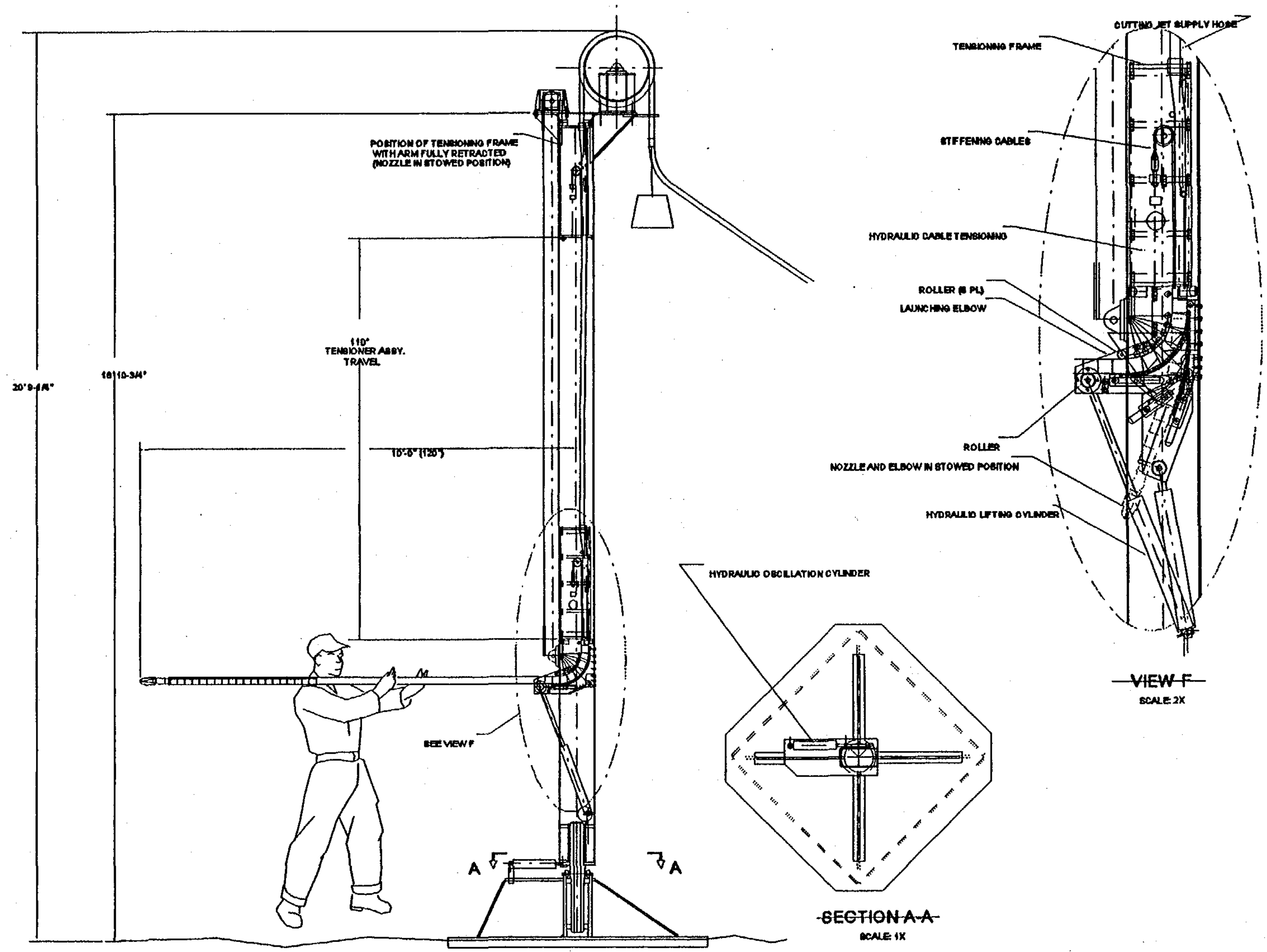

Figure 3.2 1/4-Scale Extendible-Nozzle System for Enhanced Sluicing Testing

Compared to currently used sluicing systems, the extendible-nozzle operates at increased jet pressure, significantly reduced flow rate and stand-off distance, and can be positioned to impinge directly upon the area to erode, significantly improving system performance. The extendible-nozzle technology may significantly improve retrieval by dislodging sludge heels, fracturing saltcake, decreasing the time and water required to provide safe transport of the variety of materials in the waste storage tanks.

Specific benefits of the extendible-nozzle are as follows:

- Enhanced sluicing capabilities because of high-pressure, low-volume waterjet at small stand-off distances.
- High-pressure waterjet provides increased waste removal volume per unit volume of water.
- Operates using process water or recycled slurry.
- Extreme simplicity of design and operation directly relates to a lower cost system and lower operating costs compared with conventional rotary joint robotic arms.
- Can be used to deploy end effectors or manage cable/hose systems.
- Complete retraction into a compact tool housing for insertion, retraction, and storage through a relatively small hole.

3.1 Background - Mining Applications

Waterjet Technology, Inc. worked with ESSO Resources Canada Limited for several years to adapt borehole-mining techniques to the extraction of bitumen from underground tar sands deposits.[a] As a part of this effort, Waterjet Technology, Inc. designed, built, and tested a 1/4-scale model of a tar sands borehole-mining tool. The system utilizes an extendible, erectable arm to hold a waterjet-nozzle within a few feet of the cavity wall, greatly increasing the size of cavity that can be mined and improving the economics of the process. This 1/4-scale model, shown in Figure 3.2, is the system that has been extensively tested at PNNL to evaluate extendible-nozzle waste dislodging (described in Section 6) and waste dislodging and retrieval in horizontal tanks (described in Section 7).

3.1.1 Borehole Mining of Tar Sands

Only a fraction of Canada's extensive tar sands deposits can be extracted using current technology. Shallow deposits are generally removed by strip mining. In deep deposits, bitumen is extracted by conventional tunnel mining techniques or by injecting steam into the formation and recovering the liquefied bitumen from wells by pumping. Between the shallow and deep formations lie enormous reserves of bitumen-laden tar sands that cannot be economically extracted by conventional techniques. The Hydraulic Borehole-Mining System developed by Waterjet Technology, Inc. operates best at these

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a) Quest Integrated, Inc. initiated bore hole miner development in the mid-1970s. They worked with ESSO from 1988 through 1992. The bore hole miner was patented in 1993.

intermediate depths. Previous work done by Waterjet Technology, Inc. and by others using equipment designed by Waterjet Technology, Inc. has proven the effectiveness of borehole mining for cutting and extracting underground deposits of granular materials.

Components that make up the borehole-miner system are shown in Figures 3.3 through 3.5. In Figure 3.3, a close-up view of the borehole-miner tool is shown. The inlet screen that restricts large particles from entering the jet pump is visible. In Figure 3.4, the borehole-miner deployment system trailer is shown. This trailer-mounted system has the capability to perform underground at depths up to 300 ft. The trailer-mounted pump that powers the borehole-miner system is shown in Figure 3.5. The 1800-hp pump provides flow rates up to 500 gpm at pressures up to 3000 psi.

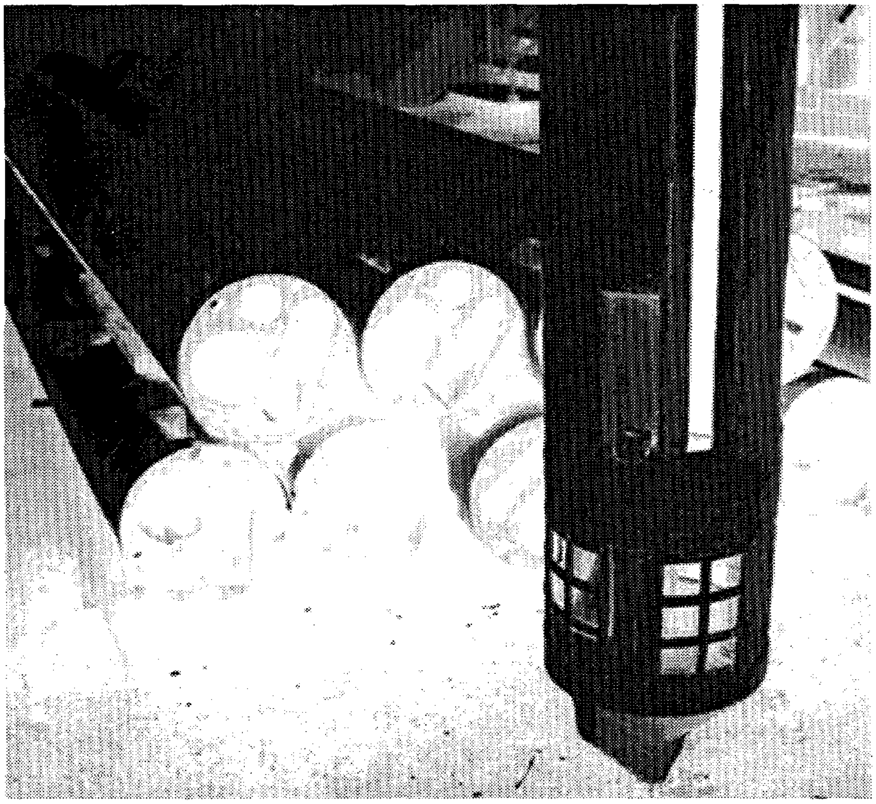


Figure 3.3 12.75-in.-Diameter Borehole-Miner Tool with Integral Jet Pump Conveyance

To be efficient in mining applications, borehole-mining must produce large cavities in the ore zone. A borehole cavity in uranium sandstone is shown in Figure 3.6. The challenge in mining tar sands by this method, however, is maintaining the stability of the cavity roof. The tar sand itself and the deposits over the tar sands are not generally competent enough to support large roof spans. Cave-ins of overburden material reduce mining efficiency by diluting the recovered ore. Tar sand sloughing from roof and walls reduces mining efficiency by producing large clumps of ore that can block the slurry conveyance inlet and require further size reduction. Some DOE sites have tanks constructed from gunite, that in its weakened condition may behave as a cavity roof. Material from these tanks may crumble and reduce retrieval efficiency at those sites.

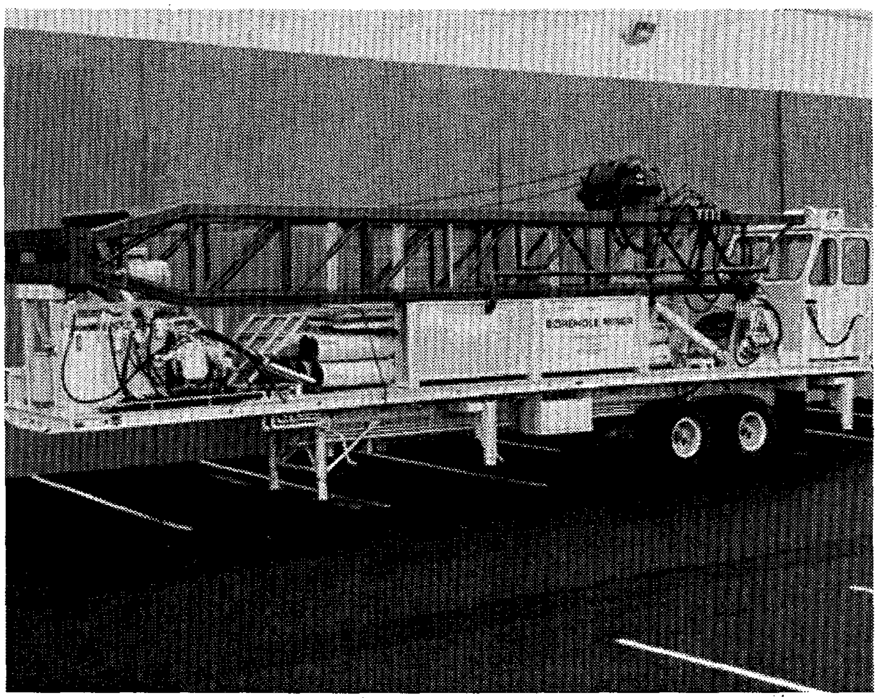


Figure 3.4 Borehole-Miner Deployment System Trailer, 300-ft Depth Capacity

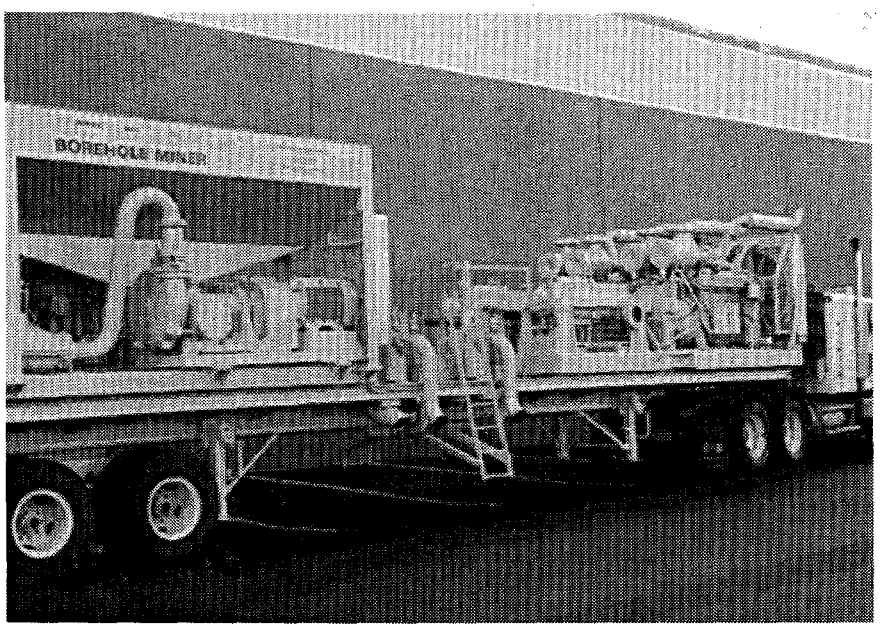


Figure 3.5 1800-hp Borehole-Mining Pump System Trailer, 300-ft Depth Capacity

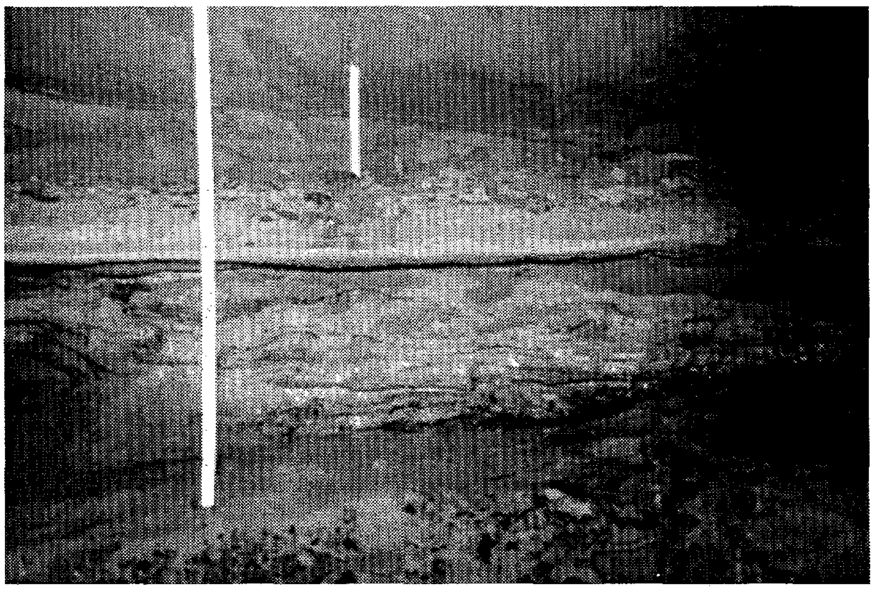


Figure 3.6 Borehole Cavity in Uranium Sandstone

3.1.2 Extendible, Erectable Borehole-Nozzle

To be effective in borehole mining, the cutting jet nozzle must be extended out from the mining tool so that it is closer to the face being cut. In previous work with ESSO, Waterjet Technology, Inc. (then known as Quest Integrated, Inc.) studied various techniques for extending the nozzle to mine large flooded cavities. Two concepts were modeled and demonstrated on a small scale. The most promising concept employs a flexible, segmented jacket surrounding a high-pressure cutting jet supply hose. By applying compression to the jacket with internal tensioning cables, the assembly can be made sufficiently rigid to support its own weight in a cantilevered horizontal position. As shown in Figure 3.2, this extendible, erectable borehole-nozzle system allows the jacketed hose assembly to be lowered vertically down the borehole-mining tool, bent to a horizontal direction within the cavity, and then extended out towards the face of the deposit being mined.

3.1.3 Tar Sands Mining Characteristics

For material to be effectively cut by waterjet, the effective pressure at the cutting face must exceed a certain threshold pressure. The degradation of the cutting jet effectiveness with stand-off distance is a phenomenon that depends on jet flow rate and pressure. The high-pressure waterjet was found to most efficiently dislodge the sandstone materials at short stand-off distances.

Basically, tar sands are a mixture of sand, clay, water, and bitumen. The sand particles are surrounded by the water, which is surrounded by bitumen. The clay is in the form of dense strata within the ore zone. In borehole mining, the waterjet loosens the sand particles from the formation and, to some extent, frees the bitumen from the sand and water. Being nearly neutrally buoyant, the freed bitumen goes into suspension in the water-filled cavity. Some of the bitumen attaches itself to air bubbles and rises to the surface; bitumen that is still attached to sand falls to the bottom of the cavity.

Ideally, the cutting jet will separate each particle of sand from its neighbors and free the bitumen. In practice, however, the tar sands deposit will be cut by the waterjet and broken into chunks of various sizes, from single particles to small clumps. These clumps must be of a small enough size for jet pump transport to the surface, or will require further size reduction by the integral mechanical chopper at the jet pump inlet. The most efficient mining technique will be the one that breaks up the tar sands most completely in a single operation.

3.2 Extendible-Nozzle Range of Performance

The extendible-nozzle water-jetting system's range of operation is restricted by the amount of thrust that the jet exerts upon the links in the extendible arm. The extendible-nozzle prototype and the system being deployed at ORNL OHF contains links with a 2-in. by 2-in. cross section and extends to 10 ft. Based on material selection, the fully extended arm must be designed to withstand the axial thrust caused by the nozzle as exerted on the arm during jet operation. To estimate permissible nozzle operating conditions, the following formulas can be used to calculate the nozzle flow rate (Q), axial thrust from the nozzle on the arm (T), and pump horsepower (hp).

$$Q = C_D \pi d^2/4 \, (2P/\rho)^{0.5} \qquad 3.1$$

where

Q = nozzle flow rate
C_D = nozzle coefficient of discharge $0.9 \leq C_D \leq 1.0$
d = nozzle diameter
P = jet pressure
ρ = fluid density.

$$Q = C_D \, 29.67 \, d^2 P^{0.5} \qquad 3.2$$

In Equation 3.2, nozzle flow rate (Q) has units of gpm, nozzle diameter (d) has units of in., and jet pressure (P) has units of psi.

$$T = \Delta P A_{inlet} \frac{[1 - (2C_D^2-1)(A_e/A_i)]}{(1+A_e/A_i)} \qquad 3.3$$

where

T = thrust load
$\Delta P = P_{upstream} - P_{downstream}$
A_e = exit area
A_i = inlet area.

To estimate the horsepower required to operate the extendible nozzle

$$hp = 0.01739\, d^2\, C_D\, P^{1.5} \qquad 3.4$$

In Equation 3.4, nozzle diameter (d) has units of in., and jet pressure (P) has units of psi.

Nozzle characterization tests conducted at PNNL, described in Section 4, showed that the nozzle coefficient of discharge is ≥ 0.95.

3.2.1 Extendible-Nozzle Waterjet Operating Range

Using Equation 3.2, the nozzle flow rate over a range of operating pressures was calculated. This summary is shown in Table 3.1. For the calculations, the nozzle coefficient of discharge C_D was assumed to be 1.0. The initial extendible-nozzle radioactive waste deployment remediation will occur at Oak Ridge National Laboratory. They have confined their maximum operating flow rate to 150 gpm. For values where 1.0 produced flow rates greater than the 150 gpm limit for the 1500 psi pump, the values at C_D = 0.95 were shown in parenthesis. Only the 0.375- and 0.406-in.-diameter nozzles cannot provide 150 gpm at 1500 psi.

Table 3.1 Extendible-Nozzle Water-jetting System Flow Rate Versus Operating Pressure

Pressure, psi	Flow Rate, gpm with C_D = 1.0 (with C_D = 0.95)				
	0.281	0.310	0.344	0.375	0.406
500	52	64	79	93	109
1000	74	90	111	132	155 (147)
1500	91	110	136	162 (154)	189 (180)
2000	105	128	157 (149)	187	219
2500	117	142	176	209	245
3000	128	156 (149)	192	229	268

Using Equation 3.4, the horsepower required to power the nozzle was estimated. This is shown in Table 3.2.

Table 3.2 Extendible-Nozzle Water-jetting System Pump Horsepower Versus Operating Pressure

Pressure, psi	Horsepower, hp, with $C_D = 1.0$				
	0.281	0.310	0.344	0.375	0.406
500	15	19	23	27	32
1000	43	53	65	77	91
1500	80	97	120	142	167
2000	123	149	184	219	256
2500	172	209	257	306	358
3000	226	275	338	401	471

3.2.2 Extendible-Nozzle Range of Motion

The extendible-nozzle system is designed to move in three directions: extension from the mast, rotation about the mast, and the angle between the horizontal and extended vertically downward. The range and rate of change of motion are summarized in Table 3.3. The nozzle length varies from 0 to 10 ft. The nozzle extends from the mast at a maximum extension rate of 10 in./s. At this rate the extendible nozzle can be fully extended or retracted in 12 s (The extension rate is controlled by an actuator in the arm elbow; the elbow moves approximately 1/4-turn over a period of 10 s). The nozzle can rotate up to 360 degrees around the mast. The mast rotation rate is 0.012 to 1.2 rpm. The nozzle can point almost downward, within 2 degrees from full vertical downward extension. All of these maximum rates can be reduced by regulating control valves in the control console.

Table 3.3 Extendible-Nozzle Water-jetting System Range and Rate of Change of Motion

Nozzle Motion	Range of Motion	Rate of Change of Motion
Rotation	360 degrees	0.012 to 1.2 rpm
Angle from the vertical	88 degrees (from 2 degrees from vertical downward to 90 degrees or horizontal)	90 degree change in 10 s, nonlinear
Extension	0 to 10 ft	10 in./s

4.0 Nozzle Performance Characterization Tests

Experiments were conducted to determine the hydraulic performance of the nozzles used on the Waterjet Technology, Inc. borehole miner extendible nozzle. The results are based on experimentally determined values of the mass flow rate, the pressure drop across the nozzle, and the fluid density for the nozzles installed on the borehole miner.

4.1 Test Objectives

The objective of these tests was to determine the relationship for the volume flow rate through the extendible nozzle as a function of the static pressure upstream of the nozzle. Tests were performed using nozzle sizes of 0.281-, 0.310-, 0.344-, 0.375-, and 0.406-in. diameter. Test were conducted for pressure drops across the nozzle of 3 to 10 MPa, 435 to 1450 psi. The nozzles were tested by discharging water into ambient air.

4.2 Test Fixture Configuration and Data Acquisition

To obtain a relationship for the volume flow rate through the nozzle as a function of the static pressure upstream of the nozzle, the discharge coefficient C_D is defined as:

$$C_D = Q_{\text{Actual Flow}}/Q_{\text{Ideal Flow}} \qquad 4.1$$

where Q = volume flow rate.

The ideal flow through a nozzle refers to flow with no losses. From the continuity equation, the velocity at the inlet of the nozzle is

$$V_i = A_e V_e/A_i \qquad 4.2$$

where

V_e = fluid velocity at the exit of the nozzle
V_i = fluid velocity at the inlet of the nozzle
A_e = nozzle cross-sectional area at the exit of the nozzle
A_i = nozzle cross-sectional area at the inlet of the nozzle.

Applying the Bernoulli equation for flow through a nozzle and Equation 4.2 yields

$$V_{e\ \text{Ideal}} = \{2(P_i - P_e)/(\rho[1 - (A_e/A_i)^2])\}^{1/2} \qquad 4.3$$

where

P_e = the pressure at the exit of the nozzle
P_i = the pressure at the inlet of the nozzle
ρ = the fluid density.

Therefore, by combining Equations 4.1 and 4.3, the discharge coefficient can be written in terms of measurable parameters.

$$C_D = Q_{actual}/\{A_e \, V_{e\ Ideal}\} \qquad 4.4$$

During the tests, the exit pressure was atmospheric and the quantity (P_i - P_e) is the static gage pressure measured upstream from the nozzle. The volume flow rate (Q_{actual}) is

$$Q_{actual} = m_{dot}/\rho \qquad 4.5$$

where

m_{dot} = the mass flow rate through the nozzle
ρ = the density of the fluid flowing through the nozzle.

By measuring the steady-state flow rate and density through the nozzle, for a given upstream static pressure, the nozzle discharge coefficient can be calculated.

The pressure was measured using a pressure transducer located immediately upstream of the nozzle. The density was determined from temperature measurements of the water taken upstream of the nozzle. The relationship for the density of water as a function of the temperature in degrees C is

$$\rho(kg/l) = 0.998707 + 6.36x10^{-6}T - 8.25x10^{-6}T^2 \;\; 4.9x10^{-8}T^3 \qquad 4.6$$

The relationship comes from developing a curve fit of the data for water density presented in the *CRC Handbook of Chemistry and Physics.*

The mass flow rate was determined by diverting the discharged fluid into a weigh tank. The force on the weigh tank load cells was recorded as a function of time. During a test, the weight indicated by the load cells was higher than that of the fluid in the tank because the fluid was flowing downward into the tank. However, the rate of change of the force on the load cells gives the flow rate of water into the tank. The flow rate was obtained by performing a linear least squares fit on the data for the load cell force as a function of time.

4.2.1 Equipment and Instrumentation

Tests were conducted at the 336 Building in the 300 Area of the U.S. Department of Energy Hanford Site in the 1/4-scale double-shell tank (DST). The nozzles were attached to the extendible nozzle which was located in the 1/4-scale DST.

Water was supplied from the 300 Area process water system via a fire hydrant. The water was pumped to the test fixture using a Halliburton HT-400[a] (serial no. 1610) high pressure pump. Water was discharged from the nozzles into a large radius polyvinylchloride elbow and diverted downward into a weigh tank which was placed inside of the 1/4-scale double-shell tank. The flow diverter, into which the nozzle discharged, is shown in Figure 4.1.

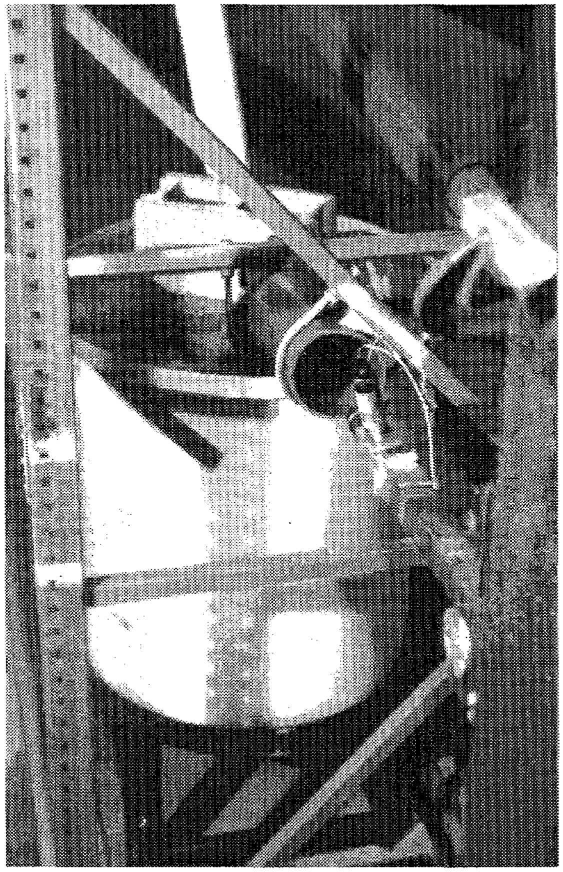


Figure 4.1 Extendible-Nozzle and Test Tank

The fluid temperature was measured just upstream of the nozzle using a standard Type J thermocouple ($\pm$ 2.2 degree C). The density was obtained from the measured temperatures using Equation 4.6.

(a) Halliburton Energy Services, Inc., Dallas, Texas.

The static pressure upstream of the nozzle was measured using a Sensotec[a] model no. TJE/B678-01-01, Serial No. 574190 pressure transducer (±0.1% of full scale). The transducer was connected to the high-pressure line via a stainless steel adapter with a 0.040-in. port in the pipe wall. The transducer provided a 4 to 20 mA signal over a range of 0 to 3000 psig.

The force on the load cells created by the collected water in the weigh tank was measured using four Transducer Techniques[b] model MLP-load cells, serial no. 72001 through 72004. Each transducer had a 300-lb range for a total of a 1200-lb range (gross weight) with approximately a 50% over range capacity. The low level strain gage signals from the load cells were summed in a Beowulf[c] Smart J-Box which produces a single low level strain gage signal. This output signal was fed to the BLH[d] model Lcp-100 weight processor, which in turn provided a 4 to 20 mA signal to the data acquisition system.

4.2.2 Data Acquisition System

The data acquisition system consisted of a Gateway[e] 486-DX2-66E PC with a Strawberry Tree ACPC-12-16 analog input card and a T-21 terminal panel. Strawberry Tree[f] Work Bench PC DOSR, version 2.4.0 was the data acquisition software used. The instrumentation specified in the previous section was connected to the data acquisition system. All of the measurements made during these tests were recorded by the data acquisition system. A block diagram of the data acquisition system is presented in Figure 4.2.

4.2.3 Test Procedure

The instrumentation was turned on at least 30 minutes prior to testing to allow it to warm up and come to equilibrium. The tests started with the nozzle directed away from the weigh tank. The logging of the test data file was started and readings for a zero flow condition were recorded by the data acquisition system prior to flow being initiated. After flow was initiated, time was provided to allow air to clear from inside the water lines.

(a) Sensotec, Inc., Columbus, Ohio.

(b) Transducer Techniques, Temecula, California.

(c) Beowulf Corp., Huntsville, Alabama.

(d) BLH Electronics, Canton, Massachusetts.

(e) Gateway 2000 Inc., North Sioux City, South Dakota.

(f) Strawberry Tree, Inc. Sunnyvale, California.

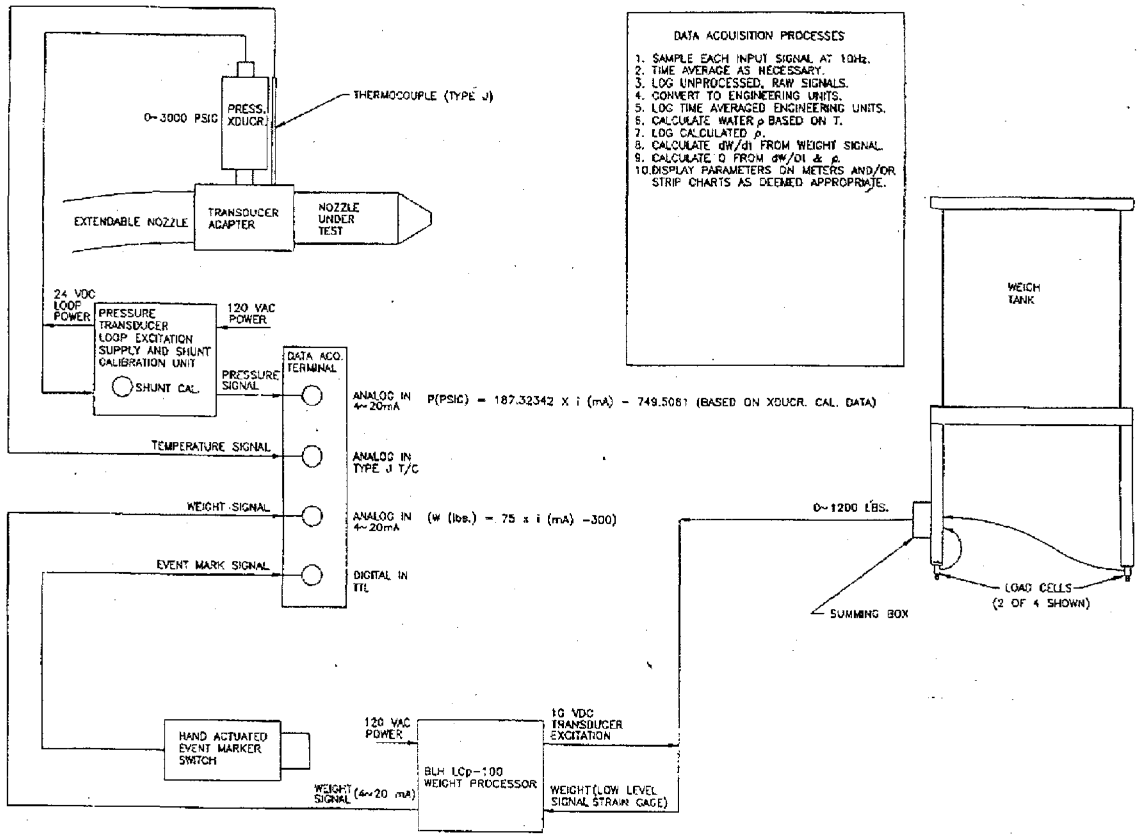


Figure 4.2 Data Acquisition System

After a steady-state condition was indicated by the data acquisition system, the nozzle discharge was brought in line with the flow diverter for the weigh tank by rotating the extendible nozzle. When the liquid level approached the top of the weigh tank, the nozzle discharge was again directed away from the weigh tank. The water flow was then terminated and the data acquisition system was left running until steady state readings for a zero flow condition were obtained. Logging of the data acquisition system readings and the test were then terminated.

4.3 Test Results

Eight valid data sets were obtained during testing. Table 4.1 contains the calculated results obtained after reducing the data. Two nozzle diameters are given for each case. The nominal diameter is the diameter used to identify the different size nozzles. The measured diameters were obtained for the bore of the nozzles tested. The diameter was determined by inserting drill bits. The diameter of the largest size drill bit that would provide a tight fit was measured. The measured diameters were used for calculating C_D and the Reynolds Number (Re).

Table 4.1 Results of Nozzle Characterization Tests

Nozzle Diameter			Average Pressure		Flow rate		Reynolds Number	Coefficient of Discharge	Uncertainty in C_D
nominal in.	measured mm	measured in.	kPa	psi	m^3/hr	gpm	Re	C_D	±
0.281	7.163	0.282	3979	577	12.45	54.8	614478	0.962	0.007
0.281	7.163	0.282	3392	492	11.59	51.1	572234	0.970	0.007
0.310	7.938	0.3125	3611	524	14.83	65.3	660524	0.979	0.007
0.310	7.938	0.3125	7082	1027	20.02	88.2	891681	0.944	0.013
0.344	8.738	0.344	5958	864	22.32	98.9	908321	0.953	0.021
0.375	9.530	0.3752	3044	411	19.58	86.3	726986	0.978	0.011
0.375	9.530	0.3752	9255	1342	34.92	154	1295149	0.999	0.045
0.406	10.292	0.4052	3302	479	23.76	105	819987	0.981	0.015

The standard deviation of the eight values calculated for C_D from the experimental data is 0.0175. The mean value for C_D is 0.971, and the standard deviation of the mean (standard error) is 0.006. Re ranged from 5.7×10^5 to 1.3×10^6. The results were analyzed to determine if any relationship between C_D and Re or between C_D and the nozzle diameter existed. No relationships were obtained from the test results. Figure 4.3 shows C_D as a function of Re. The various measured nozzle diameters are indicated on the plot.

The uncertainty in the individual values for C_D was determined using one standard deviation (σ) for the uncertainties of the experimentally determined parameters of pressure, density, and mass flow rate. Six out of the eight cases (75%) result in values for C_D that are within one standard deviation from the mean value for C_D (within 68% of the mean). The two cases with nominal diameters and pressures of 0.310 in. and 7082 kPa and 0.375 in. and 9255 kPa yield values of 0.944 and 0.999 for C_D respectively; these differ from the mean value by more than one standard deviation, σ.

The nozzles were attached to the extendible nozzle during testing, instead of in an ideal configuration; therefore, the results are only valid for nozzles as part of the extendible-nozzle system. The experimental results predict a nozzle C_D of 0.971 ± 0.006 for Reynolds numbers between 5.7×10^5 and 1.3×10^6.

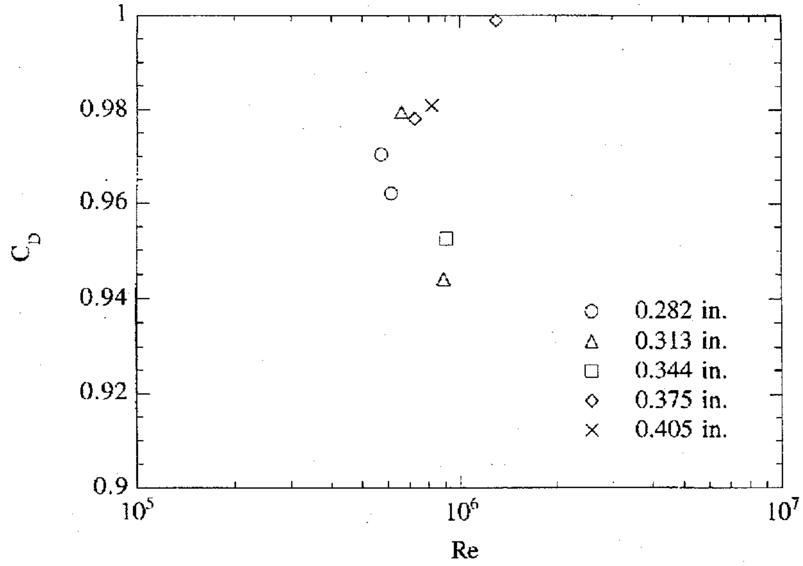


Figure 4.3 Coefficient of Discharge Versus Reynolds Number

5.0 Stationary-Nozzle Dislodging Tests

Stationary-nozzle dislodging tests were conducted at Waterjet Technology, Inc. in fiscal year 1996 to support extendible-nozzle system evaluation for in-tank deployment. The evaluation investigated dislodging data at a range of distances similar to those encountered during tank operation. Nozzle motion was eliminated from these tests to better evaluate the effects of nozzle diameter, pressure, and stand-off distance for dislodging a range of sludge and saltcake simulants. When the extendible-nozzle is deployed in a tank, operating variables are pressure and stand-off distance. The nozzle diameter remains fixed and must be changed manually when the extendible-nozzle is removed from the tank. Therefore, it is important to understand the effects of nozzle diameter upon system operation.

5.1 Test Objectives

The stationary-nozzle dislodging test objectives were to investigate the waterjet's ability to dislodge simulated sludge and saltcake waste forms to evaluate the effects of nozzle diameter, pressure, and nozzle stand-off distance. Test parameters and their evaluation range are listed in Table 5.1.

Table 5.1 Stationary-Nozzle Performance Evaluation Test Matrix

Parameter	Range
Stand-off distance, ft	10, 20, 30, 40, 50
Nozzle pressure, ksi	0.5, 1, 2, 3
Nozzle diameter, in.	0.281, 0.310, 0.344, 0.375, 0.406
Flow rate, gal/min	67 to 250

5.1.1 Stand-Off Distance

The stand-off distance range is based on extendible-nozzle performance and the range of application at the DOE sites. Two types of underground storage tanks, vertical tanks and horizontal tanks are used at DOE sites. Vertical tanks range in diameter to 75 ft at Hanford to 85 ft at Savannah River Site. Horizontal tanks range from 20 to 50 ft in length. Based on the location of risers, the stand-off distances from 10 to 50 or 60 ft could be encountered. The jet coherency is affected by the number of nozzle diameters, a non-dimensional parameter that is the ratio of the distance downstream from the nozzle to the nozzle diameter.

5.1.2 Pressure

The extendible-nozzle maximum operating pressure is 3000 psi based on hose capacity and the jet axial thrust on the extendible-nozzle links. Based on performance of the available pump, a lower bound of 500 psi was selected for evaluation.

5.1.3 Nozzle Diameter

The extendible-nozzle was designed to operate over a range of nozzle diameters from 0.281 to 0.406 in. The test range included evaluation of all the nozzles.

5.1.4 Flow Rate

Flow rate through the extendible nozzle is a dependent variable that is a function of the nozzle diameter and jet pressure.

5.2 Test Fixture Configuration and Data Acquisition

The stationary-nozzle tests were conducted using a test fixture constructed at Waterjet Technology, Inc. The test bench consisted of a nozzle turret, a simple containment shield, and a large catcher tray with a transfer pump. The turret provided the operator a safe means of aiming the high thrust waterjet at the target. The nozzle alignment test stand is shown in Figure 5.1. Containment of the dislodged simulant was necessary to prevent spills of saltcake into the storm drain.

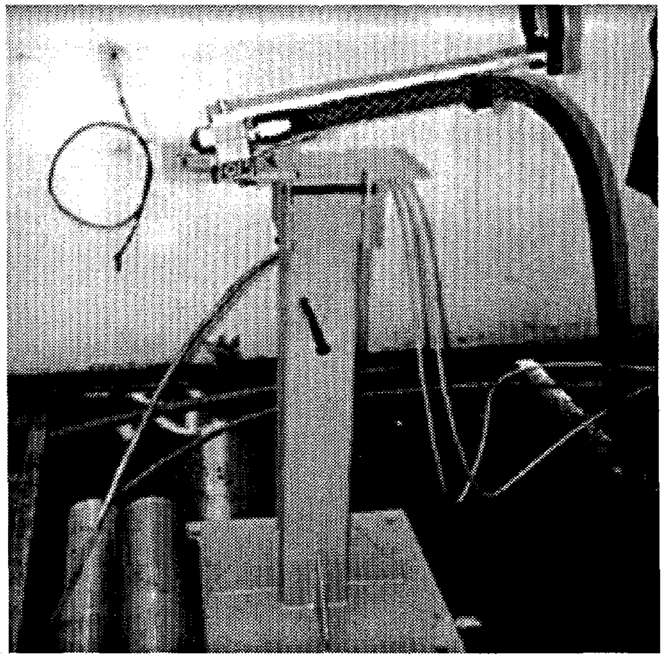


Figure 5.1 Stationary Waterjet Test Assembly

During these tests, a stationary nozzle was positioned at a fixed distance from a simulant block. After the jet reached the desired pressure, a plate in front of the block was released and the jet impacted the target for a predetermined time. The amount of solids removed from the target was measured to evaluate the dislodging rate and the jet cutting efficiency.

Recorded parameters are listed in Table 5.2.

Table 5.2 Stationary-Nozzle Test Data, Instsrumentation and Accuracy

Parameter	Measurement Method	Accuracy	Notes
Run number			sequential
Simulant			numbered
Stand-off distance	tape measure	±0.25 in.	
Pressure	pressure gauge	±100 psi	
Nozzle diameter			
Spray time	stop watch	±1 s	
Nozzle angle	observation		kept constant at 90 degrees
Flow rate			calculated using Equation 3.2 assuming $C_d = 0.9$
Volume	sand displacement		

5.3 Simulant

Saltcake and sludge simulant types were selected for evaluation. The simulant materials tested included three saltcake recipes and a form of sludge (kaolin modeling clay). The simulant compositions are summarized in Table 5.3. The simulant compressive strength was measured using ASTM standard D 1633 - 84: Compressive Strength of Molded Soil-Cement Cylinders.

Table 5.3 Simulant Composition

Simulant Name	Product Name	Composition	Density g/cm^3	Compressive Strength psi	Cure Time days
Saltcake No. 1	Dynamate	84 wt% in water	2.25±0.05	3000	30
Saltcake No. 2	Dynamate	88 wt% in water	1.94±0.05	1500 psi	30
Saltcake No. 3	Dynamate	75 wt% in water	2.27±0.05	2500 psi low porosity	30
Sludge No. SPS	Seattle Pottery Systems clay[(a)]				

(a) Seattle Pottery Supply clay in moist form. Block size ~5.5 in. x 5 in. x 12 in.

5.3.1 Saltcake Simulant Manufacture

The saltcake simulants are composed of potassium magnesium sulfate also known as "langbeinite." The product trade name is Sulfur-K-Mag; the specific type used was called Dynamate. The distributor is James Farrel & Co., Seattle, Washington.

Instructions to prepare this simulant are as follows. Mix specified wt% Dynamate in water. Use a low shear blender or hand mixing to uniformly mix the salt/water mixture. Pour mixed salt/water mixture into a well insulated mold in 1- or 2-in. layers. Compact with moderate tamping between each lift using a laboratory or industrial size air-powered cement vibrator. Cover molds tightly to minimize water evaporation from the saltcake surface during curing. If the mold top surface is not capped or covered tightly, water will evaporate from the top surface and the result will be a lower strength at the top surface of saltcake. A plastic mold is recommended because water will not be absorbed. If a wood container is used, line the mold interior with plastic to reduce water absorption. The hydration reaction reaches 73% completion after 14 days and 87% completion after 30 days when cured at 15 to 35 degrees C.

5.4 Saltcake Dislodging Test Results

The tests were videoed and samples were photographed. Data collected included dislodged material volume and weight. Dislodging efficiency was evaluated in terms of dislodging rate as a function of nozzle flow rate. Waterjet Technology, Inc. reported some variation in simulant properties between the simulant batches. No independent measurements of compressive strength were made for each block. This complicated the data analysis.

Tests were completed at stand-off distances of 10, 20, 30, and 40 ft. These data are summarized in Tables 5.4 through 5.7.

The data were plotted based on simulant type and stand-off distance to evaluate data trends. Two types of plots are shown as a function of nozzle diameter, dislodging rate in gpm and dislodging ratio (the ratio of the volume dislodged to the volume of water used). The 10-ft stand-off distance plots are shown in Figures 5.2, 5.3, and 5.4. The 20-ft stand-off distance plots are shown in Figures 5.5, 5.6, and 5.7. The 30-ft-stand-off distance plots are shown in Figures 5.8, 5.9, and 5.10. The 40-ft stand-off distance data did not include a complete set of tests and plots are not shown.

From the plots, the 0.310- and 0.344-in.-diameter nozzle data operated at 2000 psi show the best overall results in terms of removal efficiency and dislodging rate over the range of simulants tested. The data will be evaluated further to determine dislodging correlations for the simulants based on nondimensional stand-off distance.

Table 5.4 10-ft Stand-Off Distance (SOD) Dislodging Data

Run	Simulant	SOD (ft)	Pres (ksi)	Noz. (in)	Time (sec)	Angle (deg)	Flow (gpm)	Volume (ml)	Rate (gal/min)	Ratio (gal/gal)
181	1	10	0.5	0.281		90	47.2	pump stalled		
182	2	10	0.5	0.281		90	47.2	pump stalled		
183	3	10	0.5	0.281		90	47.2	pump stalled		
184	1	10	1	0.281	5	90	66.7	105	0.333	0.0050
185	2	10	1	0.281	5	90	66.7	50	0.159	0.0024
186	3	10	1	0.281	30	90	66.7	45	0.024	0.0004
187	1	10	2	0.281	2	90	94.3	85	0.674	0.0071
188	2	10	2	0.281	2	90	94.3	100	0.793	0.0084
189	3	10	2	0.281	10	90	94.3	20	0.032	0.0003
190	1	10	3	0.281	2	90	115.5	20	0.159	0.0014
191	2	10	3	0.281	2	90	115.5	35	0.277	0.0024
192	3	10	3	0.281	5	90	115.5	192	0.609	0.0053
193	1	10	0.5	0.310	60	90	57.4	45	0.012	0.0002
194	2	10	0.5	0.310	5	90	57.4	60	0.190	0.0033
195	3	10	0.5	0.310	60	90	57.4	70	0.018	0.0003
196	1	10	1	0.310	10	90	81.2	30	0.048	0.0006
197	2	10	1	0.310	2	90	81.2	80	0.634	0.0078
198	3	10	1	0.310	30	90	81.2			
199	1	10	2	0.310	10	90	114.8	50	0.079	0.0007
200	2	10	2	0.310	5	90	114.8	245	0.777	0.0068
201	3	10	2	0.310	10	90	114.8	60	0.095	0.0008
202	1	10	3	0.310	5	90	140.6	145	0.460	0.0033
203	2	10	3	0.310	5	90	140.6			
204	3	10	3	0.310	10	90	140.6	155	0.246	0.0017
205	1	10	0.5	0.344	45	90	70.7	35	0.012	0.0002
206	2	10	0.5	0.344	10	90	70.7	120	0.190	0.0027
207	3	10	0.5	0.344	30	90	70.7	50	0.026	0.0004
208	1	10	1	0.344	20	90	99.9	30	0.024	0.0002
209	2	10	1	0.344	5	90	99.9	130	0.412	0.0041
210	3	10	1	0.344	20	90	99.9	70	0.055	0.0006
211	1	10	2	0.344	5	90	141.3	570	1.807	0.0128
212	2	10	2	0.344	5	90	141.3	212	0.672	0.0048
213	3	10	2	0.344	15	90	141.3	100	0.106	0.0007
213	3	10	2	0.344	10	90	141.3	75	0.119	0.0008
214	1	10	3	0.344	5	90	173.1	350	1.110	0.0064
215	2	10	3	0.344	5	90	173.1	450	1.427	0.0082
216	3	10	3	0.344	5	90	173.1	235	0.745	0.0043
217	1	10	0.5	0.375	6	90	84.0	140	0.370	0.0044
218	2	10	0.5	0.375	5	90	84.0	185	0.586	0.0070
219	3	10	0.5	0.375	10	90	84.0	30	0.048	0.0006
220	1	10	1	0.375	5	90	118.8	175	0.555	0.0047
221	2	10	1	0.375	2.5	90	118.8	160	1.014	0.0085
222	3	10	1	0.375	30	90	118.8	45	0.024	0.0002
223	1	10	2	0.375	20	90	168.0	475	0.376	0.0022
224	2	10	2	0.375	5	90	168.0	935	2.964	0.0176
225	3	10	2	0.375	15	90	168.0	550	0.581	0.0035
226	1	10	3	0.375	5	90	205.7	30	0.095	0.0005
227	2	10	3	0.375	5	90	205.7	730	2.314	0.0112
228	3	10	3	0.375	5	90	205.7	610	1.934	0.0094
229	1	10	0.5	0.406	45	90	98.4	50	0.018	0.0002
230	2	10	0.5	0.406	5	90	98.4	165	0.523	0.0053
231	3	10	0.5	0.406	25	90	98.4	45	0.029	0.0003
232	1	10	1	0.406	20	90	139.2	65	0.052	0.0004
233	2	10	1	0.406	2	90	139.2	25	0.198	0.0014
234	3	10	1	0.406	15	90	139.2	245	0.259	0.0019
235	1	10	2	0.406	5	90	196.9	520	1.648	0.0084
236	2	10	2	0.406	2	90	196.9	95	0.753	0.0038
237	3	10	2	0.406	5	90	196.9	35	0.111	0.0006
238	1	10	3	0.406		90	241.1			
239	2	10	3	0.406		90	241.1			
240	3	10	3	0.406		90	241.1			

Table 5.5 20-ft Stand-Off Distance Dislodging Data

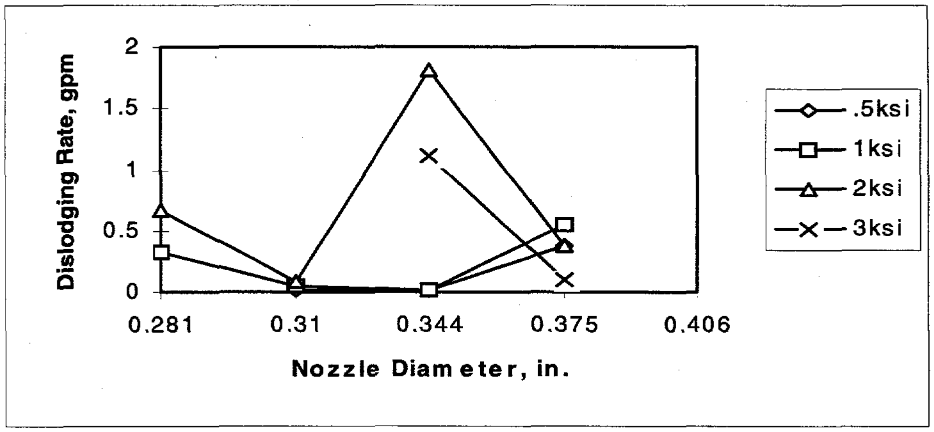
Run	Simulant	SOD (ft)	Pres (ksi)	Noz. (in)	Time (sec)	Angle (deg)	Flow (gpm)	Volume (ml)	Rate (gal/min)	Ratio (gal/gal)
1	1	20	0.5	0.281		90	47.2	stalled pump		
2	2	20	0.5	0.281		90	47.2	stalled pump		
3	3	20	0.5	0.281		90	47.2	stalled pump		
4	1	20	1	0.281	30	90	66.7	90	0.048	0.0007
5	2	20	1	0.281	30	90	66.7	100	0.053	0.0008
6	3	20	1	0.281	30	90	66.7	95	0.050	0.0008
7	1	20	2	0.281	30	90	94.3	250	0.132	0.0014
8	2	20	2	0.281	30	90	94.3	1100	0.581	0.0062
9	3	20	2	0.281	30	90	94.3	75	0.040	0.0004
10	1	20	3	0.281	10	90	115.5	100	0.159	0.0014
11	2	20	3	0.281	10	90	115.5	505	0.800	0.0069
12	3	20	3	0.281	10	90	115.5	100	0.159	0.0014
13	1	20	0.5	0.310	30	90	57.4	125	0.066	0.0012
14	2	20	0.5	0.310	30	90	57.4	500	0.264	0.0046
15	3	20	0.5	0.310	30	90	57.4	40	0.021	0.0004
16	1	20	1	0.310	20	90	81.2	315	0.250	0.0031
17	2	20	1	0.310	20	90	81.2	400	0.317	0.0039
18	3	20	1	0.310	20	90	81.2	75	0.059	0.0007
19	1	20	2	0.310	10	90	114.8	510	0.808	0.0070
20	2	20	2	0.310	10	90	114.8	580	0.919	0.0080
21	3	20	2	0.310	10	90	114.8	100	0.159	0.0014
22	1	20	3	0.310	5	90	140.6	40	0.127	0.0009
23	2	20	3	0.310	5	90	140.6	75	0.238	0.0017
24	3	20	3	0.310	5	90	140.6	45	0.143	0.0010
25	1	20	0.5	0.344	20	90	70.7	40	0.032	0.0004
26	2	20	0.5	0.344	20	90	70.7	340	0.269	0.0038
27	3	20	0.5	0.344	20	90	70.7	155	0.123	0.0017
28	1	20	1	0.344	20	90	99.9	350	0.277	0.0028
29	2	20	1	0.344	20	90	99.9	440	0.349	0.0035
30	3	20	1	0.344	20	90	99.9	75	0.059	0.0006
31	1	20	2	0.344	15	90	141.3	140	0.148	0.0010
32	2	20	2	0.344	10	90	141.3	470	0.745	0.0053
33	3	20	2	0.344	20	90	141.3	260	0.206	0.0015
34	1	20	3	0.344	5	90	173.1	105	0.333	0.0019
35	2	20	3	0.344	5	90	173.1	610	1.934	0.0112
36	3	20	3	0.344	15	90	173.1	205	0.217	0.0013
37	1	20	0.5	0.375	30	90	84.0	100	0.053	0.0006
38	2	20	0.5	0.375	30	90	84.0	410	0.217	0.0026
39	3	20	0.5	0.375	30	90	84.0	80	0.042	0.0005
40	1	20	1	0.375	40	90	118.8	100	0.040	0.0003
41	2	20	1	0.375	20	90	118.8	230	0.182	0.0015
42	3	20	1	0.375	60	90	118.8	145	0.038	0.0003
43	1	20	2	0.375	15	90	168.0	365	0.386	0.0023
44	2	20	2	0.375	2.5	90	168.0	285	1.807	0.0108
45	3	20	2	0.375	10	90	168.0	40	0.063	0.0004
46	1	20	3	0.375	2.5	90	205.7	505	3.202	0.0156
47	2	20	3	0.375	2.5	90	205.7	210	1.331	0.0065
48	3	20	3	0.375	10	90	205.7	70	0.111	0.0005
49	1	20	0.5	0.406	60	90	98.4	105	0.028	0.0003
50	2	20	0.5	0.406	15	90	98.4	205	0.217	0.0022
51	3	20	0.5	0.406	10	90	98.4	180	0.285	0.0029
52	1	20	1	0.406	15	90	139.2	355	0.375	0.0027
53	2	20	1	0.406	5	90	139.2	365	1.157	0.0083
54	3	20	1	0.406	30	90	139.2	75	0.040	0.0003
55	1	20	2	0.406	5	90	196.9	405	1.284	0.0065
56	2	20	2	0.406	2.5	90	196.9	155	0.983	0.0050
57	3	20	2	0.406	15	90	196.9	245	0.259	0.0013
58	1	20	3	0.406		90	241.1	need thicker samples		
59	2	20	3	0.406		90	241.1	need thicker samples		
60	3	20	3	0.406		90	241.1	need thicher samples		

Table 5.6 30-ft Stand-Off Distance Dislodging Data

Run	Simulant	SOD (ft)	Pres (ksi)	Noz. (in)	Time (sec)	Angle (deg)	Flow (gpm)	Volume (ml)	Rate (gal/min)	Ratio (gal/gal)
1	1	30	0.5	0.281		90	47.2			
2	2	30	0.5	0.281		90	47.2			
3	3	30	0.5	0.281		90	47.2			
4	1	30	1	0.281	300	90	66.7	150	0.008	0.0001
5	2	30	1	0.281	30	90	66.7	410	0.217	0.0032
6	3	30	1	0.281	300	90	66.7	275	0.015	0.0002
7	1	30	2	0.281	90	90	94.3	875	0.154	0.0016
8	2	30	2	0.281	30	90	94.3	315	0.166	0.0018
9	3	30	2	0.281	180	90	94.3	105	0.009	0.0001
10	1	30	3	0.281	120	90	115.5	140	0.018	0.0002
11	2	30	3	0.281	45	90	115.5	815	0.287	0.0025
12	3	30	3	0.281	90	90	115.5	125	0.022	0.0002
13	1	30	0.5	0.310	600	90	57.4	335	0.009	0.0002
14	2	30	0.5	0.310	180	90	57.4	570	0.050	0.0009
15	3	30	0.5	0.310	600	90	57.4	315	0.008	0.0001
16	1	30	1	0.310	240	90	81.2	135	0.009	0.0001
17	2	30	1	0.310	60	90	81.2	905	0.239	0.0029
18	3	30	1	0.310	240	90	81.2	200	0.013	0.0002
19	1	30	2	0.310	120	90	114.8	170	0.022	0.0002
20	2	30	2	0.310	15	90	114.8	520	0.549	0.0048
21	3	30	2	0.310	150	90	114.8	165	0.017	0.0002
22	1	30	3	0.310	120	90	140.6	210	0.028	0.0002
23	2	30	3	0.310	5	90	140.6	260	0.824	0.0059
24	3	30	3	0.310	90	90	140.6	155	0.027	0.0002
25	1	30	0.5	0.344	480	90	70.7	610	0.020	0.0003
26	2	30	0.5	0.344	50	90	70.7	475	0.151	0.0021
27	3	30	0.5	0.344	360	90	70.7	380	0.017	0.0002
28	1	30	1	0.344	210	90	99.9	270	0.020	0.0002
29	2	30	1	0.344	30	90	99.9	535	0.283	0.0028
30	3	30	1	0.344	120	90	99.9	190	0.025	0.0003
31	1	30	2	0.344	90	90	141.3	240	0.042	0.0003
32	2	30	2	0.344	10	90	141.3	510	0.808	0.0057
33	3	30	2	0.344	90	90	141.3	195	0.034	0.0002
34	1	30	3	0.344	60	90	173.1	200	0.053	0.0003
35	2	30	3	0.344	5	90	173.1	235	0.745	0.0043
36	3	30	3	0.344	60	90	173.1	125	0.033	0.0002
37	1	30	0.5	0.375		90	84.0			
38	2	30	0.5	0.375		90	84.0			
39	3	30	0.5	0.375		90	84.0			
40	1	30	1	0.375		90	118.8			
41	2	30	1	0.375	480	90	118.8	1050	0.035	0.0003
42	3	30	1	0.375		90	118.8			
43	1	30	2	0.375	240	90	168.0	640	0.042	0.0003
44	2	30	2	0.375	60	90	168.0	335	0.088	0.0005
45	3	30	2	0.375	150	90	168.0	370	0.039	0.0002
46	1	30	3	0.375	80	90	205.7	220	0.044	0.0002
47	2	30	3	0.375	5	90	205.7	205	0.650	0.0032
48	3	30	3	0.375	60	90	205.7	100	0.026	0.0001
49	1	30	0.5	0.406		90	98.4			
50	2	30	0.5	0.406		90	98.4			
51	3	30	0.5	0.406		90	98.4			
52	1	30	1	0.406	45	90	139.2	685	0.241	0.0017
53	2	30	1	0.406	30	90	139.2	720	0.380	0.0027
54	3	30	1	0.406	180	90	139.2	265	0.023	0.0002
55	1	30	2	0.406	10	90	196.9	695	1.102	0.0056
56	2	30	2	0.406	10	90	196.9	255	0.404	0.0021
57	3	30	2	0.406	60	90	196.9	175	0.046	0.0002
58	1	30	3	0.406		90	241.1			
59	2	30	3	0.406		90	241.1			
60	3	30	3	0.406		90	241.1			

Table 5.7 40-ft Stand-Off Distance Dislodging Data

Run	Simulant	SOD (ft)	Pres (ksi)	Noz. (in)	Time (sec)	Angle (deg)	Flow (gpm)	Volume (ml)	Rate (gal/min)	Ratio (gal/gal)
1	1	40	0.5	0.281		90	47.2			
2	2	40	0.5	0.281		90	47.2			
3	3	40	0.5	0.281		90	47.2			
4	1	40	1	0.281		90	66.7			
5	2	40	1	0.281	600	90	66.7	560	0.015	0.0002
6	3	40	1	0.281	600	90	66.7	505	0.013	0.0002
7	1	40	2	0.281		90	94.3			
8	2	40	2	0.281	240	90	94.3	550	0.036	0.0004
9	3	40	2	0.281	300	90	94.3	165	0.009	0.0001
10	1	40	3	0.281		90	115.5			
11	2	40	3	0.281	180	90	115.5	675	0.059	0.0005
12	3	40	3	0.281		90	115.5			
13	1	40	0.5	0.310		90	57.4			
14	2	40	0.5	0.310		90	57.4			
15	3	40	0.5	0.310		90	57.4			
16	1	40	1	0.310	600	90	81.2	530	0.014	0.0002
17	2	40	1	0.310	180	90	81.2	1080	0.095	0.0012
18	3	40	1	0.310		90	81.2			
19	1	40	2	0.310	240	90	114.8	1120	0.074	0.0006
20	2	40	2	0.310	90	90	114.8	645	0.114	0.0010
21	3	40	2	0.310		90	114.8			
22	1	40	3	0.310		90	140.6			
23	2	40	3	0.310	60	90	140.6	395	0.104	0.0007
24	3	40	3	0.310		90	140.6			
25	1	40	0.5	0.344		90	70.7			
26	2	40	0.5	0.344		90	70.7			
27	3	40	0.5	0.344		90	70.7			
28	1	40	1	0.344	900	90	99.9	740	0.013	0.0001
29	2	40	1	0.344	60	90	99.9	950	0.251	0.0025
30	3	40	1	0.344	600	90	99.9	510	0.013	0.0001
31	1	40	2	0.344	540	90	141.3	360	0.011	0.0001
32	2	40	2	0.344	25	90	141.3	640	0.406	0.0029
33	3	40	2	0.344	240	90	141.3	755	0.050	0.0004
34	1	40	3	0.344	300	90	173.1	200	0.011	0.0001
35	2	40	3	0.344	15	90	173.1	710	0.750	0.0043
36	3	40	3	0.344	300	90	173.1	290	0.015	0.0001
37	1	40	0.5	0.375		90	84.0			
38	2	40	0.5	0.375		90	84.0			
39	3	40	0.5	0.375		90	84.0			
40	1	40	1	0.375	600	90	118.8	585	0.015	0.0001
41	2	40	1	0.375	300	90	118.8	310	0.016	0.0001
42	3	40	1	0.375	600	90	118.8	340	0.009	0.0001
43	1	40	2	0.375	300	90	168.0	310	0.016	0.0001
44	2	40	2	0.375	60	90	168.0	1165	0.308	0.0018
45	3	40	2	0.375	300	90	168.0	310	0.016	0.0001
46	1	40	3	0.375	150	90	205.7	255	0.027	0.0001
47	2	40	3	0.375	15	90	205.7	275	0.291	0.0014
48	3	40	3	0.375	120	90	205.7	510	0.067	0.0003
49	1	40	0.5	0.406		90	98.4			
50	2	40	0.5	0.406		90	98.4			
51	3	40	0.5	0.406		90	98.4			
52	1	40	1	0.406		90	139.2			
53	2	40	1	0.406		90	139.2			
54	3	40	1	0.406		90	139.2			
55	1	40	2	0.406		90	196.9			
56	2	40	2	0.406		90	196.9			
57	3	40	2	0.406		90	196.9			
58	1	40	3	0.406		90	241.1			
59	2	40	3	0.406		90	241.1			
60	3	40	3	0.406		90	241.1			



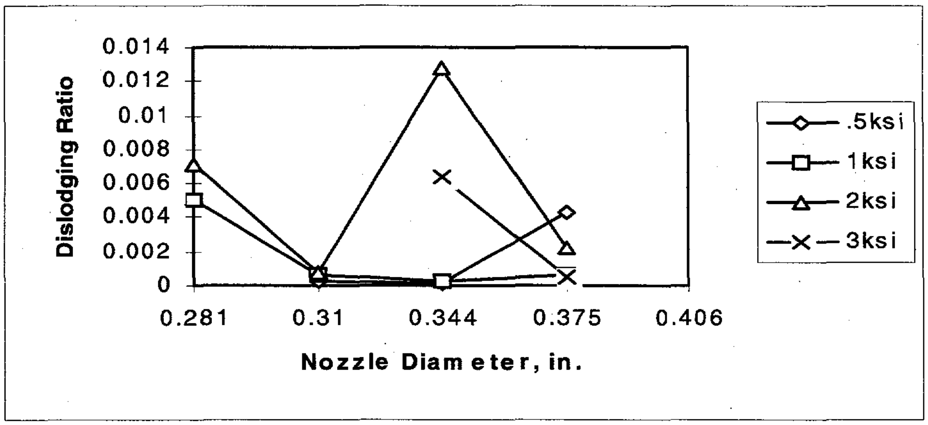
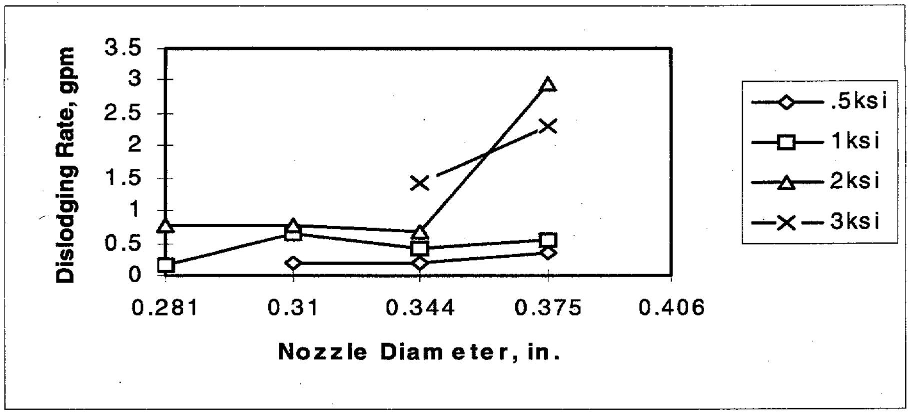


Figure 5.2 Saltcake No. 1 Solids Dislodging at 10-ft Stand-Off Distance



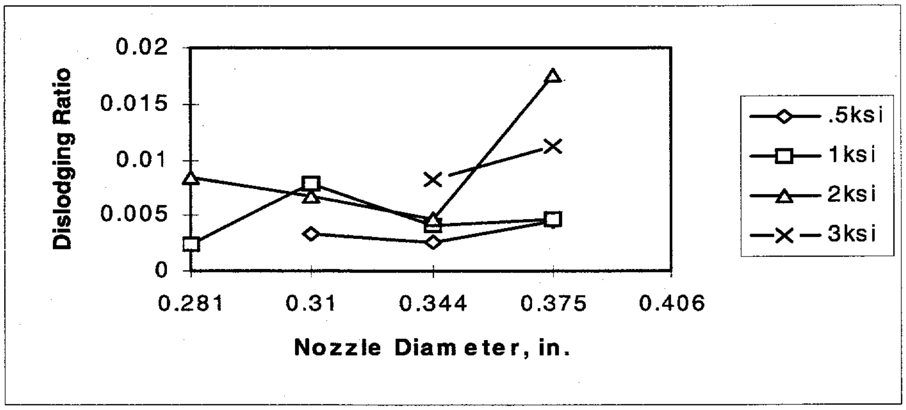
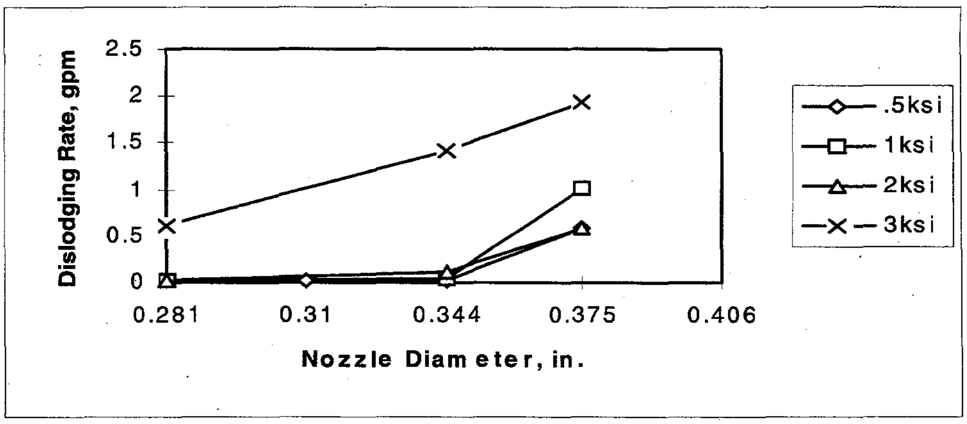


Figure 5.3 Saltcake No. 2 Solids Dislodging at 10-ft Stand-Off Distance



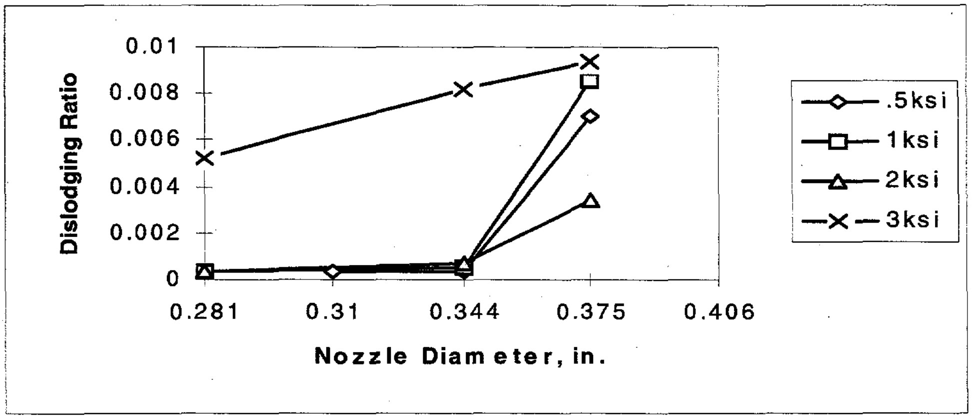


Figure 5.4 Saltcake No. 3 Solids Dislodging at 10-ft Stand-Off Distance

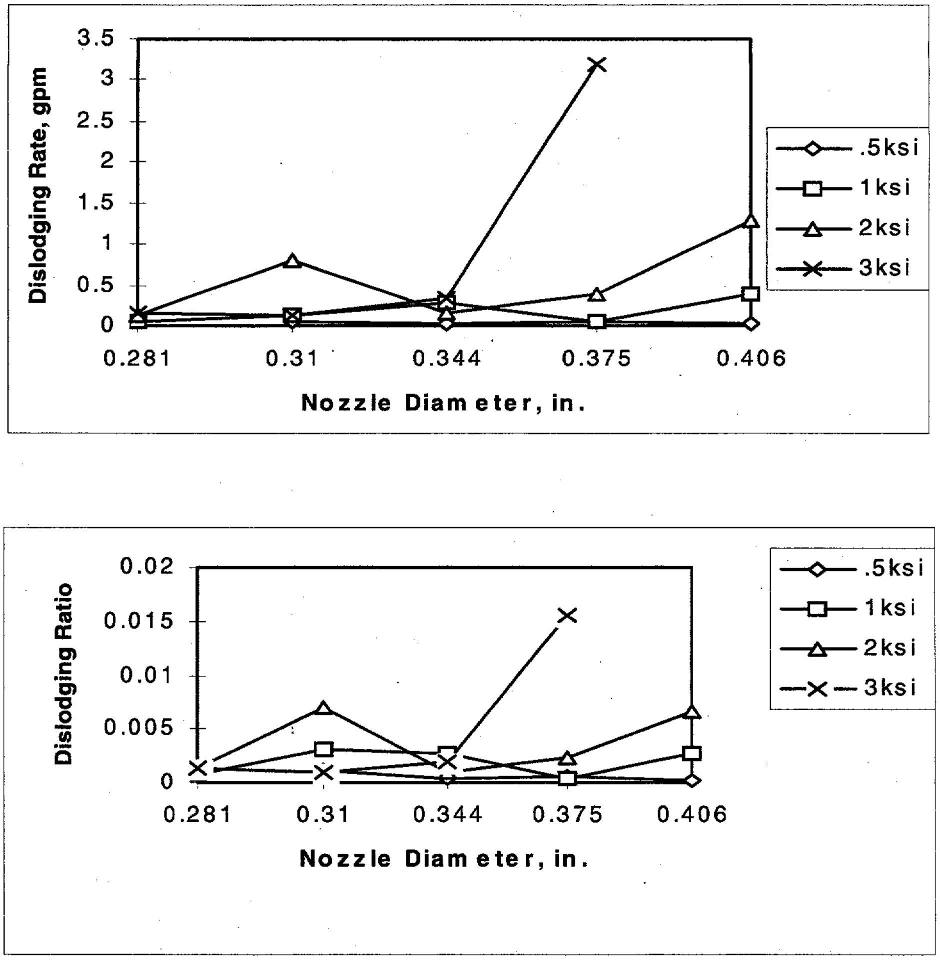
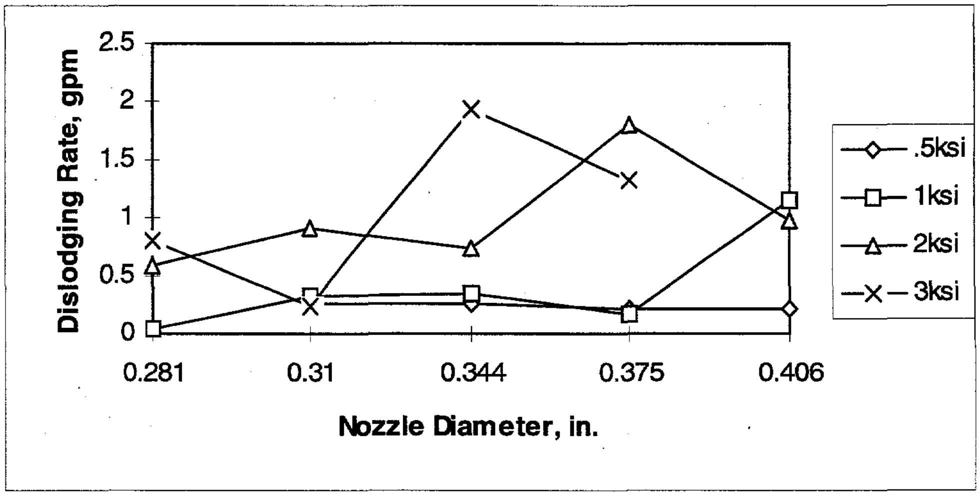


Figure 5.5 Saltcake No. 1 Solids Dislodging at 20-ft Stand-Off Distance



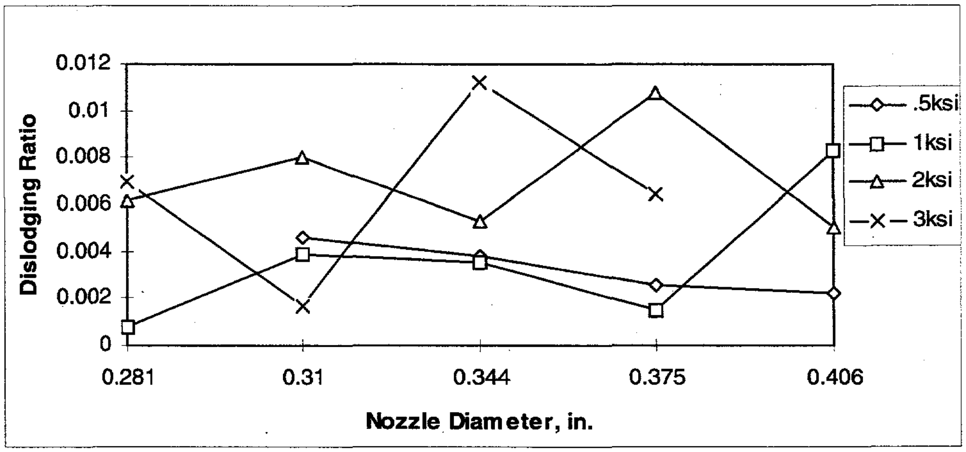


Figure 5.6 Saltcake No. 2 Solids Dislodging at 20-ft Stand-Off Distance

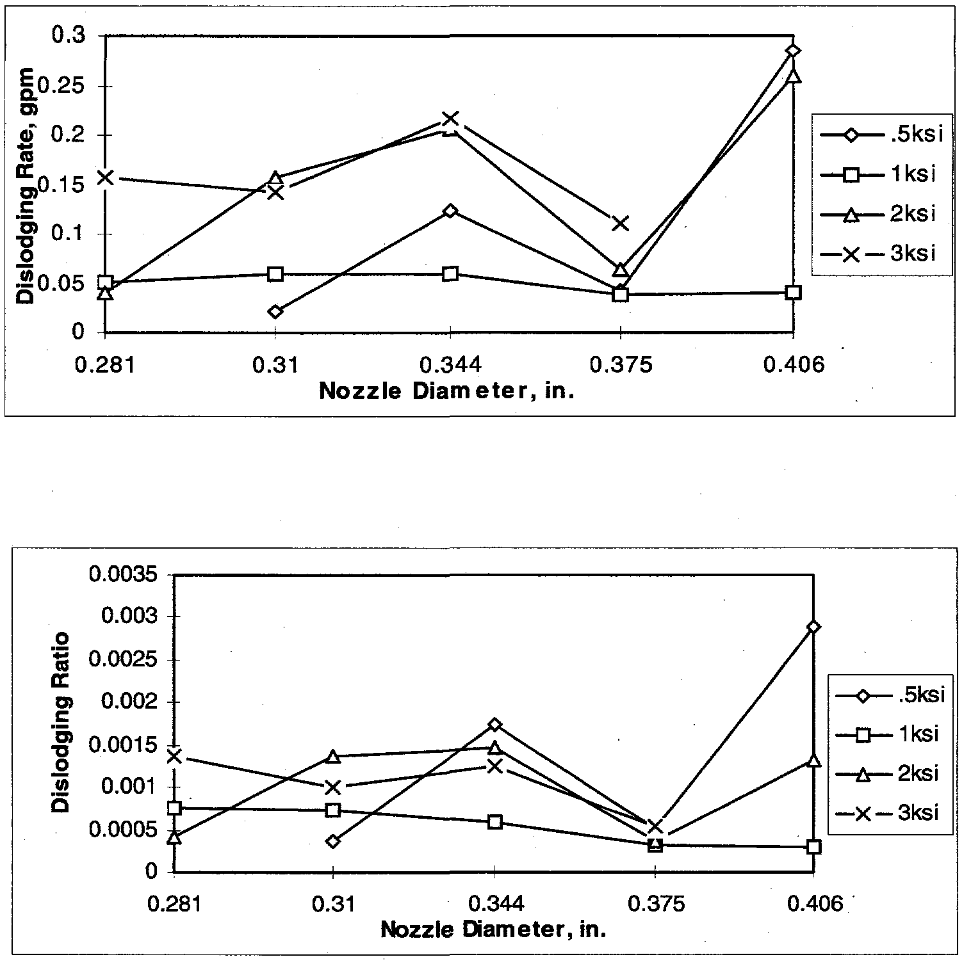


Figure 5.7 Saltcake No. 3 Solids Dislodging at 20-ft Stand-Off Distance

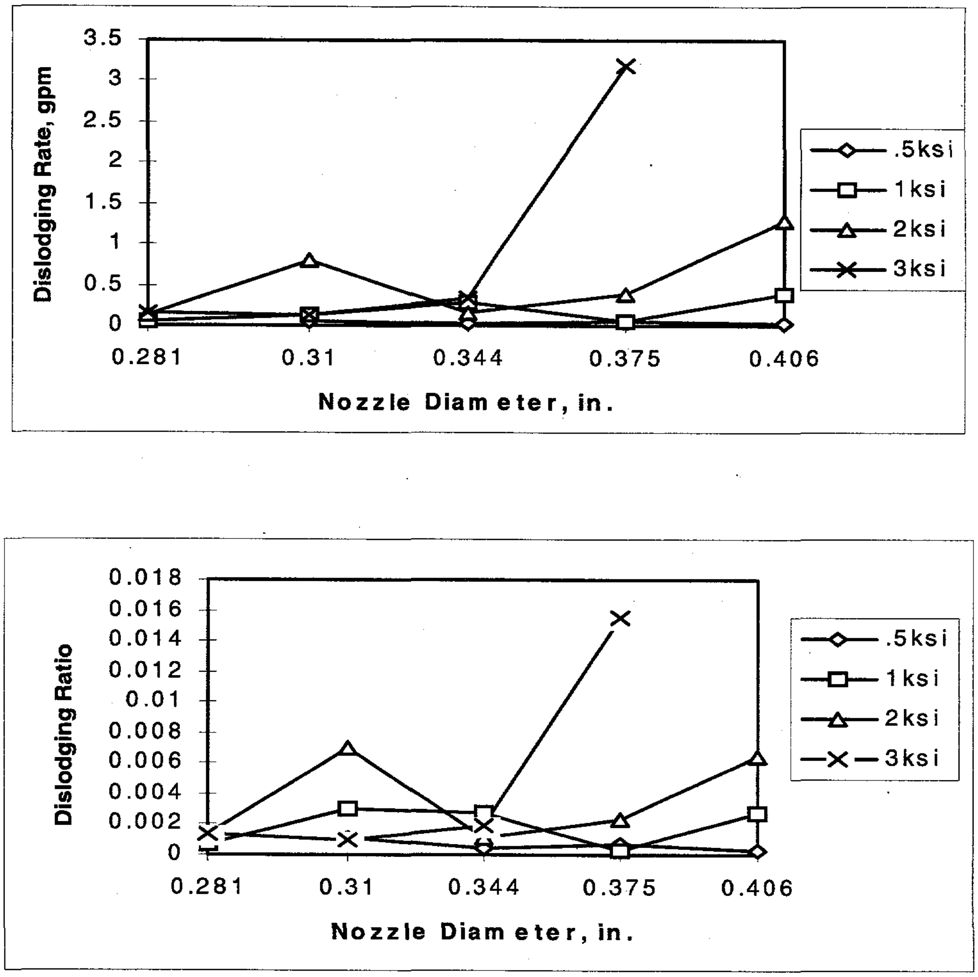


Figure 5.8 Saltcake No. 1 Solids Dislodging at 30-ft Stand-Off Distance

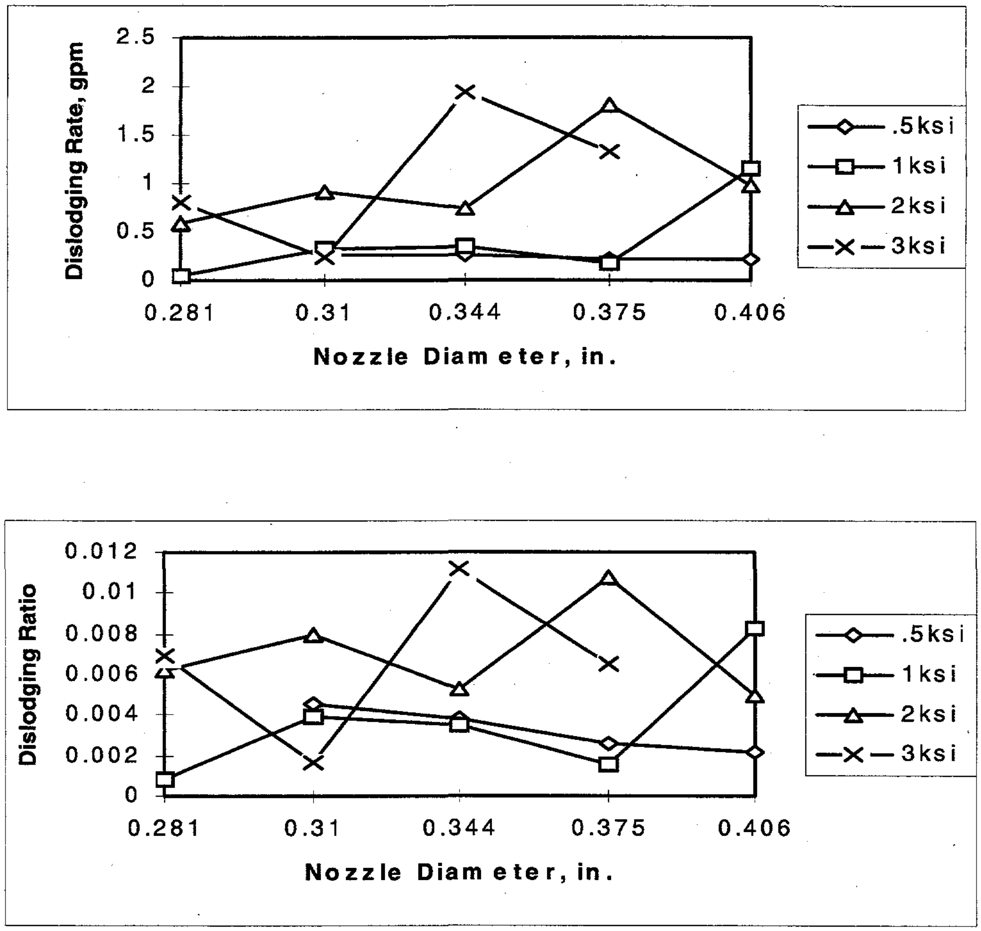


Figure 5.9 Saltcake No. 2 Solids Dislodging at 30-ft Stand-Off Distance

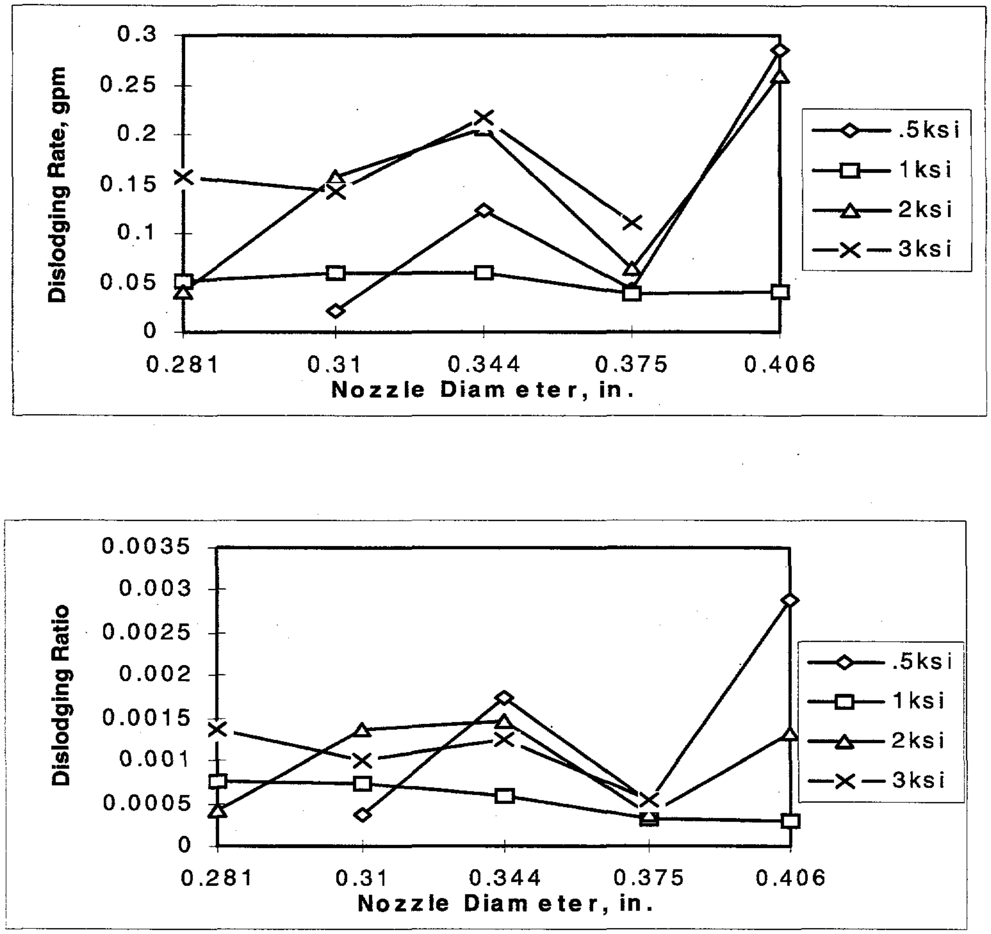


Figure 5.10 Saltcake No. 3 Solids Dislodging at 30-ft Stand-Off Distance

5.5 Sludge Dislodging Tests

Sludge dislodging tests were conducted with premixed moist clay. This data is summarized in Table 5.8. Tests were conducted using the 0.281-in.-diameter nozzle at stand-off distances from 20 to 50 ft over a range of water pressures. The jet severed the clay blocks at close stand-off distances. At larger stand-off distances, the sludge was deformed by the jet. Only qualitative data was obtained from the sludge tests.

Table 5.8 Sludge Test Results

Date	Simulant	Simulant Thickness in.	Stand-off Distance ft	Water Pressure psi	Calculated Flow Rate gpm[a]	Jet Duration	Observations Erosion Area in.
11/29	SPS[b]	5	20	1000	81	2 s traverse Right to left	Two clay blocks encased in cardboard box. Clay sliced into two chunks.
	SPS	15	20	1000	81	2 s traverse Right to left	Jet sliced through ~13 in.
	SPS	5.5	20	500	57	2 s traverse Right to left	Block split into two chunks
	SPS	15	20	500	57	2 s traverse Right to left	Jet sliced through ~11 in.
	SPS	5.5	30	500	57	2 s traverse Right to left	Sludge deformed.
	SPS	5.5	40	500	57	2 s traverse Right to left	Large indentation in sludge
	SPS	5.5	40	1000	81	2 s traverse Right to left	Sludge deformed by jet
	SPS	5.5	50	1000	81	2 s traverse Right to left	Block abraded ~ ½ in.
	SPS	5.5	50	2000	115	2 s traverse Right to left	Block abraded, crater in center
	SPS	5.5	50	3000	141	2 s traverse Right to left	Block abraded, large crater
	SPS	5.5	50	3000[c]	141	10 s dwell	Large crater formed

(a) Flow rate calculated using Equation 3.2 for nozzle diameter of 0.281 in. and coefficient of discharge of 0.95.
(b) Seattle Pottery Supply clay in moist form. Block size ~5.5 in. W x 5 in. L x 12 in. H.
(c) Time to pressurize from 1000 to 3000 psi is ~8 s. This waterjet exposure is in addition to the time listed.

6.0 Integrated Extendible-Nozzle Dislodging

The integrated extendible-nozzle dislodging tests represent a continuation of extendible-nozzle tests conducted at Waterjet Technology, Inc. during October 1995 through July 1996. These tests evaluated the fracturing and dislodging performance of a stationary nozzle over a range of nozzle diameters, stand-off distances, water pressures, and simulants. These tests were conducted at large stand-off distances from 10 to 40 ft.

6.1 Test Objectives

The purpose of the integrated extendible-nozzle dislodging tests was to evaluate integrated system operation such as will occur during waste retrieval in an underground storage tank. The objectives of the tests were 1) to evaluate the aerosol generation potential of extendible-nozzle operation, 2) evaluate the shape of the waterjet core and the jet pressure distribution and force exerted by the extendible-nozzle waterjet, 3) to evaluate the ability of the extendible nozzle to erode waste simulants, and 4) to recommend a mining strategy for extendible-nozzle deployment.

These tests were conducted in the 1/4-scale double-shell-tank test facility. The results of the dislodging tests will be described.

6.1.1 Key Data for Solids Fracturing and Dislodging

The ability of the jet to fracture and dislodge the solids is a function of the jet properties and the physical properties of the solids. It is important to characterize properties of both. Physical properties of the simulants such as densities, void fractions, particle sizes and shear strengths were characterized in the laboratory by evaluating samples taken from the simulant batch and cured similarly to the larger quantities used for testing. For each simulant test, the extendible-nozzle jet properties that were evaluated included jet stand-off distance, jet pressure, nozzle diameter, and traverse time. The type of erosion was monitored to determine whether the solids eroded or fractured to develop an understanding of which mechanisms dominated the solids removal process as a function of stand-off distance and the jet properties.

6.1.2 Key Data for Mining Strategy Evaluation

The mining strategy evaluation was integrated with the tests conducted above to define solids dislodging and fracturing. The extendible-nozzle system operates by traversing the nozzle back and forth, from left to right, or right to left while the nozzle is at a fixed extension length. To vary the elevation of the nozzle, the jet was raised or lowered in steps. The arm was raised by varying the extendible-arm angle.

The mining strategy was developed while keeping these operating preferences in mind. The number of passes required to erode a thickness of solids was also evaluated. After each cut across the simulant block was completed, the jet angle was lowered (stepped down) and another series of passes was evaluated. The objective of the tests was to evenly erode the solids without fracturing large chunks from the simulants.

6.2 Test Fixture Configuration and Data Acquisition

The pilot-scale borehole-miner demonstration was conducted in the 336 Building in the 300 Area of the Hanford Site. Tests were conducted in the 1/4-scale model of a 1-million-gallon double-shell tank. The tank was used to contain the sample and also used to capture the aerosols generated. The tank models the diameter, height, knuckle and dome space of a 75-ft-diameter, million-gallon tank. A comparison between prototype and 1/4-scale vessel dimensions is made in Table 6.1.

Table 6.1 Prototype and 1/4-Scale Vessel Dimensions

Parameter	Full-Scale	1/4-Scale
Nominal diameter	22.9 m, 75 ft	5.73 m, 18.75 ft
Knuckle radius	0.30 m, 1.0 ft	0.075 m, 0.25 ft
Capacity	3875 m^3, $1x10^6$ gal	59 m^3, 15,625 gal
Vapor space above liquid, based on 30-ft fill level	~1330 m^3, ~47,000 ft^3	~20 m^3, 730 ft^3
Maximum fluid depth	9.1 m, 30 ft	2.3 m, 7.5 ft

The dome for the 1/4-scale tank is removable, and the vessel functions with or without the dome in place. The dome has four circular entry risers and a central square entry. The dome mates with the vessel and is able to accept both positive and negative pressure surges of ±7.6 cm (±3 in.) H_2O from ambient.

Test components included a simulant box, mounted on a platform scale inside the 1/4-scale tank, the extendible nozzle, the high-pressure pump to power the nozzle, and the retrieval pump to remove liquids and solids dislodged during extendible-nozzle operation and instrumentation to measure process parameters, aerosol generation, and solids dislodging. Waterjet Technology, Inc. furnished the extendible nozzle. This extendible nozzle has a maximum working pressure of 3000 psi and extends a distance of 10 ft. The nozzle can be positioned at angles from 30 degrees from vertical to horizontal. University of Missouri at Rolla, Missouri furnished the high-pressure pump to power the extendible nozzle. An existing diaphragm pump was used to pump liquids and dislodged solids from the test tank.

6.2.1 Simulant Mold

The simulant mold is shown in Figure 6.1. The mold width (29 in.) and height (29 in.) did not vary; the mold was deeper at the base than at the top, and varied linearly between the base and the top; this variation provided the ability to cut simulants of varying thicknesses. The simulant box was placed on a platform scale to measure weight loss during the tests.

Figure 6.1 Simulant Sample Box Mounted in 1/4-Scale Tank

6.2.2 Extendible Nozzle

The extendible-nozzle configuration used for these tests is shown in Figure 6.2. The nozzle consists of a segmented extendible arm located inside a vertical mast. The arm position is hydraulically controlled to set nozzle elevation, nozzle extension and arm angular position. The arm has an extended length of 10 ft. It can be positioned at angles from 30 degrees from the vertical downward to horizontal. The mast of this extendible-nozzle configuration rotates over a 270 degree angle. The extendible-nozzle system operates at a maximum working pressure of 3000 psi. The high-pressure hose in contact with personnel is rated with a 12,000 psi burst pressure. The high-pressure hose embedded inside the extendible links is rated with an 8,000 psi burst pressure.

6.2.3 High-Pressure Pump

A Halliburton HT-400 pump, powered by a Cummins 335-hp diesel engine, was used to power the extendible nozzle. The piping system contained a calibrated safety relief valve set to release at 4500 psi and a calibrated pressure gauge. The pump was mounted on a skid located to the south of 336 Building.

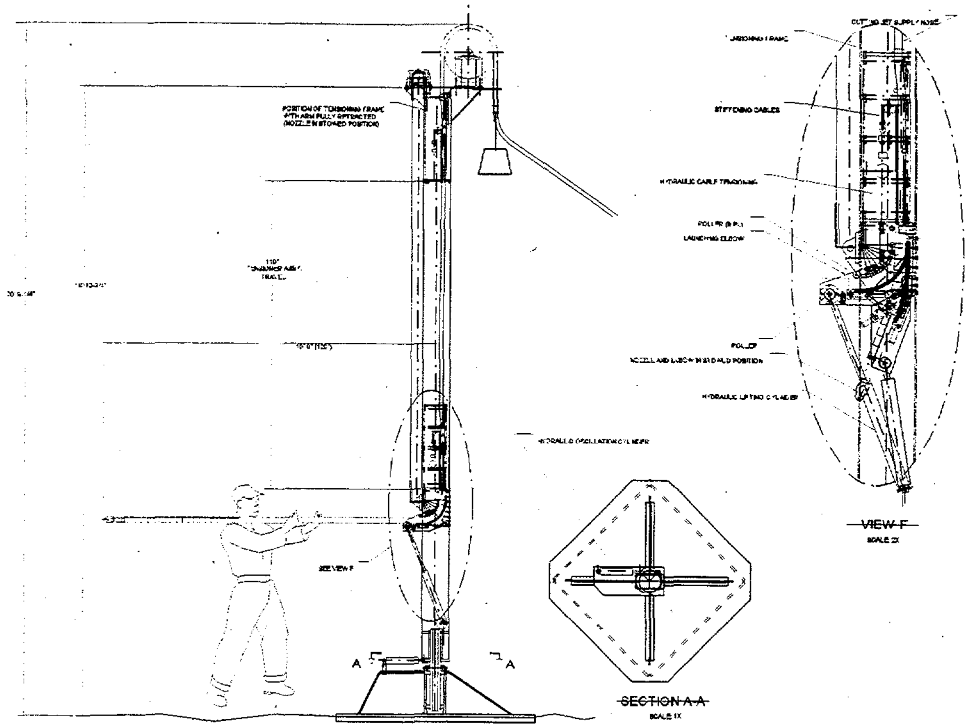


Figure 6.2 Details of the Borehole-Miner Positioning Arm

6.2.4 Hydraulic Power System

The Hydraulic Controls Inc. hydraulic power supply provided 5000-psi hydraulic pressure to the extendible-nozzle control system.

6.2.5 Water Supply

Process water was supplied via connection to fire hydrant no. 55 located at the southwest corner of 336 Building. The hydrant connection was installed by Hanford water plant services and contains a valve and backflow preventer.

6.2.6 Data and Instrumentation

Data recorded during the dislodging tests included the pressure at the pump, the weight of the solids in the sample box and the time that the jet impacted the sample. A pressure gauge was used to measure pump pressure; a stop watch was used to record traverse time, and the platform scale was used to record the weight of the sample before and after the traverse. All these data were recorded manually.

6.3 Simulant Selection

Simulants to model both sludge and saltcake wastes were evaluated. Saltcake was developed to model hard crystalline wastes present in Hanford tanks. The sludge simulants were developed to model the zeolite present in Savannah River Site Tank 19. The saltcake simulant recipes are described in Section 4. The zeolite simulant compositions are listed in Table 6.2.

Table 6.2 *Zeolite Simulant Composition*

Composition	SRS-KPS-W Weak Simulant	SRS-KPS-S Strong Simulant
20 to 50 mesh sand	59.9 wt%	62.6 wt%
Kaolin clay	20.1 wt%	14.7 wt%
Plaster of paris	0.0 wt%	6.9 wt%
Water	20.0 wt%	15.8 wt%
EPK pulverized kaolin clay supplier is Feldspar Corporation, Edgar, Florida. "Durabond Plaster of Paris" supplier is DAP, Inc. of Dayton, Ohio.		

The available characterization and waste history data for the zeolite heel in Savannah River Site Tank 19 were reviewed in an effort to develop a suitable waste simulant. Mechanisms have been identified whereby the zeolite heel strength may have significantly increased since the last waste extraction campaign in 1981. Unfortunately, the extent to which these mechanisms may have occurred cannot be determined from the available data.

Two waste simulants were recommended for sampler and retrieval system testing. The mechanical strength and waterjet resistance of these two simulants are expected to bound that of the Tank 19 solids. The simulants are numbered SRS-KPS-W and SRS-KPS-S.

6.4 Test Matrix

The test matrix for the sludge and saltcake tests is listed in Table 6.3.

Table 6.3 Test Matrix for Dislodging Tests

Simulant	Range of Pressures Tested, psi			
	Nozzle Diameter 5-ft Stand-off Distance		Nozzle Diameter 10-ft Stand-Off Distance	
	0.281	0.310	0.281	0.310
Sludge			80, 300, 500, 1000	
Saltcake no. 1	1000, 2200, 3200	1000, 1500	1000, 2200	1000, 1500
Saltcake no. 2	2200	1600, 2600	2200	1600, 2700
Saltcake no. 3	2200, 2400, 3000		2200	1600, 2100

Two nozzle diameters were selected that were sized to operate at pressures to 3000 psi, see Table 3.1. The test sequences were run as a series of cuts across the sample block. The sequence is as follows:

- Cut 1 - one pass across the sample
- Cut 2 - two passes across the sample
- Cut 3 - four passes across the sample
- Cut 4 - six passes across the sample.

Weight loss was recorded after each pass. At the completion of the four initial cuts, the sample was photographed and measured. The important features were the type of cut (erosion, dissolution, or slice) and the width and depth of the cut. Then the nozzle stand-off distance was changed to 5 ft and a second series of cuts were made in between cuts 1 through 4. Again weights were recorded. After completion of these passes, a series of long-term, jet dislodging ~5- to 10-min duration runs were completed. These tests provided long term dislodging rates and provided input on how long the jet would need to operate to dislodge the simulant bed. Examples of these steps are shown in Figures 6.3 through 6.5. Sludge dislodging is shown in Figure 6.6.

6.5 Test Results

As evidenced by the photographs, the sludge and saltcake wastes have different methods of dislodging. The sludge is deformed by the waterjet; the saltcake is eroded and dissolved by the waterjet. The dislodging rates for sludge are significantly higher than those for saltcake. The saltcake data showed dislodging rates of 0.4 lbm/s at pressures of 2200 psi decreasing to 0.2 lbm/s at pressures of 1000 psi. The sludge dislodging rates were as high as 10 lbm/s at 1000 psi decreasing to 5 lbm/s at 500 psi. Correlations to describe the dislodging rates will be developed.

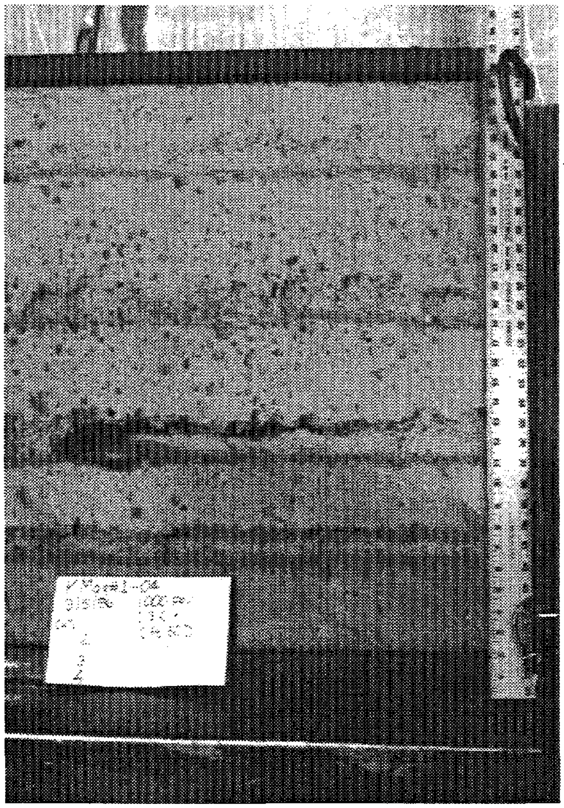


Figure 6.3 Four Cuts Across Saltcake No. 1 at 1000 psi with a 0.310-in.-Diameter Nozzle

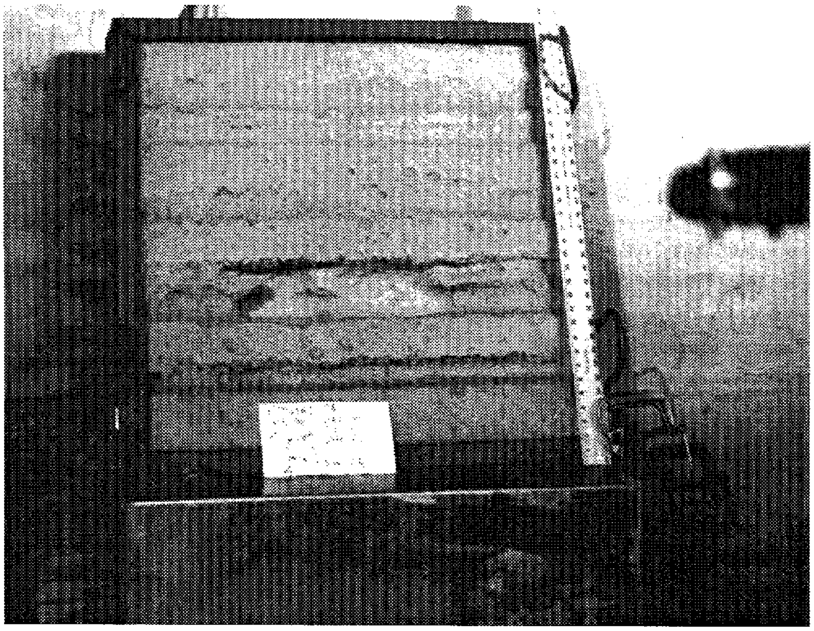


Figure 6.4 Six Cuts Across Saltcake No. 1 at 1000 psi with a 0.310-in.-Diameter Nozzle

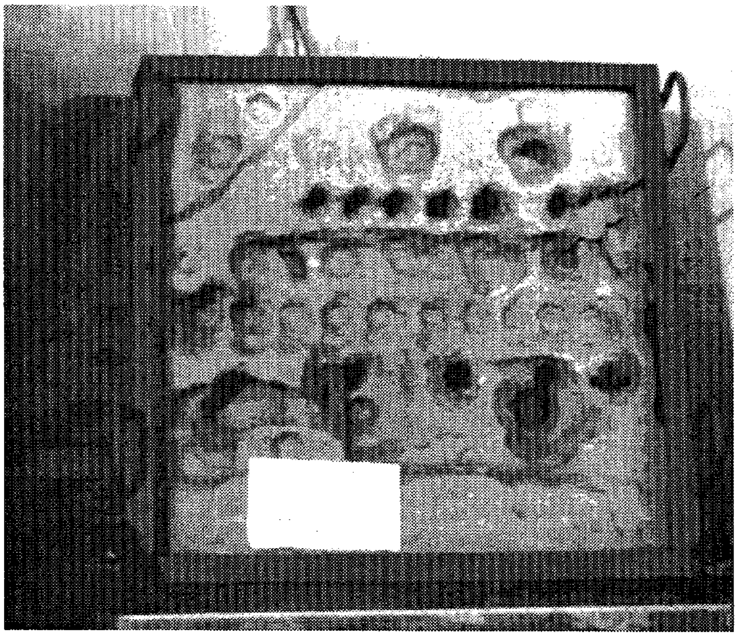


Figure 6.5 20 min of Dislodging Saltcake No. 1 at 1000 psi with a 0.281-in.-Diameter Nozzle

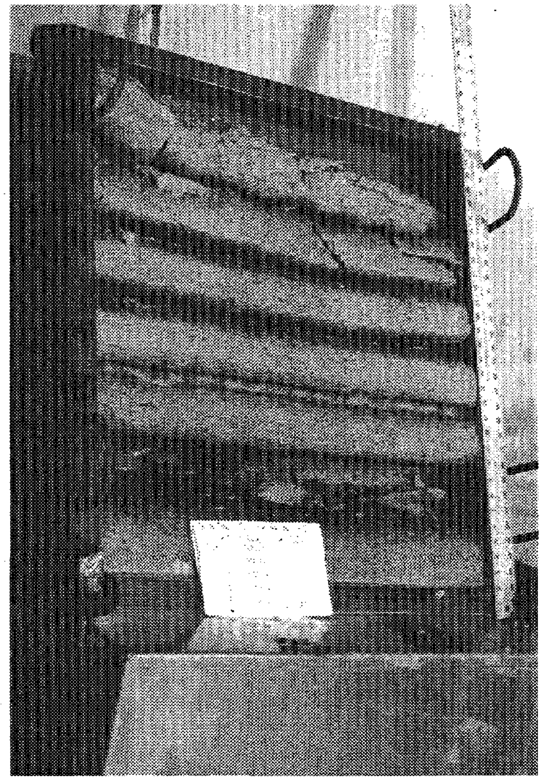


Figure 6.6 Six Cuts (from top to bottom) Across Sludge Block Rev #1 at Pressures from 50 to 3000 psi using a 0.281-in-Diameter Nozzle

7.0 Horizontal Tank Tests - Extendible-Nozzle Integrated Dislodging and Retrieval

Extendible-nozzle integrated dislodging and retrieval experiments simulating remediation of sludge and supernate from the ORNL Old Hydrofracture Facility tanks were conducted in a full-diameter half-length open-top model of a horizontal underground storage tank to evaluate operating scenarios and recommend deployment strategies for extendible-nozzle operation at ORNL. The tests were conducted outside the 336 Building in the 300 Area of the Hanford Site. These tests, the test fixture, and experimental results are described in this section.

7.1 Test Objectives

The objectives of the horizontal tank tests were 1) to evaluate large-scale dislodging capability of the borehole miner in a horizontal tank configuration to recommend operating and retrieval strategies and 2) to recommend a range of nozzle diameters for system installation at ORNL OHF. The test results supported extendible-nozzle water-jetting system deployment at the ORNL OHF tanks in FY98 and the tank remediation. The OHF tanks contain settled, solidified sludge and supernate that must be removed to remediate the tanks.

Nozzle diameter effect on performance is the most important guidance to provide ORNL because the extendible nozzle must be removed from the tank prior to manually changing the nozzle. This parameter must be selected prior to extendible-nozzle system installation. All other extendible-nozzle system parameters such as operating pressure, nozzle extension and nozzle motion can be adjusted in real-time during operation. The second most important item to recommend is the supernate use strategy. The quantity of clear, unmixed supernate available at OHF is limited. Supernate use strategy and retrieval pump operating strategy are related.

The task scope includes experiments to:

- Identify nozzle diameter and pressure ranges recommended for dislodging of the ORNL OHF sludge.

  Two nozzle diameters were evaluated at 1000 psi, a pressure 500 psi lower than the maximum operating pressure of 1500 psi. Also tank rinsing with a lower pressure 500-psi jet was evaluated to determine the ability to rinse the tank after retrieval has been completed.

- Evaluate the effect of supernate level on sludge suspension and retrieval.

  Two suspension strategies were evaluated with the extendible nozzle: 1) jet impacting exposed sludge that simulates waste with the supernate removed, prior to dislodging and 2) jet impacting sludge simulant covered with a supernate layer. In each evaluation, suspension was initiated with a water jet. After a specified amount of water addition and slurry retrieval, the jet feed was switched from water to slurry and suspension continued with the retrieved slurry.

- Evaluate the effect of retrieval strategy upon extendible-nozzle operation.

  Two retrieval scenarios were evaluated: 1) concurrent balanced operation with the nozzle flow rate matched to the retrieval pump flow rate producing no net gain of liquid in the horizontal tank and 2) unbalanced retrieval with the nozzle flow rate greater than the retrieval pump flow rate. The preferred retrieval strategy is balanced retrieval. Retrieval was conducted using a prototypic retrieval pump inlet and prototypic retrieval rates.

- Evaluate the effect of sludge shear strength and sludge composition upon slurry dislodging.

  Three types of sludge, one that models OHF sludge properties, one with a shear strength that is 5 times that expected at OHF, and one with a shear strength of 60 times that expected at OHF were tested. Dislodging was initiated with and without a simulated supernate layer.

- Categorize the fluid motion and acoustic response of the jet impacting surfaces encountered during retrieval.

  All of the tests were video recorded to capture jet and fluid motion, initial mixing, and the sound of the jet as different surfaces were impacted. Typical in-tank surfaces include tank walls, supernate, and sludge. The acoustic response is an additional method to provide real-time feed back of system performance inside the closed tank.

- Evaluate the effects of extendible-nozzle motion.

  Two types of nozzle motion were evaluated: 1) moving the nozzle from side to side by rotating the mast at a constant nozzle-extension length and 2) changing the point of jet impact by increasing or decreasing the nozzle angle with the floor (an extendible-nozzle arm generated angle).

- Recommend a mining strategy for extendible-nozzle water-jetting system deployment.

  Based on the results, of these tests, a mining strategy for OHF remediation was recommended. Parameters to be prioritized include nozzle diameter range, supernate use strategy, retrieval pump operating strategy, jet motion and jet pressure.

7.2 ORNL OHF Tank Remediation Information

The ORNL OHF tanks include five inactive liquid low-level waste tanks located at the Old Hydrofracture Facility in the Melton Valley area of Oak Ridge National Laboratory. The extendible nozzle was used to remediate these tanks by dislodging the settled sludge and mixing it with supernate. Before final tank disposition is implemented, the OHF Tanks Content Removal Project was conducted to remove the current liquid and sludge contents from each of the five tanks. The goal was to remove ≥95% of the existing sludge and supernate. This action consists of removing transuranic mixed waste from the OHF Facility underground storage tanks and transporting the waste via pipeline to the Melton Valley Storage Tank Facility. This was accomplished using the extendible-nozzle water-jetting system advanced sluicing technology coupled with a tie-in to the existing pipeline to perform the material transfer.

7.2.1 OHF Tank Configuration

Construction details and riser information[(a)] for the OHF tanks are summarized in Table 7.1 (LMERP 1996). Four of the tanks are between 42 and 44 ft in length; the fifth tank is 23.8-ft long, approximately half the length of the other tanks. The tanks range from 8 to 10.5 ft in diameter and are buried from 4.1 to 5.6 ft below grade. For tanks T1 through T4 the average distance from the central riser centerline to the end riser centerline is 16.8 ft. The average distance from the end riser centerline to the tank end is estimated to be 4.9 ft.

Table 7.1 OHF Tank Configurations

Tank	Tank Diameter, ft	Tank Length, ft	Shell Thickness, in.	Tank Lining	Riser Diameter, in.		Riser Distance from Center Line of Central Riser, ft		Distance from Riser to End of Tank ft	Central Riser Offset from Tank Center ft	Distance Below Grade ft
					North South	Center	N	S			
T1	8.0	44.1	5.46	none	27	18	17.1	14.1	6.5	3.1 (S)	4.7
T2	8.0	44.1	5.62	none	27	18	17.2	14.3	6.3	3.1 (S)	5.6
T3	10.5	42.3	2.36	rubber	27	18	17.8	17.8	3.4	0	4.1
T4	10.5	42.3	6.10	rubber	27	18	18.3	17.4	3.3	0	4.1
T9	10.0	23.8	4.55	none	27	18	7.3	7.0	4.8	0	4.4

7.2.2 OHF Waste Characteristics

The five OHF tanks contain a total of about 42,000 gal of LLLW (low level liquid waste) consisting of both liquid and sludge (about 36,000 gal of liquid radioactive and mixed waste, and approximately 6,000 gal of sludge categorized as TRU (transuranic) and mixed waste). It is reported that the five tanks contain a total of 30,000 Ci, and 97% of this total is located in the sludge. The volumes of liquid and sludge and the curie content for each tank are summarized in Table 7.2 (LMERP 1996).

(a) Distances from central riser centerline to end riser centerline was provided via personal communication from G. F. Boris, May 19, 1997.

Table 7.2 Liquid, Sludge, and Curie Quantities in the OHF Tanks

Tank	Liquid, gal	Sludge, gal	Curies, Ci
T1	7,650	800	7,400
T2	9,500	1,200	3,900
T3	1,100	2,050	10,300
T4	13,350	1,350	6,500
T9	4,650	500	1,400
Total	36,250	5,900	29,500

The waste sampling occurred in 1988, 1996, and 1997. The depth of the waste in the tanks has been summarized based on the 1997 information. This data is summarized in Table 7.3.[a] The average depth of the sludge is 10 in. based on in-tank measurements. The minimum measured sludge depth is 3 in. and the maximum measured sludge depth is 22 in.

Table 7.3 Liquid and Sludge Depths in the OHF Tanks

Tank	Tank Diameter, ft	Total Waste Depth, ft			Sludge Depth, ft			Liquid Depth, ft		
		North	South	Avg	North	South	Avg	North	South	Avg
T1	8.0	5.50	5.42	5.46	0.25	0.25	0.25	5.25	5.17	5.21
T2	8.9	5.66	5.58	5.62	0.08	0.92	0.50	5.58	4.66	5.12
T3	10.5	2.36	2.36	2.36	1.36	1.86	1.61	1.00	0.50	0.75
T4	10.5	6.10	6.10	6.10	0.85	1.27	1.06	5.25	4.83	5.04
T9	10.0	4.72	4.39	4.55	0.47	1.30	0.89	4.25	3.09	3.66

(a) Boris, G.F. 1997. Field Data Spread Sheet. Personal Communication. Lockheed Martin Energy Systems, Oak Ridge, Tennessee.

7.2.3 OHF Waste Retrieval System

The OHF waste retrieval system utilizes the extendible-nozzle water-jetting system for waste dislodging and submersible pumps for dislodged waste and supernate retrieval.

Extendible-Nozzle Water-Jetting System

The extendible-nozzle water-jetting system for deployment at ORNL OHF was designed by Waterjet Technology, Inc.[a] under subcontract to Pacific Northwest National Laboratory. The extendible-nozzle mast was inserted in the central riser of each tank. Extendible-nozzle operating details are provided in Section 8.0.

Extendible-Nozzle Sluicer Pump

The sluicer pump that provides pressurized fluid to the extendible-nozzle water-jetting system was selected to provide a maximum flow rate of 150 gpm at a pressure of 1500 psi. This permits system operation with all nozzle diameters without limiting system operation based on thrust on the nozzle.

Retrieval Pump

A submersible retrieval pump has been selected for waste retrieval. One pump was be installed in each of the end risers of each tank. The pump, model HSUL, is manufactured by Goulds Pumps, Inc.[b] The pump suction is located 2 in. above the floor. The suction line diameter is 2 in. The inlet configuration for the retrieval pump is shown in Figure 7.1.

7.2.4 OHF Waste Retrieval Strategy

The ORNL OHF waste retrieval strategy was to clean each tank sequentially. Waste supernate from the tanks was used to mobilize and mix the waste. After the tank reached the desired slurry concentration, the waste was pumped from the tank into a receiver tank, tank T9, and then pumped to the Melton Valley storage tanks.

Using retrieval pumps located in the end risers of the tank, supernate was pumped to tank T9. When the supernate levels in tank T9 and the tank from which waste was being retrieved were acceptable, the extendible-nozzle water-jetting system began operation.

(a) Waterjet Technology, Inc. 1997. *Extendible Nozzle Water-jetting System 90% Design Overview*, Waterjet Technology, Inc., Kent, Washington, April 14.

(b) Goulds Pumps, Inc., Slurry Pump Division, Ashland, Pennsylvania.

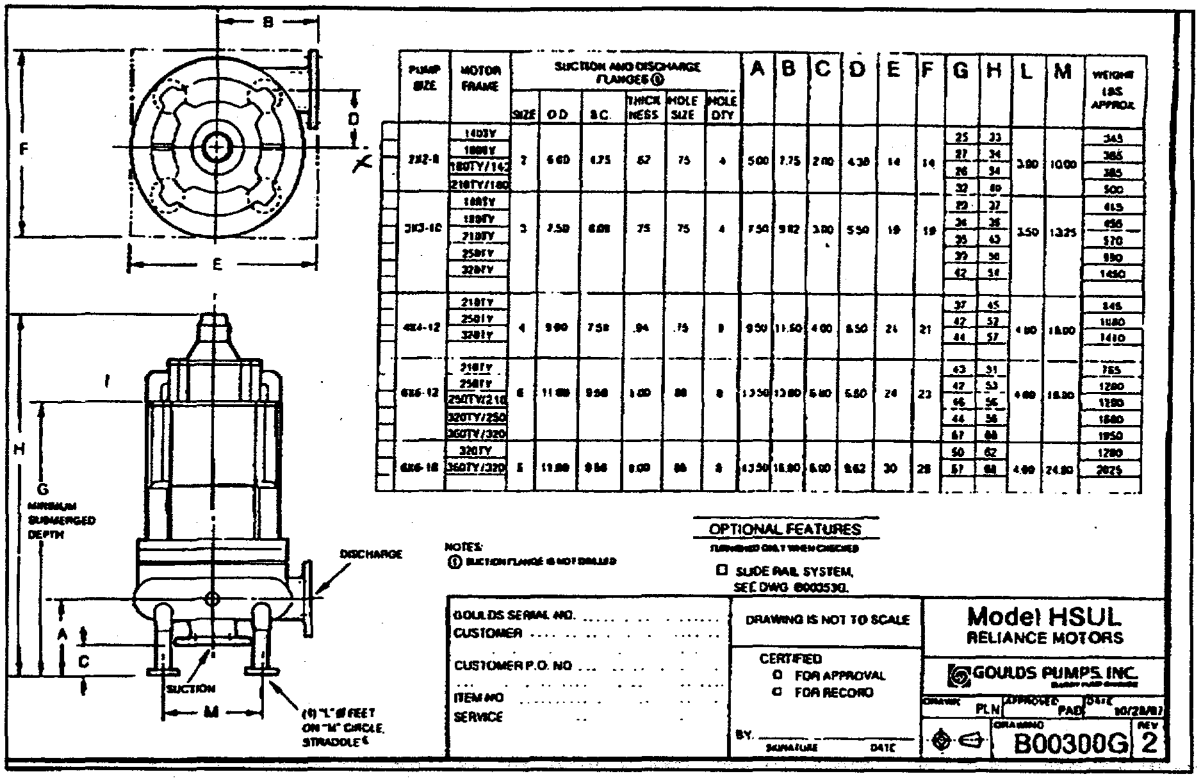


Figure 7.1 Retrieval Pump Inlet Configuration

Tank T3 was selected to be sluiced first because it contained the highest solids-to-liquid ratio. Supernate from other tanks must be used to provide the target of 10 wt% solids.[(a)] Once the correct ratio of supernate and solids in T3 is sufficient for mixing and transfer, sluicing operations will be initiated and completed. Sluicing operations are defined as sluicing through the extendible nozzle, slurry retrieval from T3 to T9, recycling through T3 as necessary for mixing and sluicing, and transfer from T9 to the Melton Valley storage tanks (MVST). The process of sluicing and recycling through T3 and T9 also mixes the existing contents of T9. When the operation is complete, both T3 and T9 will be essentially empty.

Tanks T1, T2, and T4 each contain surplus supernate; therefore, the order of sluicing in these tanks is not critical. Surplus supernate may be temporarily stored in one of these tanks or in the cleaned T3 tank for later use. If T9 has not been sufficiently cleaned by the mixer, the mixer will be removed from the tank and T9 sluiced. The surplus supernate will be used for sluicing T9. Once each of the tanks has been cleaned, the remaining supernate will be transferred to MVST.

The amount of supernate in the tank to be sluiced at sluicing initiation has not yet been established.

(a) CDM Federal Programs Corporation. 1997. *Oak Ridge National Laboratory Old Hydrofracture Facility Tanks Contents Removal Project 100% Configuration, Volume 1.* CDM Federal Programs Corporation, Oak Ridge, Tennessee. May 20.

7.3 Extendible-Nozzle Horizontal-Tank Test Fixture Configuration and Data Acquisition

Test equipment includes the extendible-nozzle system, the horizontal tank test fixture, the retrieval system, the 336 Building piping system and ancillary tanks, and instrumentation.

7.3.1 Extendible-Nozzle Dislodging System

Extendible-nozzle dislodging system components include the extendible nozzle, the high-pressure pump to power the nozzle, and the hydraulic power unit and controller to control the arm position and motion. A standard operating procedure[(a)] was developed to govern operation of the extendible-nozzle system.

Extendible-Nozzle Prototype

Waterjet Technology, Inc. furnished the extendible nozzle used in the tests. The free-standing extendible-nozzle prototype configuration is shown in Figure 7.2. The nozzle consists of a segmented extendible arm located inside a vertical mast. The arm position is hydraulically controlled to set nozzle elevation, nozzle extension, arm angular position, and the tension in the cables positioning the arm. The arm has an extended length of 10 ft. It can be positioned at angles from 30 degrees from the vertical downward to horizontal. The mast rotates over a 270 degree angle.

The extendible-nozzle system operates at a maximum working pressure of 3000 psi. The high-pressure hose in contact with personnel is rated with a 12,000 psi burst pressure. The high-pressure hose embedded inside the extendible links is rated with an 8,000 psi burst pressure. The extendible-nozzle hardware was installed using the building's 5-ton overhead crane.

High-Pressure Pump

University of Missouri at Rolla, Missouri furnished the high-pressure pump, a Haliburton HT-400 pump shown in Figure 7.3, powered by a Cummins 335-hp diesel engine, to power the extendible nozzle. The pump piping system contains a calibrated safety relief valve set to release at 4500 psi and a calibrated pressure gauge. The pump was mounted on a skid located to the south of the 336 Building.

Hydraulic Power Supply

The Hydraulic Controls Inc. hydraulic power supply, shown in Figure 7.4, supplied 5000 psi hydraulic pressure to the extendible-nozzle control system.

(a) Bamberger, J. A. 1996. *Standard Operating Procedure Extendible Nozzle Demonstration*, Rev. 1, August 9, 1996.

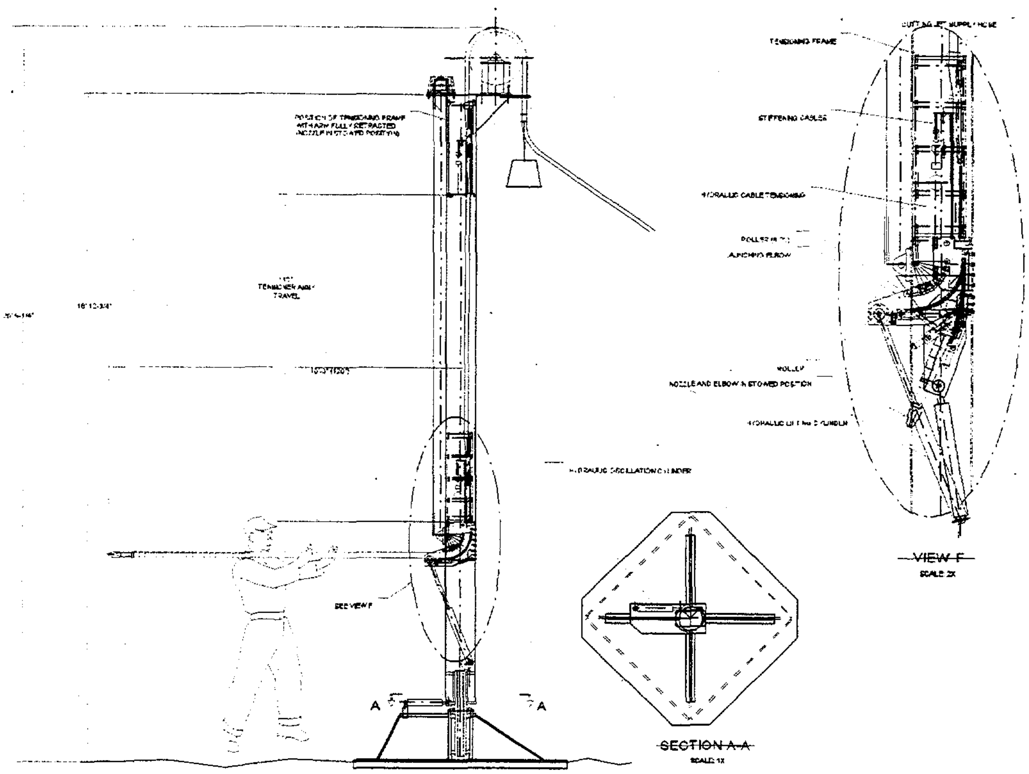


Figure 7.2 Details of Extendible-Nozzle Prototype Floor-Mounted Test Stand

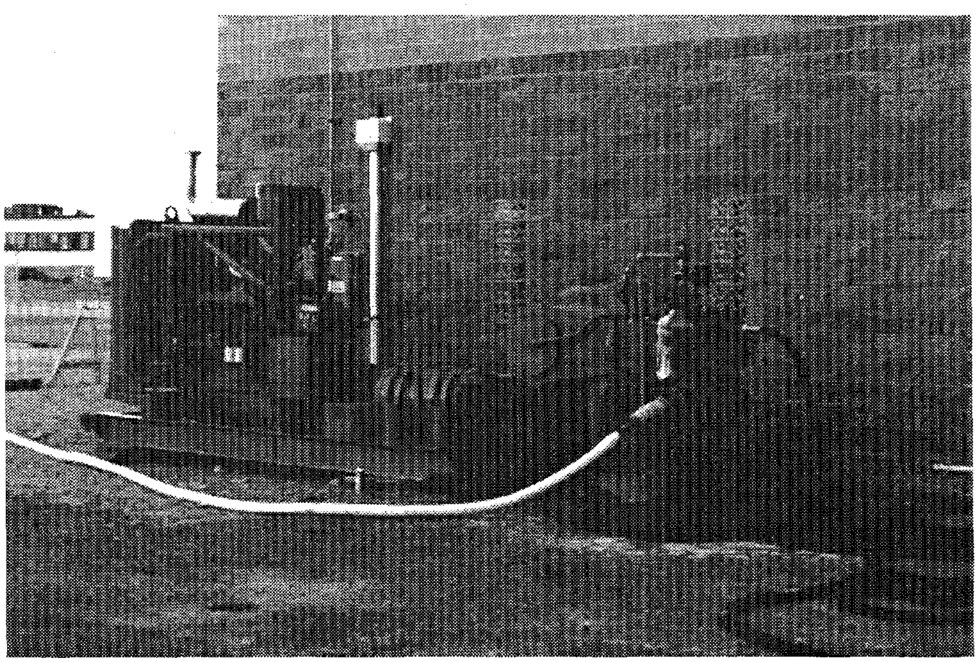


Figure 7.3 Halliburton HT-400 Pump

Figure 7.4 Hydraulic Power Supply

Water Supply

Process water was supplied via connection to fire hydrant no. 55 located at the southwest corner of 336 building, shown in Figure 7.5. The hydrant connection was installed by Hanford water plant services and contains a valve and back flow preventer.

7.3.2 Horizontal Tank Test Fixture

The horizontal tank test fixture is shown in Figure 7.6. The open-top tank has a curved bottom with a 4 ft radius. The sides extend up 4 ft above the tank centerline, to a height of 8 ft. The tank is 22-ft long with flat ends. The end closest to the extendible nozzle is cut out to permit insertion of the extendible nozzle; this end is 32-in. high and permits the extendible nozzle to enter the tank at an angle as low as 30 degrees from the vertical. The far end has an opening for insertion of retrieval pump piping.

The 8-ft diameter, 22-ft long horizontal tank models the diameter and half the length of four of the ORNL OHF tanks. These tanks range in diameter from 8 to 10.5 ft and in length from 42.3 to 44.1 ft. The horizontal tank provides a nearly full-scale model of tank T9, that is 10 ft in diameter and 23.8 ft in length.

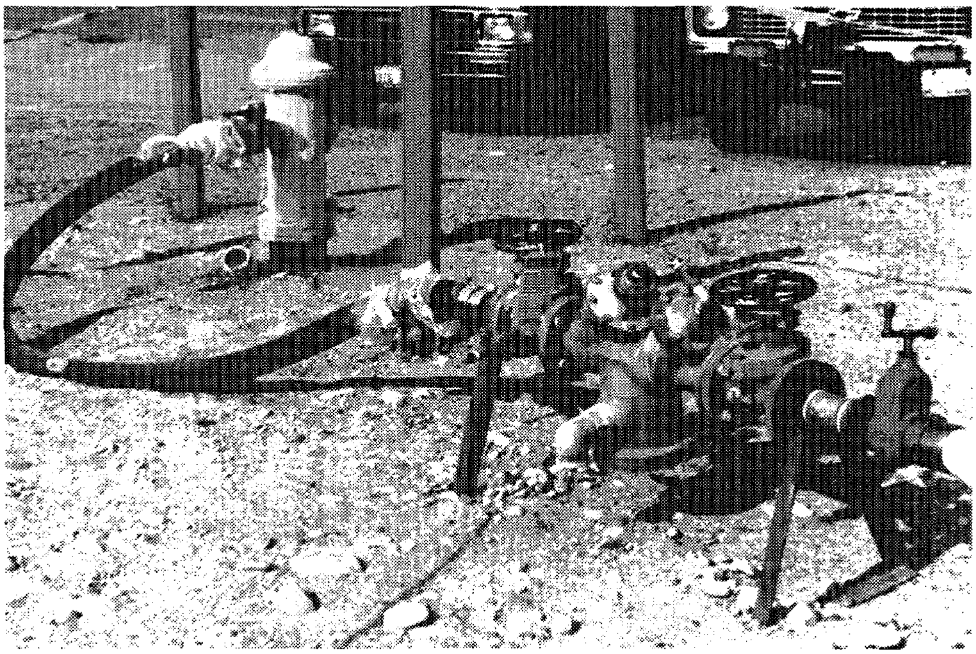


Figure 7.5 Low-Pressure Water Fire-Hydrant Connection

7.3.3 Piping System and Ancillary Tanks

The process flow diagram for the extendible-nozzle tests is shown in Figure 7.7. Two flow paths were employed during the tests: using process water through the extendible nozzle or using slurry. Both paths are indicated on the diagram. A diaphragm pump, shown in Figure 7.8 was used to pump liquids and dislodged solids from the test tank.

The 1/4-scale tank test fixture components are shown in Figure 7.9. The test fixture includes the 1/4-scale model of a Hanford double-shell tank with dome, a supernate holding tank and a slurry holding tank. Slurry retrieved from the horizontal tank was stored in the supernate tank. This tank was used as the supply tank for tests that used slurry as the working fluid. Slurry was supplied from the bottom of the tank. During the majority of tests slurry was pumped into the top of the tank. The supernate holding tank is 10.8 ft in diameter with a capacity of 12,000 gal. It is constructed with a rounded bottom to facilitate supernatant transfer. Estimating the volume of the tank as a right circular cylinder, at 1 ft of depth the tank holds 92 ft^3 or ~690 gal. A depth of 3 ft would hold ~2068 gal.

7.3.4 Instrumentation

Instrumentation is required to measure the slurry properties, and monitor the extendible-nozzle and retrieval pump operating parameters. The selected sensors and their accuracies are summarized in Table 7.4. A functional diagram of the instrumentation system is shown in Figure 7.10.

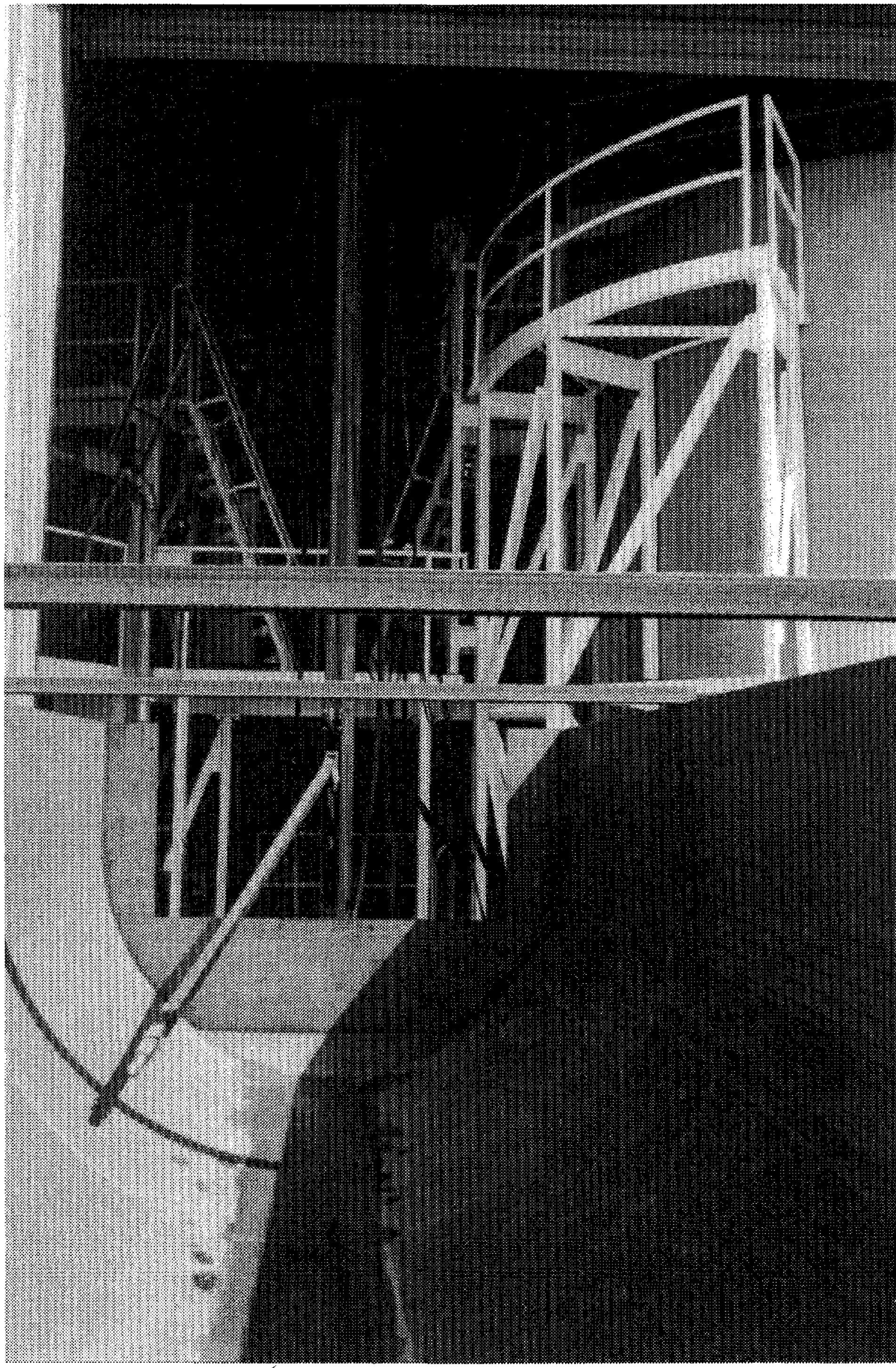


Figure 7.6 Horizontal Tank Configuration (looking north toward extendible-nozzle arm)

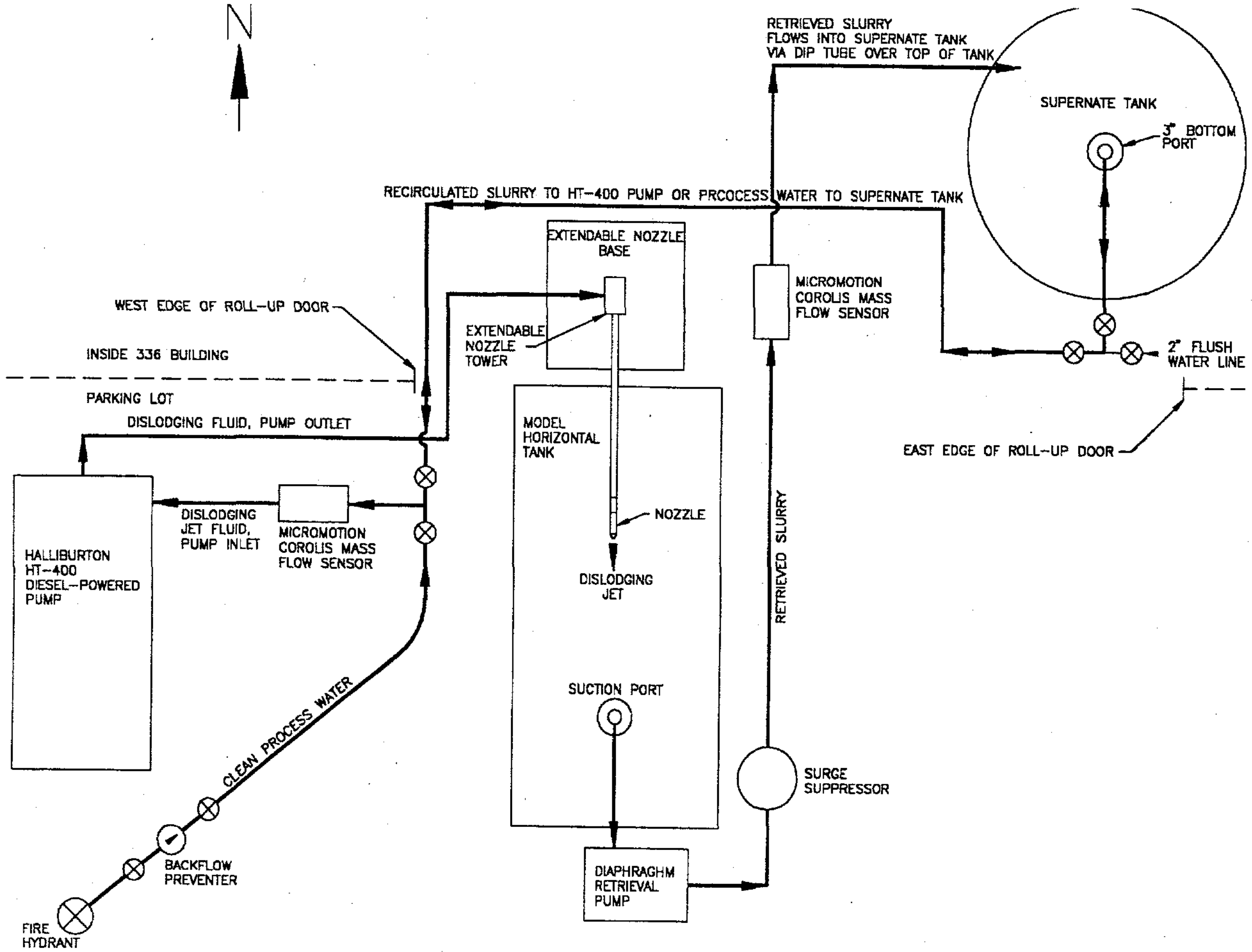


Figure 7.7 Process-Flow and Instrumentation Diagram

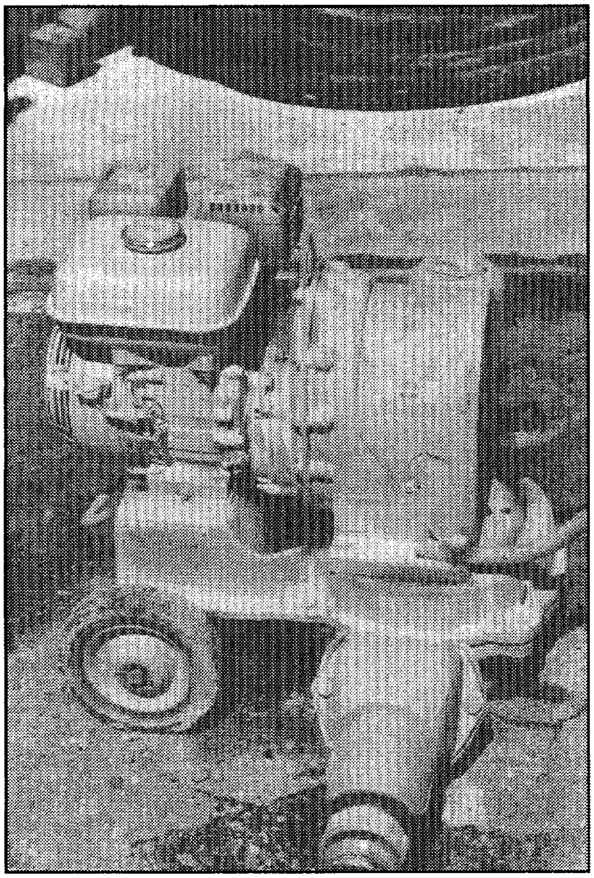


Figure 7.8 Retrieval Pump

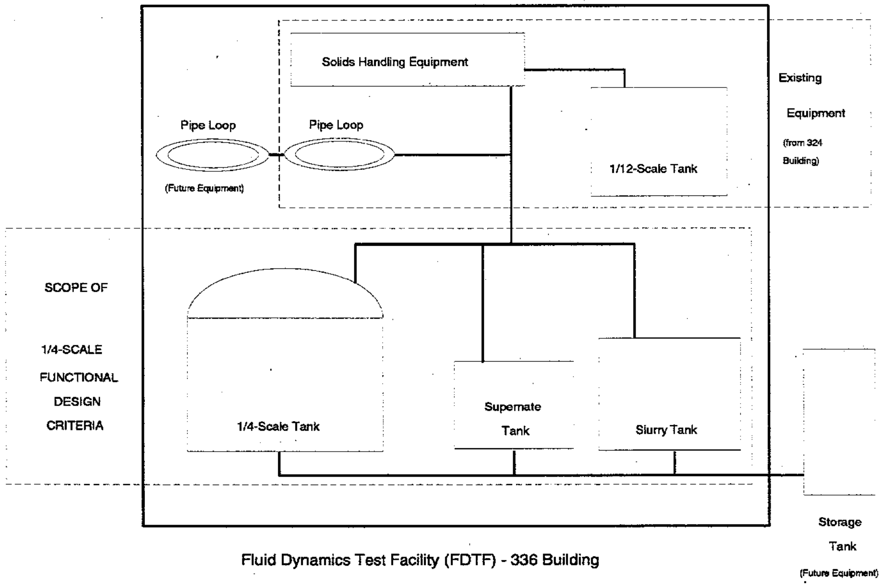


Figure 7.9 1/4-Scale Tank Test Fixture Components

Table 7.4 Instrumentation Summary

Sensed Parameter	Sensor/Signal Conditioning	Range ± Uncertainty	Notes
Elapsed time	Computer internal clock	1 s ± 0.01 s	Data acquisition system time 1 s counter
Fluid pressure at pump	Pressure gauge	0 to 5000 psi ± 100 psi	Used to gauge pump operating condition and magnitude for high-pressure line
Fluid pressure at waterjet nozzle	Sensotronics TJE/B678-01-01 Pressure transmitter s/n 574190	± 0.1% full scale	Used to calculate flow rate and indicate fluid pressure at nozzle
Fluid temperature at waterjet nozzle	Type J thermocouple	± 2.2 C	Used to calculate density of water at the nozzle
Sluicer pump slurry flow rate	MicroMotion coriolis flow sensor DS300S155SU s/n 162935 MicroMotion coriolis flow transmitter RFT 9739E1SU s/n 1511637	± 0.2% actual	Used to quantify the slurry-based dislodging feed to the extendible nozzle
Sluicer pump slurry density	MicroMotion coriolis flow sensor DS300S155SU s/n 162935 MicroMotion coriolis flow transmitter RFT 9739E1SU s/n 1511637	± 0.2% actual	Used to measure density of fluid flowing through nozzle
Retrieval pump slurry flow rate	MicroMotion coriolis flow sensor DS300S155SU s/n 162935 MicroMotion coriolis flow transmitter RFT 9739E1SU s/n 1511637	± 0.2% actual	Used to quantify the slurry-based dislodging feed to the extendible nozzle
Retrieval pump slurry density	MicroMotion coriolis flow sensor DS300S155SU s/n 162935 MicroMotion coriolis flow transmitter RFT 9739E1SU s/n 1511637	± 0.2% actual	Used to measure density of fluid in retrieval line
Supernate tank weight	BLH Z-Blok load cells s/n 31713, 31719, 31721; BLH J-Box 306 assembly s/n 469357; BLH LCp-100 weight processor s/n 6461392	± 0.3%	Used to measure the weight of the contents of the supernate tank

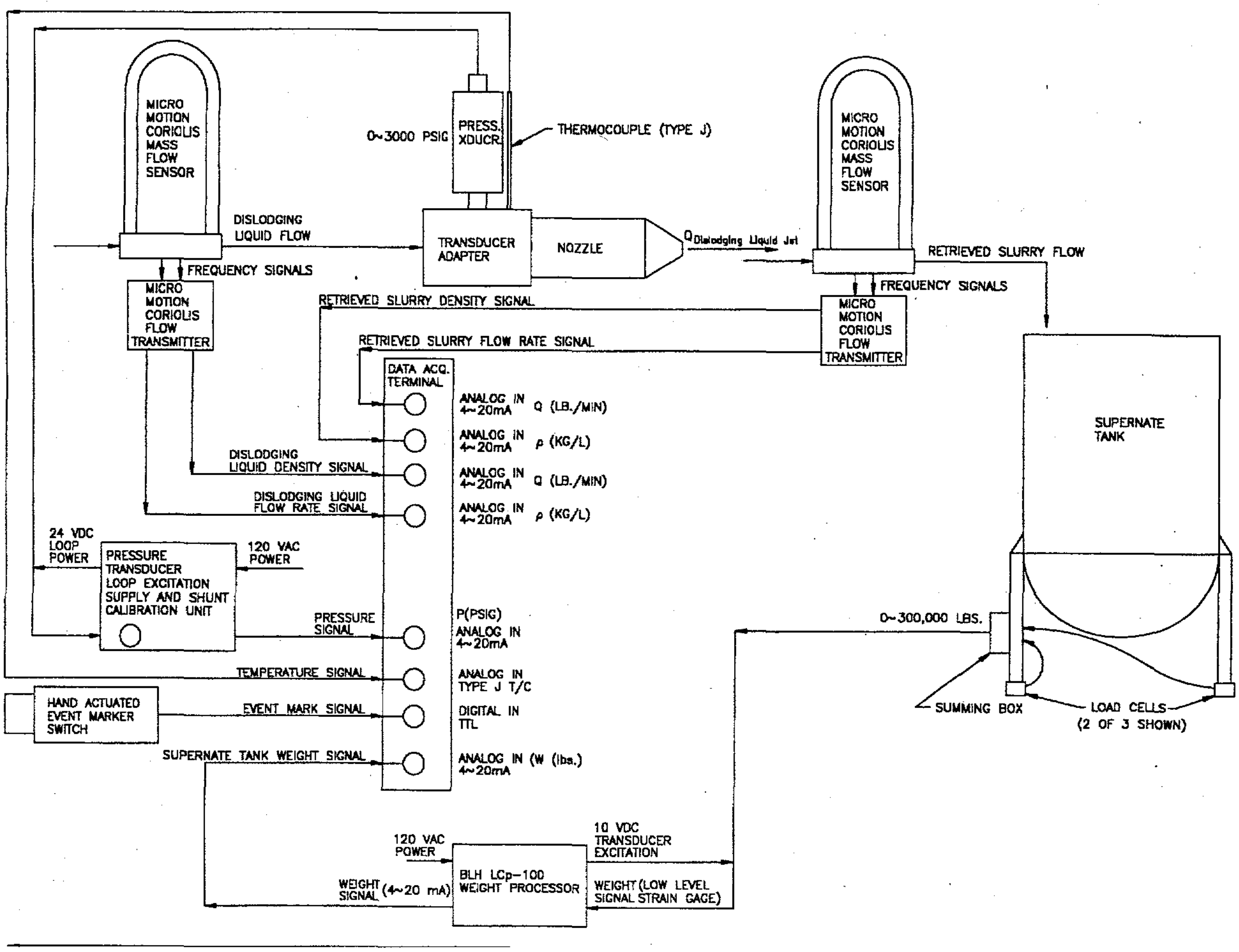


Figure 7.10 Instrumentation Block Diagram

The data acquisition system used a Gateway[a] 486-DX2-66E PC with a Strawberry Tree ACPC-12-16 analog input card and a T-21 terminal panel. Strawberry Tree[b] Work Bench PC DOS^R, version 2.4.0 is the data acquisition software used. The instrumentation specified in Table 7.4 is connected to the data acquisition system. All of the measurements made during these tests were recorded by the data acquisition system.

All input signals were sampled at 10 Hz. Generally these input's data were averaged for 1 s. As necessary, some data were averaged over a longer time period to provide a steadier reading. The Sensotec[c] pressure transducer, the MicroMotion[d] flow and density transducer, and the load cell 4 to 20 mA signals were recorded. Data acquisition system software was used to convert the signals from current to engineering units. The type J thermocouple signal was processed by the data acquisition system hardware and software to provide the temperature in degrees C. The MicroMotion density sensor provided density of the extendible-nozzle and retrieval pump flow streams. In addition, the water density was calculated using the temperature and a curve fit of the CRC Handbook of Chemistry and Physics' data of water density versus temperature.[e]

Digital meters for the time-averaged pressure, temperature, weight, density, and mass flow rate were displayed on the personal computer monitor. The time history of the averaged flow rate, weight, and pressure were displayed on the monitor in scrolling strip chart fashion. Data was recorded in the units provided by the instrumentation. The accuracy and precision for the data is summarized in Tables 7.4 and 7.5, respectively. The specified accuracies include the uncertainties of the data acquisition system. All of the specified accuracies are well within the range of standard, conventional instrumentation that was utilized for this task.

The extendible-nozzle operation during the horizontal tank tests were recorded on video. These records provided a real-time audio and visual record of the extendible-nozzle operation and motion of the fluid and slurry in the horizontal tank. The recording was initiated before water flow was started to provide a time stamp to correlate with the recorded data. Two cameras, one located behind the extendible nozzle and the other located above the horizontal tank on the supernate tank walkway, provided an overview of the entire horizontal tank and nozzle.

(a) Gateway 2000 Inc., North Sioux City, South Dakota.

(b) Strawberry Tree, Inc., Sunnyvale, California.

(c) Sensotec, Inc., Columbus, Ohio.

(d) MicroMotion, Inc., Boulder, Colorado.

(e) ρ (kg/l) = $0.9998707 + 0.0000636\,T - 0.00000825\,T^2 + 0.000000049\,T^3$. T is in degrees C.

7.4 ORNL OHF Sludge Simulants

The available tank characterization and waste history data for the sludge in the ORNL OHF tanks were reviewed to develop a suitable waste simulant. Relatively little physical property characterization data are available for undisturbed OHF sludge.[a] It is possible, however, to estimate some physical properties based on the videos taken during the extrusion of sludge samples in the glovebox at ORNL.[b]

Table 7.5 Measurement Precision

Parameter	Precision	Units	Source
time	XXX.XX	s	acquired
jet pressure	X.XXX	mA	acquired
jet pressure	XXXX.X	psig	calculated
jet fluid temperature	XX.X	C	acquired
jet and retrieval flow rates	X.XXX	mA	acquired
jet and retrieval flow rates	XXX.X	lbm/min	calculated
jet and retrieval specific gravity	X.XXX	mA	acquired
jet and retrieval density	X.XXXX	g/cm^3	calculated
supernate tank weight	X.XXX	mA	acquired
supernate tank weight	XXXXX	lbm	calculated
total jet liquid	XXXX.X	lbm	calculated
total retrieved slurry	XXXX.X	lbm	calculated

The sludge samples were extruded vertically out of the sampling tube into a beaker. Segments reached between 5 and 10 cm in length before breaking free and falling into the beaker. Previous testing with a variety of sludge simulants (Powell et al. 1995) showed that the tensile strength of such samples are in the range of 3 to 5 kPa. Further, the vane shear strength is roughly linear with tensile strength for the sludge simulants tested. The previous test data imply that the OHF sludge shear strengths are between 1 and 3 kPa. The sludge simulant shear strength has been previously found to correlate with the waterjet pressure required to induce mobilization (Powell 1996).

(a) Video. 1996. OHF Tank Interior Inspection: T4 - January 10, T3 - January 18, and T3 - January 18. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

(b) Video. T1 S1/S2 Sludge and T2 S1/S2 Sludge, 3047 Hot Cell. March 7. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Another property of the OHF sludge noted from the glovebox handling of the samples was the sensitivity of the sludge to disruption. As the sludge was extruded from the sampler, it appeared to have a consistency similar to that of peanut butter. The extruded sample was mixed without dilution using a stirring rod for a short time and a milkshake-like slurry formed.

7.4.1 OHF Simulants

From this data four simulants were developed for the extendible-nozzle tests in the horizontal tank: 1) OHF-SS an OHF simulant with a representative shear strength, 2) OHF-HS a commercial pottery clay simulant with a shear strength five times that of OHF-SS, 3) kaolin/plaster/sand an OHF type simulant with large particles, and 4) hard pan a simulant with a shear strength 150 times that of the OHF simulant. The recipes and physical properties of these simulants are listed in Table 7.6.

Table 7.6 OHF Sludge Simulants

Composition	OHF-SS	OHF-HS	Kaolin/Plaster/ Sand	Hard Pan
	representative simulant	strong simulant	large particles	very strong simulant
kaolin clay, wt%	50		34.1	22.5
plaster of paris, wt%	13		16.0	40.0
pottery clay, wt%		77.55		
coarse sand, medium grade, wt%			3.8	
fine sand, wt%			12.9	
water, wt%	37	22.45	33.2	37.5
Sludge Properties				
Bulk density, g/cm^3	1.65 ± 0.05	1.95 ± 0.05 1.93 ± 0.05 calculated from wt% solids	1.68 ± 0.04	1.65 ± 0.05
Vane shear strength, kPa	2.5 ± 0.5	12 ± 1	5.5 ± 0.8	150 ± 30

The estimated shear and tensile strengths as well as the tendency of the OHF sludge to become more fluid upon mixing were used to formulate a non-hazardous waste simulant for testing that is expected to be representative of the OHF sludge. This simulant, OHF-SS, is composed of kaolin clay, plaster of paris, and water. A second sludge simulant was also tested. This simulant, labeled OHF-HS, is a commercial pottery clay, which is roughly five times stronger than the OHF-SS simulant. The strength of this simulant is high enough that it is very likely to exceed that of any of the OHF sludge. In this sense, the OHF-HS simulant can be considered to bound the OHF sludge strength.

Two additional simulants were also selected. Kaolin/Plaster/Sand simulant was selected to model retrieval of larger particulate. This simulant included coarse and fine sand. The size distributions for this sand are shown in Table 7.7.

Table 7.7 Size Distribution for Sand

Solids Type		Fine Sand Test 1		Fine Sand Test 2		Medium Sand Test 1		Medium Sand Test 2	
Sieving time, min		10		10		10		10	
Quantity, g		167.62		178.32		159.10		181.78	
Sieve Size									
USA Sieve Number	Opening mm	Mass Retained g	Percent Passing	Mass Retained g	Percent Passing	Mass Retained g	Percent Passing	Mass Retained g	Percent Passing
4	4.75	0.48	99.7	1.77	99.0	0	100	0	100
8	2.36	2.19	98.4	2.3	97.7	0	100	0	100
18	1.00	6.67	94.4	7.59	93.5	149.59	5.9	172.58	5.0
30	0.60	55.69	61.2	71.71	53.2	3.01	4.0	3.63	3.0
50	0.30	89.65	7.7	84	6.1	4.52	1.2	4.14	0.7
100	0.15	8.59	2.5	7.65	1.8	0.88	0.6	0.51	0.5
Pan		4.26	0	3.24	0	1.03		0.84	
Total weight of sample, g		167.53		178.26		159.03		181.7	

7.4.2 Suppliers

The simulants were obtained from the following sources:

- EPK Pulverized Kaolin Clay, Feldspar Corporation, Edgar, Florida.
  Sold in 50-lb bags.

- Plaster of paris, DAP, Inc., Dayton, Ohio. Trade name "Durabond Plaster of Paris - slow set."
  Sold in 25-lb bags.

- EM210 white clay blocks, Ceramic Creations, Richland, Washington. The pottery clay is a mixture of kaolin and ball clays. Solid in 25-lb blocks.

7.4.3 Preparation

To prepare the OHF-SS sludge simulant, the ingredients must be mixed in the proper order.

- The water and kaolin clay must first be mixed until a uniform slurry is formed.
- Then the plaster is added while mixing. Care should be taken to minimize the mixing time applied to the simulant after the plaster has been added. The resulting mixture has a consistency similar to that of a milkshake.
- Once the plaster has been added and the mixture appears uniform, the slurry is poured into the tank and allowed to cure.
- The simulant should be covered while it cures to minimize water loss. Previous testing of plaster-containing waste simulants indicates that the plaster is fully-cured within 24 hours after simulant preparation. Further, the curing reaction proceeds rapidly after 20 to 30 minutes from the time the plaster is mixed with water.
- It is highly recommended that the simulant be prepared and placed within its curing container in 15 minutes or less.
- It is permissible to prepare large quantities of this simulant by mixing up several smaller quantities and packing them together.

These simulants are characterized primarily by their vane shear strengths. A hand-held shear vane (model CL-612 from ELE International[a]) rotated at roughly 0.3 rpm is used to quantify the shear strength of the fully cured simulants. Simulant density is determined using a pycnometer, and wt% solids is determined by measuring the weight loss on drying at 200 degrees C for a minimum of 2 hours.

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a) ELE International, Lake Bluff, Illinois.

7.5 Horizontal-Tank Experiment Design

This section describes the rationale and method used to select the parameters and their ranges to be investigated during the horizontal-tank experiments. The experiments consist of a sequence of operations to dislodge the waste simulant and retrieve it from the horizontal tank. Each of the experiments was conducted as a series of test phases. The test phases and their purposes and data obtained during the phases are described.

7.5.1 Experiment Design

The task scope, described in Section 7.1, consists of six items:

- Identify nozzle diameter and pressure ranges for dislodging the ORNL OHF sludge.
- Evaluate the effect of supernate level on sludge suspension and retrieval.
- Evaluate the effect of retrieval strategy upon extendible-nozzle operation.
- Evaluate the effect of sludge shear strength upon slurry dislodging and categorize the fluid motion and acoustic response of the jet impacting surfaces encountered during retrieval.
- Evaluate the effects of extendible-nozzle motion.

Based on the results of these evaluations, a dislodging/retrieval strategy for extendible-nozzle water-jetting system deployment will be recommended.

Test parameters that support this scope are summarized in Table 7.8. Each of the parameters, their range of operation and their priority are discussed. Key test parameters are listed in Table 7.8 in order of priority. Upper and lower bounds for each parameter are listed; the basis for selection is described below.

Nozzle Diameter

The extendible-nozzle system includes five nozzle diameters: 0.281, 0.310, 0.344, 0.375, and 0.406 in. For a given pressure, flow rate increases about 20% when nozzle diameter is increased by one size. The 0.310-in.-diameter nozzle was selected as the condition for initial dislodging tests. This size nozzle provides a moderate flow rate with the ability to conserve supernate while dislodging solids. The initial plan was to switch to the 0.375-in.-diameter nozzle, which provided a 47% increase in flow rate at 1000 psi from the 0.310-in.-diameter nozzle. However, during initial tests the 0.310-in.-diameter nozzle was able to successfully dislodge both exposed and submerged simulants OHF-SS and OHF-HS; therefore, the 0.281-in.-diameter nozzle was selected as the second nozzle diameter for evaluation. This selection was based on the excellent performance of the 0.310-in.-diameter nozzle because it provided an 18% decrease in flow rate at 1000 psi from the 0.310-in.-diameter nozzle. The 0.281-in.-diameter nozzle is the smallest extendible-nozzle diameter available from the current selection.

Table 7.8 Test Parameters and Range

Parameter	Planned Range			Tested Range		
	Initial Condition	Intermediate Condition	Final Condition	Lower Bound	Intermediate Condition	Upper Bound
Nozzle diameter	0.310 in.	0.375 in.	none or TBD	0.281 in.	none selected	0.310
Nozzle pressure	1000 psi	500 psi	1500 or maximum operating pressure	500 psi	none selected	1000
Sludge type	OHF-SS $\rho = 1.65$ g/cm^3 $\tau = 2.5$ kPa	none	OHF-HS $\rho = 1.95$ g/cm^3 $\tau = 12$ kPa	OHF-SS $\rho = 1.65$ g/cm^3 $\tau = 2.5$ kPa	OHF-HS $\rho = 1.95$ g/cm^3 $\tau = 12$ kPa	Hard pan $\rho = 1.65$ g/cm^3 $\tau = 150$ kPa
Supernate level	0 in.	6 in.	TBD or 12 in.	0 in.	12 in.	18 in.
Retrieval strategy	concurrent	none	sequential	unbalanced $Q_{jet} > Q_{retrieval}$	none	balanced $Q_{jet} \sim= Q_{retrieval}$
Jet fluid	water	slurry	water rinse	water	slurry	water rinse
Nozzle motion	mast rotation, oscillation	nozzle oscillation about the vertical	extension	mast rotation, oscillation, extension		nozzle oscillation about the vertical, extension
Retrieval pump inlet location	5 ft from the end of the tank, opposed from the nozzle	none	1 ft from the tank end near the extendible-nozzle base	5 ft from the end of the tank, opposed from the nozzle; simulates multiple-riser deployment	none	at the tank end near the extendible-nozzle base; simulates single-riser deployment

Jet Pressure

The extendible-nozzle system is designed to operate at pressures up to 3000 psi. However, ORNL chose to limit operation to pressures up to 1500 psi based on the pump selected to power this system. 1000 psi was selected as the initial test pressure. This pressure provides an intermediate operating pressure that was estimated to be adequate to dislodge the ORNL sludge simulant. This was confirmed during initial tests; the 0.310-in.-diameter nozzle was able to successfully dislodge both exposed and submerged simulants OHF-SS and OHF-HS. The initial plan was to switch to 1500 psi, which provided a 22% increase in flow rate and a 50% increase in pressure for the 0.310-in.-diameter nozzle. However, the pressure of 1000 psi was adequate to dislodge both exposed and submerged simulants so no tests were completed at 1500 psi.

An operating pressure of 500 psi was selected for use during the rinse portion of the test. This lower pressure was selected to limit supernate or water use during tank rinse after completion of sluicing operations.

Simulant Selection and Bed Configuration

OHF-SS (sludge simulant) was specially developed to model OHF sludge waste properties. OHF-HS (hard sludge simulant) was selected to provide an upper bound of sludge waste properties during the horizontal-tank extendible-nozzle performance evaluation. Based on excellent dislodging of these two simulants, two additional simulants, kaolin/plaster/sand and hard pan, were tested. Their properties are listed in Table 7.6. The kaolin/plaster/sand simulant was developed to include large diameter particles to evaluate the ability of the retrieval pump configuration to transfer large particles out of the horizontal-tank. The hard pan simulant was tested to determine whether this simulant, with a shear strength 60 times greater than that of the OHF-SS simulant, represented an upper limit for system performance.

The simulant layer thickness was selected as 0.5 ft. This depth was selected based on several factors: 1) the sludge depth in the ORNL OHF tanks and 2) the amount of simulant needed to provide a representative bed. In the ORNL OHF tanks, the minimum sludge depth is 0.25 ft; the maximum depth is 1.61 ft; the average depth excluding the maximum depth sample is 0.68 ft. The test condition of 0.5 ft is slightly less than this average depth; however, based on the simulant consistency, it was deemed acceptable for testing.

Two simulant bed lengths, 5 and 10 ft, were tested. The beds were formed at the far end of the tank away from the nozzle. This location with greater stand-off-distance was expected to be more challenging to dislodge than simulant located beneath the nozzle. A full-length simulant bed was not tested to reduce the test time, simulant cost, and disposal cost and to permit evaluation of more configurations.

Supernate Level

OHF tanks contain 36,000 gal of supernate. This supernate must be used to dislodge and retrieve sludge from the five tanks. The supernate, or process water, may also be used at the completion of sludge retrieval to rinse the tank. ORNL can select the amount of supernate used to cover the waste prior to dislodging. To provide guidance, two suspension strategies were evaluated with the extendible nozzle: 1) jet impacting exposed sludge, that simulates waste that has been "pumped dry" prior to dislodging, and 2) jet impacting sludge covered with liquid. The sludge simulant beds were 6-in. deep; exposed tests were conducted with no liquid layer; submerged tests were conducted with total supernate fluid depth of 12 in. and 18 in., resulting in 6 and 12 in. of supernate fluid covering the sludge bed, respectively.

Retrieval Strategy

Two retrieval scenarios were planned: 1) concurrent retrieval (with no net gain of liquid in the horizontal-tank) and 2) sequential retrieval with retrieval commencing after a predetermined amount of liquid had been added to the tank. These scenarios were modified to 1) a balanced retrieval rate with the jet flow rate into the tank equaling the retrieved flow out of the tank and 2) an unbalanced retrieval rate with the jet flow into the tank greater than the retrieved flow out of the tank. The balanced tests were conducted with the 0.281-in.-diameter nozzle at 1000 psi; the unbalanced tests were conducted with the 0.310-in.-diameter nozzle at 1000 psi.

Jet Fluid

Water was selected to model the ORNL OHF supernate. Water was used to provide the liquid layer as well as the initial jet fluid. The total water quantity was selected to provide a final dilution of approximately 10 wt% solids, the ORNL OHF criteria for transfer from OHF to the Melton Valley storage tanks. The initial dislodging sequences were conducted using a waterjet. During these sequences, dislodged slurry was retrieved from the horizontal-tank and accumulated in the supernate tank. Later dislodging sequences were conducted using the slurry as the jet fluid. All tests ended with a low-pressure water rinse.

Nozzle Motion

Two types of nozzle motion were evaluated: 1) oscillating the nozzle from side to side by rotating the mast without changing the nozzle azimuthal angle from the vertical or 2) changing the nozzle angle from the vertical without significant oscillation from side to side. Both of these motions were evaluated while varying the nozzle extension length. These were the primary motion patterns of the test phase.

Retrieval Pump Inlet Location

ORNL plans to install retrieval pumps in each of the tank end risers and the extendible nozzle in the central riser; this simulates a multiple-riser deployment for the extendible-nozzle system. The retrieval pump inlet location of 5 ft from the end of the tank was selected based on the average length of the ORNL OHF retrieval pump from the end of the OHF tanks, based on riser penetration geometry. This data is summarized in Table 7.1. One additional test was conducted with the retrieval inlet line moved to the tank end near the extendible nozzle; this simulated a single-riser deployment.

Fluid Motion and Acoustic Response

Video (visual and acoustic) recordings of the each of the tests were made. The video recordings captured the interactions between the jet and the sludge layer, the jet and a liquid layer, and the jet and the sides of the tank. The videos provided a real-time, time-stamped link with the recorded data. The video records provide a basis for understanding the audible response obtained for various operating conditions. This data is expected to differ from that obtained in a closed tank; however, understanding the jet-tank-slurry interactions and differences in acoustic response in the open tank may provide guidance for closed tank operation.

7.5.2 Scaling the Horizontal-Tank Extendible-Nozzle Experiments

ORNL criteria for sludge dislodging, slurry retrieval, and transport are to obtain a solids loading of 10 wt% solids during solids transfer via pipeline to the Melton Valley storage tanks. This concentration is achievable based on their sludge and supernate inventory. Operating bounds for the process are estimated to range from 5 to 15 wt% solids with an average particle diameter of 0.01 in. ORNL plans to install a strainer in the retrieval pump system transfer line to limit the diameter of solids in the slurry used to feed the extendible nozzle. The maximum particle diameter is expected to be 0.125 in. at very low (≤ 1) wt%.

Simulant Volumes

An analysis of the volumes of the horizontal-tank and the supernate tank was conducted to estimate fluid handling requirements. This information is summarized in Table 7.9. The analysis assumed that the horizontal-tank was level. In its test configuration, it had a slight slope away from the nozzle, ~1 in./10 ft. The table presents information for fluid heights in the horizontal-tank from 1 to 24 in. The cross-sectional area of the horizontal segment for each fluid depth is presented. To evaluate the volumes of the simulant beds, beds with lengths of 1, 5, 10, and 22 ft were sized. The 22-ft bed corresponds to covering the entire tank bottom with liquid. To determine the impact of waste generation and handling, the height obtained by transferring all of the slurry to the supernate tank was calculated. This calculation did not account for hold up in the transfer piping or the supernate tank curved bottom; also, the supernate tank volume was estimated by assuming a right circular cylinder. A 6-in. layer in the horizontal-tank corresponds to a fluid depth of 0.31 ft in the supernate tank.

Table 7.9 Summary of Horizontal and Supernate Tank Volumes

Fluid level above tank bottom	Area of segment	Segment Volume for Specified Segment Length								Supernate tank level
		1 ft		5 ft		10 ft		22 ft		
in.	ft^2	ft^3	gal	ft^3	gal	ft^3	gal	ft^3	gal	ft
1	0.089	0.089	0.67	0.45	3.3	0.90	6.6	2.0	15	0.02
2	0.255	0.25	1.9	1.3	9.6	2.6	19	5.6	42	0.06
6	1.28	1.3	9.6	6.4	48	12.8	96	28	211	0.31
9	2.38	2.4	18	12	89	24	179	52	393	0.57
12	3.62	3.6	27	18	136	36	271	80	597	0.86
15	5.03	5.0	38	25	188	50	377	111	830	1.20
18	6.52	6.5	49	33	244	65	489	143	1076	1.56
24	9.82	9.8	74	49	368	98	737	216	1620	2.34

Obtaining 10 Wt% Solids

ORNL criteria for sludge dislodging, slurry retrieval, and transport are to obtain a solids loading of 10 wt% solids. To estimate jet spray times to provide the desired amount of liquid addition required to obtain the target 10 wt% solids, mass balances were calculated for simulant bed lengths ranging from 1 to 10 ft. The results of this analysis are presented in Table 7.10. Separate analyses are provided for the two sludge simulants; their densities range from 1.65 to 1.95 g/cm^3.

These calculations were based on a simulant bed height of 6 in. The simulant bed volume, obtained from Table 7.9 and the simulant density were used to calculate the simulant weight. Dilution required to provide a 10 wt% slurry is also presented in gal (based on a water density of 0.9978 g/cm^3 at a water temperature of 22 degrees C).

To determine the spray duration required to provide this dilution, the flow rates from the 0.281- and 0.310-in.- diameter nozzles at 500 and 1000 psi were evaluated. The equivalent supernate tank level for the dilution water is also shown.

Table 7.10 Sludge to Water Ratios to Obtain 10 Wt% Solids

OHF-SS Sludge Simulant, ρ = 1.65 g/cm^3							
Length of 6-in. high bed segment	Segment weight	Dilution for 10 wt% solids	Spray time, min				Equivalent supernate tank level for water
			500 psi		1000 psi		
ft	kg	gal H_2O	0.281 in. 52 gpm	0.310 in. 64 gpm	0.281 in. 74 gpm	0.310 in. 90 gpm	ft
1	59.8	143	2.8	2.2	1.9	1.6	0.21
5	299	714	13.7	11.2	9.6	7.9	1.03
10	598	1429	27.5	22.3	19.3	15.9	2.06
OHF-HS Hard Sludge Simulant, ρ = 1.95 g/cm^3							
Length of 6-in. high segment	Segment weight	Dilution for 10 wt% solids	Spray time, min				Equivalent supernate tank level for water
			500 psi		1000 psi		
ft	kg	gal H_2O	0.281 in. 52 gpm	0.310 in. 64 gpm	0.281 in. 74 gpm	0.310 in. 90 gpm	ft
1	70.7	169	3.3	2.6	2.3	1.9	0.24
5	354	845	16.3	13.2	11.4	9.4	0.98
10	707	1690	32.5	26.4	22.8	18.8	1.96

7.5.3 Test Phases

To simplify conducting the experiment and tracking the dislodging and retrieval performance, the tests were divided into test phases. The test phases included: 1) simulant manufacture, placement and curing; 2) pre-test measurements and Phase 0 addition of supernate layer; 3) Phase W water-based dislodging; 4) Phase S slurry-based dislodging; 5) Phase R tank rinsing; and 6) post-test inspection. Phases W, S, and R consisted of a sequential number of timed jet operational phases where W signifies a number of high-pressure water jet phases, S signifies a number of high-pressure slurry jet phases, and R signifies a low-pressure water rinse phase. Data gathered during the phases were recorded using the data acquisition system and video camera.

Simulant Preparation and Characterization

Simulant preparation involved manufacturing the simulant, loading it into the tank, curing the simulant in the tank, and prior to test initiation removing the forms required to hold the simulant in place during simulant curing. It also includes characterizing the simulant properties. The simulant characterization measurements are summarized in Table 7.11.

Table 7.11 Simulant Characterization Measurements

Parameter	Units	Measurement Location	Frequency
density, ρ	g/cm^3	laboratory	during preparation
shear strength, τ	kPa	laboratory	after curing
composition, wt%	wt%	preparation site	during preparation
mass, W	lbm	preparation site	during tank loading
supernate density	g/cm^3	laboratory	sample from retrieval line, one per test phase
solid chunks	lbm	laboratory	chunks removed from tank after test completion

Pre-Test Setup

Pre-test setup involved verifying that the test fixture and components were configured as required to conduct the test. If a liquid layer simulating supernate was required, it was added at this time. It also involved initiating the data acquisition system, taking pre-test photos and initiating video recording.

Water-Based Dislodging

The initial dislodging phase was conducted using water supplied to the sluicer pump from the fire hydrant. The duration of the water-based dislodging phase was planned to add enough water to provide a slurry with a composition of 10 wt% solids. Water addition times varied based on the simulant depth and bed length. For a 6-in. high simulant layer, 5 ft in length, typical jet operation times range from 8 to 19 minutes. If a supernate layer covers the simulant bed, the water addition time was reduced to still provide a 10 wt% slurry. At the completion of the water dislodging, a grab sample to measure the bulk density of the slurry was taken from the retrieval line prior to its emptying into the top of the supernate tank. The retrieval pump remained in operation until the required fluid depth was achieved in the horizontal-tank.

Slurry-Based Dislodging

Prior to the start of slurry-based dislodging, the water supply line from the fire hydrant was disconnected and the outlet from the bottom of the supernate tank was connected to the sluicer pump inlet. The succeeding phases of sluicing were conducted using the slurry collected in the supernate tank to feed the extendible nozzle. The sluicing time for this activity was selected to be 8 min.

The purpose of the slurry-based dislodging phases was to determine the effectiveness of using slurry to dislodge sludge. At the completion of the slurry-based dislodging, the sluicer pump was stopped while retrieval continued until the prescribed liquid level in the horizontal-tank was obtained. A grab sample was taken from the retrieval line as it emptied into the top of the supernate tank to measure the bulk density of the slurry. The slurry-based dislodging step was completed several times.

Water Rinse

At the completion of the slurry-based dislodging the water supply from the hydrant was reconnected to the sluicer pump inlet and the tank was rinsed for a period of ~2 min at a jet pressure of 500 psi. The purpose of this step was to determine whether a water or supernate rinse at the completion of sluicing removed additional solids from the tank and cleaned tank walls. After the rinse water was turned off, the retrieval pump continued to run until all slurry above the slurry pump inlet was removed from the horizontal-tank. During this transfer, a grab sample was taken from the retrieval line prior to its emptying into the supernate tank.

Post Test

At the completion of the test, photographs of the tank were taken and any solid chunks remaining in the slurry were collected and weighed, and grab samples were analyzed.

7.5.4 Test Matrix

The horizontal-tank test matrix is shown in Table 7.12. The tests are separated by simulant type with the simulants listed in order of increasing shear strength. All but one of the tests were conducted with the retrieval pump inlet 5 ft from the end of the tank. In the other test, the retrieval pump inlet was placed at the end of the tank closest to the extendible nozzle, simulating single-riser horizontal tank dislodging and retrieval.

7.6 Test Results

The nine tests listed in Table 7.12 will be discussed individually in the sections that follow. Comparisons between the tests will be made to evaluate the effect of changes in nozzle diameter, supernate level, balanced or unbalanced retrieval, simulant shear strength, and nozzle motion. The basic data from the individual tests is summarized in Table 7.13. This table shows the number of test phases, the duration of the phase, the mean jet pressure during the phase, and the slurry density measured from a grab sample taken from the retrieval line at the completion of dislodging.

Table 7.12 Extendible-Nozzle Horizontal-Tank Test Matrix

Date	Run Number	Simulant	Bed Length ft	Nozzle Diameter in.	Jet Pressure psi	Supernate Depth in.	Retrieval Pump Location ft from end
7/11	1	OHF-SS	5	0.310	1000	0	5
7/23	3	OHF-SS	10	0.310	1000	0	5
7/31	5	OHF-SS	10	0.310	1000	12	5
8/5	6	OHF-SS	10	0.281	1000	18	5
7/21	2	OHF-HS	5	0.310	1000	0	5
7/29	4	OHF-HS	5	0.310	1000	12	5
8/14	9	OHF-HS	5	0.281	1000	12	22
8/8	7	Kaolin Plaster Sand	5	0.281	1000	12	5
8/12	8	Hard Pan	5	0.281	1000	12	5

Table 7.13 Summary of Extendible-Nozzle Horizontal-Tank Experiments

Date	Simulant	Bed Length ft	Simulant Weight lb		Nozzle Diam. in.	Phase	Pressure, psi		Jet Fluid	Jet Duration min		Total Liquid Depth in.	Nozzle Motion	Retrieved Fluid Density g/cm³
			Pre-test	Post-test			Planned	Actual		Planned	Actual			
7/11	OHF-SS	5	610		0.310	1	1000	987±193	water	8	7.7	0	horizontal	[(a)]
	OHF-SS	5			0.310	2	1000	184±170	slurry	8	8.2	2	horizontal	
	OHF-SS	5			0.310	3	500	409±197	water rinse	2.2	2.9	2	vertical	
				No visible solids, solids not collected										
7/21	OHF-HS	5	700		0.310	1	1000	1016[(b)]	water	8	8.0	0	horizontal	
	OHF-HS	5			0.310	2	1000	970±203	water	8	8.5	2	vertical	
	OHF-HS	5			0.310	3	1000	91±112	slurry	8	8.0	2	horizontal	
	OHF-HS	5			0.310	4	1000	864±262	slurry	8	8.2	2	vertical	
	OHF-HS	5			0.310	5	500	532±22	water rinse	2.2	2.0	2	vertical	
				66										

(a) Not measured.
(b) This number obtained from computer screen print; data file lost.

Date	Simulant	Bed Length ft	Simulant Weight lb		Nozzle Diam. in.	Phase	Pressure, psi		Jet Fluid	Jet Duration min		Total Liquid Depth in.	Nozzle Motion	Retrieved Fluid Density g/cm^3
			Pre-test	Post-test			Planned	Actual		Planned	Actual			
7/23	OHF-SS	10	1208		0.310	1	1000	987±203	water	8	8.5	0	horizontal	1.0329
	OHF-SS	10			0.310	2	1000	954±306	water	8	8.2	2	vertical	1.0036
	OHF-SS	10			0.310	3	1000	604±231 jet off 850±218	slurry	8	3.9 1.9 2.2	2	horizontal	1.0379
	OHF-SS	10			0.310	4	1000	916±139	slurry	8	8.3	2	vertical	1.0299
	OHF-SS	10			0.310	5	500	592±199	water rinse	2.2	1.3	2	vertical	
				No solids visible, solids not collected										
7/29	OHF-HS	5	700		0.310	0						12		
	OHF-HS	5			0.310	1	1000	992±311	water	4.4	4.9	12	horizontal	1.0175
	OHF-HS	5			0.310	2	1000	964±248	slurry	8	8.1	12	horizontal	1.0404
	OHF-HS	5			0.310	3	1000	1040±129	slurry	8	8.0	6	vertical	1.0308
	OHF-HS	5			0.310	4	1000	993±116	slurry	8	8.2	6	horizontal	1.0303
	OHF-HS	6			0.310	5	500	396±42	water rinse	2.2	2.2	2	vertical	1.0003
				1.8										

Date	Simulant	Bed Length ft	Simulant Weight lb		Nozzle Diam. in.	Phase	Pressure, psi		Jet Fluid	Jet Duration min		Total Liquid Depth in.	Nozzle Motion	Retrieved Fluid Density g/cm^3
			Pre-test	Post-test			Planned	Actual		Planned	Actual			
7/31	OHF-SS	10	1203		0.310	0						12		
	OHF-SS	10			0.310	1	1000	971±270	water	5	5.4	12	horizontal	
	OHF-SS	10			0.310	2	1000	996±194	water	5	5.2	12	vertical	
	OHF-SS	10			0.310	3	1000	1019±140	slurry	8	8.1	12	horizontal	1.0329
	OHF-SS	10			0.310	4	1000	956±125	slurry	8	8.1	9	vertical	1.0330
	OHF-SS	10			0.310	5	1000	983±123	slurry	8	8.1	6	horizontal	1.0328
	OHF-SS	10			0.310	6	500	516±34	rinse	2.2	2.2	2	vertical	1.0027
				No solids visible, solids not collected										

Date	Simulant	Bed Length ft	Simulant Weight lb		Nozzle Diam. in.	Phase	Pressure, psi		Jet Fluid	Jet Duration min		Total Liquid Depth in.	Nozzle Motion	Retrieved Fluid Density g/cm^3
			Pre-test	Post-test			Planned	Actual		Planned	Actual			
8/5	OHF-SS	10	1261		0.281	0						18		
	OHF-SS	10			0.281	1	1000	1019±226	water	5	5.3	18	horizontal	1.0354
	OHF-SS	10			0.281	2	1000	1076[(a)]	slurry	5	5.1	18	vertical	1.0404
	OHF-SS	10			0.281	3	1000	1049±138	slurry	8	8.2	12	horizontal	1.0402
	OHF-SS	10			0.281	4	1000	1067±142	slurry	8	8.2	9	vertical	1.0491
	OHF-SS	10			0.281	5	1000	1081±90	slurry	8	8.1	6	horizontal	1.0393
	OHF-SS	10		[(b)]	0.281	6	500	631±67	water rinse	2.2	2.2	2	vertical	1.0034

(a) This number obtained from computer screen print; data file lost.
(b) No solids visible, solids not collected

Date	Simulant	Bed Length ft	Simulant Weight lb		Nozzle Diam. in.	Phase	Pressure, psi		Jet Fluid	Jet Duration min		Total Liquid Depth in.	Nozzle Motion	Retrieved Fluid Density g/cm^3
			Pre-test	Post-test			Planned	Actual		Planned	Actual			
8/8	Sand	5	621		0.281	0						12		
	Sand	5			0.281	1	1000	1081±47	water	5	4.9		horizontal	1.0273[a]
	Sand	5			0.281	2	1000	1064±17	water		2.8	12	horizontal	
	Sand	5			0.281	2A	1000	666±202	slurry	8	8.0	12	horizontal	1.0149[a]
	Sand	5			0.281	3	1000	1130±26	slurry	8	7.8	9	vertical	1.0177[a]
	Sand	5			0.281	4	1000	1075±47	slurry	8	8.0	6	horizontal	1.0173[a]
	Sand	5			0.281		500	521±15	water rinse	2.2	2.2	2	vertical	1.0013[a]
				16[b]										

(a) Solids settled out prior to sample.
(b) No solids visible-gravel and sand settled.

Date	Simulant	Bed Length ft	Simulant Weight lb		Nozzle Diam. in.	Phase	Pressure, psi		Jet Fluid	Jet Duration min		Total Liquid Depth in.	Nozzle Motion	Retrieved Fluid Density g/cm^3
			Pre-test	Post-test			Planned	Actual		Planned	Actual			
8/12	Hard Pan	5	605		0.281	0						12		
	Hard Pan	5			0.281	1	1000	1106±145	water	5	5.2	12	horizontal	1.0266
	Hard Pan	5			0.281	2	1000	1125±201	slurry	8	8.4	12	horizontal	1.0144
	Hard Pan	5			0.281	3	1000	1177±121	slurry	8	8.0	9	vertical	1.0264
	Hard Pan	5			0.281	4	1000	1143±121	slurry	8	7.6	6	horizontal	1.0006[(a)]
	Hard Pan	5			0.281	5	500	535±126	water rinse	2.2	2.0	2	vertical	1.0251
				34.9[(b)]										

(a) Retrieval line clogged, unplugged with water.
(b) Large oval chunks 6x10 in. max.

Date	Simulant	Bed Length ft	Simulant Weight lb		Nozzle Diam. in.	Phase	Pressure, psi		Jet Fluid	Jet Duration min		Total Liquid Depth in.	Nozzle Motion	Retrieved Fluid Density g/cm³
			Pre-test	Post-test			Planned	Actual		Planned	Actual			
Retrieval Pump Installed at Nozzle End of Tank														
8/14	OHF-HS	5	700		0.281	0						12		
	OHF-HS	5			0.281	1	1000	1140±29	water	5	5.0	12	horizontal	1.0111
	OHF-HS	5			0.281	2	1000	1160±32	slurry	8	8.0	12	horizontal	1.0264
	OHF-HS	5			0.281	3	1000	1160±34	slurry	8	8.0	9	vertical	1.0380
	OHF-HS	5			0.281	4	1000	1151±33	slurry	8	8.0	6	horizontal	1.0397
	OHF-HS	5			0.281	5	500	526±44	water rinse	2.2	2.3	2	vertical	1.0145
				18[a]										

(a) Some chunks visible- more submerged.

7.6.1 OHF-SS Simulant Tests

Four tests were conducted using simulant OHF-SS, the sludge simulant designed to match rheological properties of OHF sludge. The differences between the tests are shown in Table 7.12. The first three tests were conducted using the 0.310-in.-diameter nozzle; the last test was conducted using the 0.281-in.-diameter nozzle. The first test evaluated dislodging a 5-ft-long bed; the other three tests evaluated dislodging a 10-ft-long bed. The first two tests were conducted with no supernate layer; the last two tests were conducted with total fluid depths of 12- and 18-in., respectively.

Run 1 - OHF-SS Simulant with 5-ft Bed, 0.310-in.-Diameter Nozzle, No Supernate Layer

This run modeled unbalanced retrieval. The flow rate of the extendible nozzle was greater than that of the retrieval pump; therefore, after the flow to the extendible nozzle stopped, retrieval continued until the tank was pumped down and the retrieval pump inlet was exposed. Run 1 consisted of three jet-dislodging and slurry-retrieval phases.

Phase 0 - Simulant Bed. The 5-ft-long simulant bed is shown in Figure 7.11 The bed contained 610 lb of OHF-SS simulant.

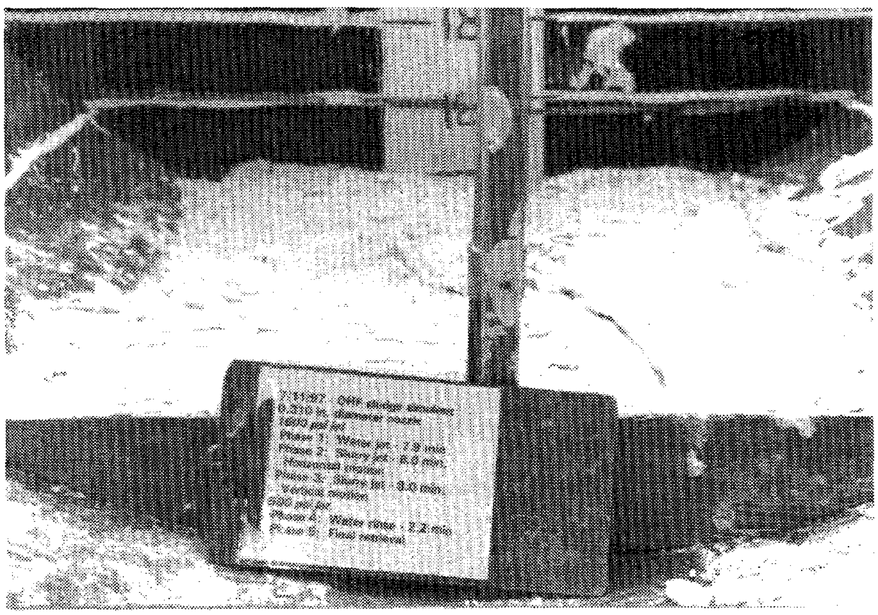

Figure 7.11 Run 1 OHF-SS Simulant Bed Prior to Test

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 7.7 min of waterjet dislodging at an average pressure of 987±193 psi. The pressure plot, shown in Figure 7.12, showed that the pressure remained relatively constant throughout the test. At the completion of Phase 1, the fluid remaining in the horizontal-tank was pumped down to a level of ~2 in. The slurry was transferred to the supernate tank. Figure 7.13 shows the tank after the jet was stopped; liquid motion induced by the retrieval pump can be observed along the sides of the tank. The 6-in.-thick sludge simulant is no longer visible; the liquid layer is ~2-in. deep.

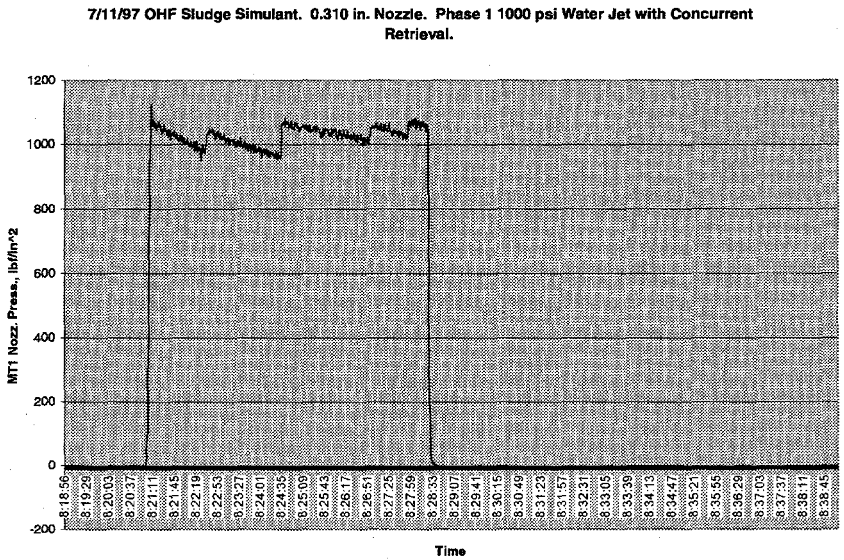

Figure 7.12 Run 1 - Waterjet Pressure During Phase 1

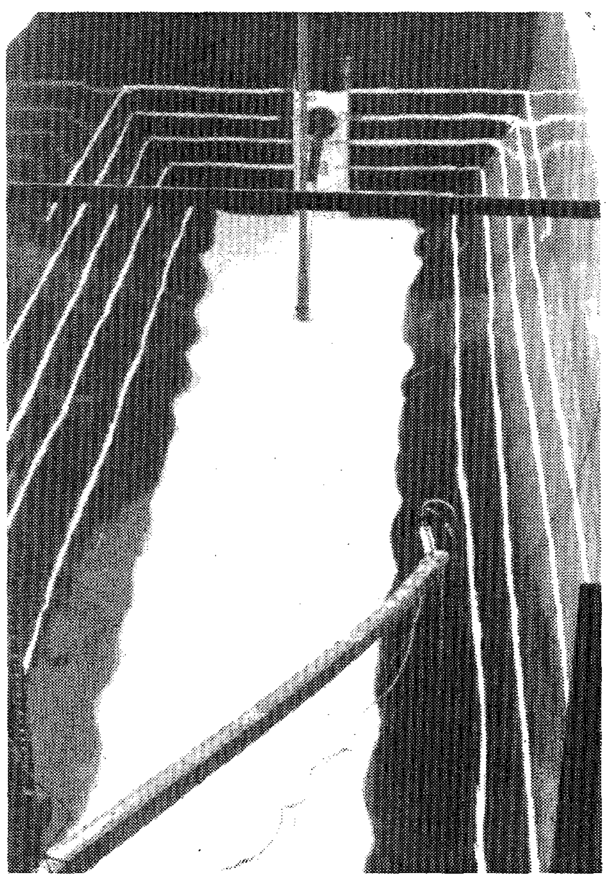

Figure 7.13 Run 1 - After Phase 1, 7.7 min of 987 psi Waterjet Spray

Phase 2 - Slurry-Jet Dislodging and Retrieval. In Phase 2, the slurry in the supernate tank was used as the dislodging fluid. Both the slurry supply line feeding the high-pressure pump and the retrieval line from the horizontal-tank were connected to the bottom of the supernate tank. This configuration starved the high-pressure pump feed; therefore, the jet pressure averaged 184±170 psi, as shown in Figure 7.14. The initial pressure of >1000 psi occurred during start up. This was not the ~1000 psi jet pressure planned. The phase was completed at this lower-than-desired jet pressure. The condition of the horizontal-tank after completion of Phase 2 is shown in Figure 7.15 it is very similar in condition to what occurred during Phase 1. The first phase was conducted at high pressure and the simulant was dislodged during this initial phase. Solids, visible along the floor of the tank but not in the liquid layer, settled after jet dislodging ceased but before slurry retrieval was completed.

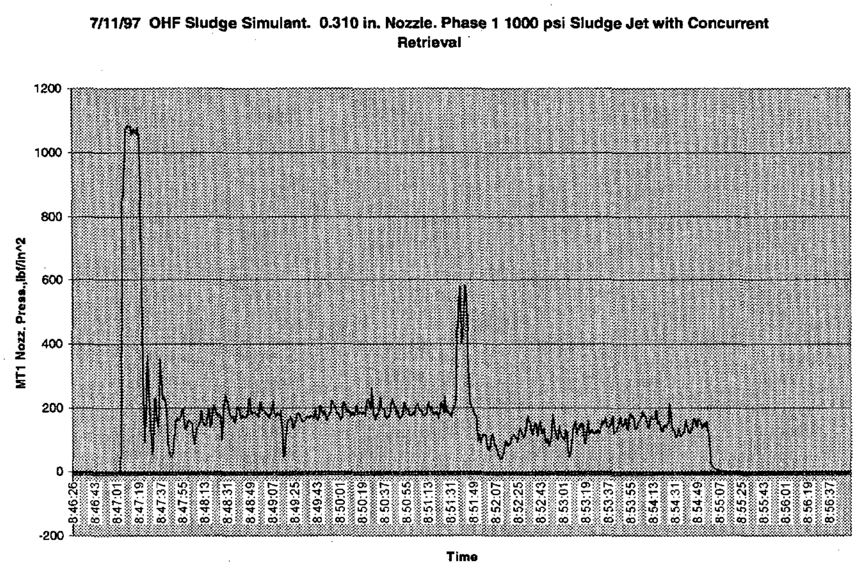

Figure 7.14 Run 1 - Waterjet Pressure During Phase 2

Phase 3 - Low-Pressure Waterjet Rinse. Phase 3 consisted of 2.2 min of waterjet rinse at an average pressure of 409±197 psi. The pressure plot is shown in Figure 7.16. In Phase 3, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.17 shows the tank after completion of Phase 3. The remaining liquid is a dilute slurry; the sides of the tank are clean.

Run 1 - Mass Balance. A summary of test conditions and a mass balance for Run 1 is shown in Table 7.14. The total inventory of solids and liquids added to the horizontal-tank is shown under Horizontal-Tank Input. Slurry wt% solids based on initial water addition was 9.7 wt%, near the target 10 wt% solids. The total inventory of solids and liquids added to the horizontal-tank is shown. This mass was compared to the supernate tank weight and/or the retrieved slurry weight was used to estimate the percent of retrieved slurry. About 97% of the slurry was retrieved. This compares well with 95%, an estimate of the amount of fluid remaining in the horizontal-tank based on a calculation using the fluid height.

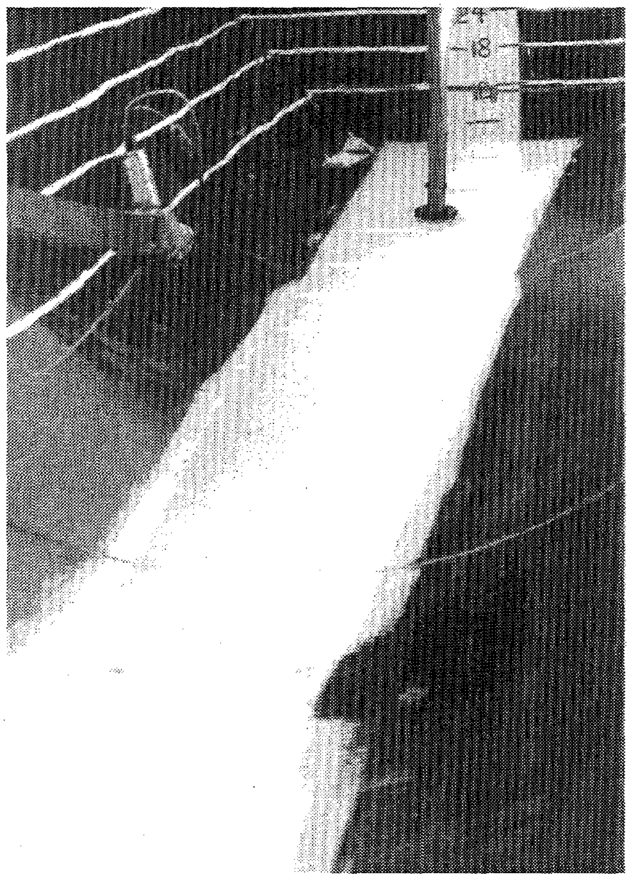

Figure 7.15 Run 1 - After Phase 2, 8.2 min of 184 psi Slurry-Jet Spray

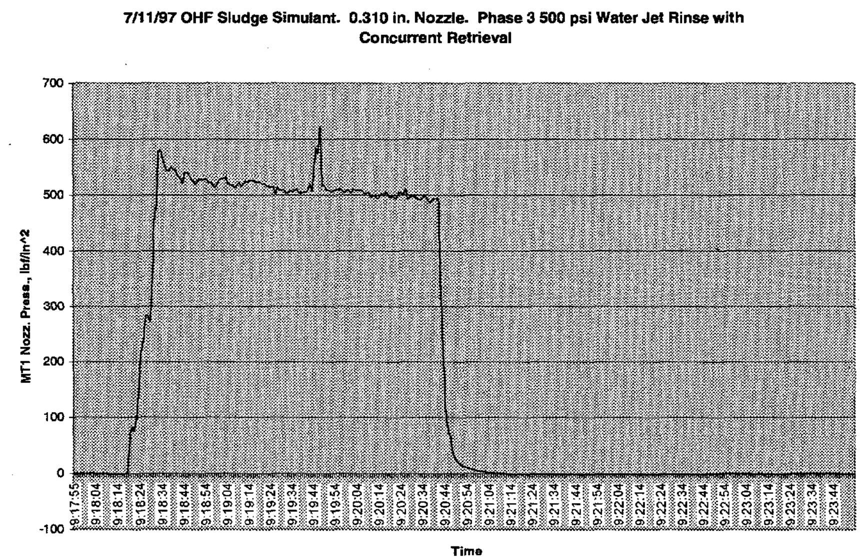

Figure 7.16 Run 1 - Waterjet Pressure During Phase 3

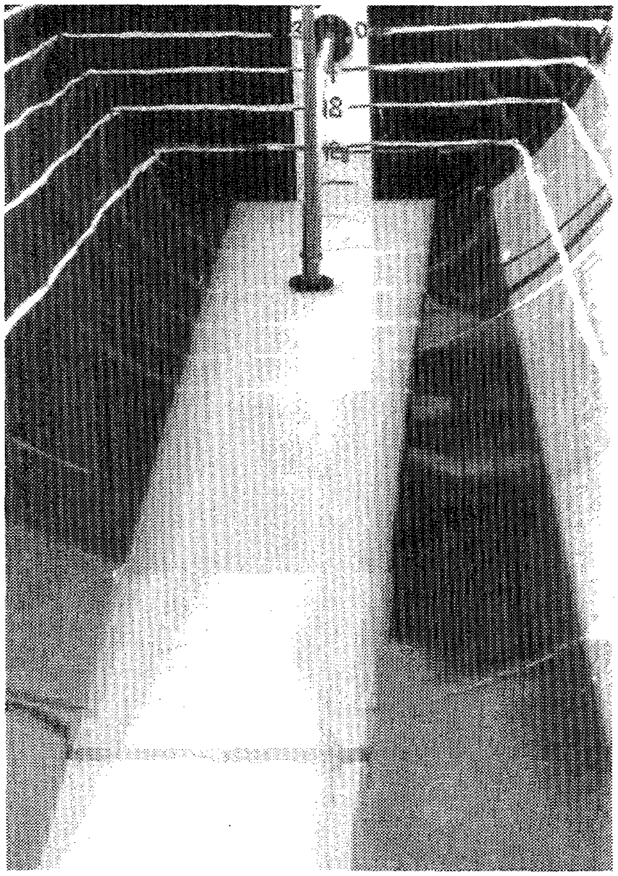

Figure 7.17 Run 1 - After Phase 3, 2.2 min of 409 psi Waterjet Rinse

Table 7.14 Run 1 - Mass Balance Between Horizontal-Tank and Supernate Tank

Phase	Horizontal-Tank Input lbm			Average wt% Solids	Jet Slurry lbm	Super-nate Tank Weight lbm	Re-trieved Slurry lbm	Total Retrieved Based on *-ed Columns, lbm	Percent Retrieved
	Solids	Water	Total						
0	610		610						
1		5691	6301	9.7		5450*	7161	5450	86
2					3459	5339*	2172	5339	85
3		1279	7580	8.0		6487	2009*	7348	97
Post Test	~0	350 lb remaining in horizontal-tank, estimated from 2 in. water layer							95

Run 3 - OHF-SS Simulant with 10-ft Bed, 0.310-in.-Diameter Nozzle, No Supernate Layer

This run was similar to Run 1; however, the simulant bed length was increased to 10 ft. This run modeled unbalanced retrieval. The flow rate of the extendible nozzle was greater than that of the retrieval pump; therefore, after the flow to the extendible nozzle stopped, retrieval continued until the tank was pumped down and the retrieval pump inlet was exposed. Run 3 consisted of two waterjet and two slurry-jet-dislodging and slurry-retrieval phases and a final waterjet rinse.

Phase 0 - Simulant Bed. The 10-ft-long simulant bed is shown in Figure 7.18. The bed contained 1208 lb of OHF-SS simulant. The inlet to the retrieval pump was submerged in the simulant.

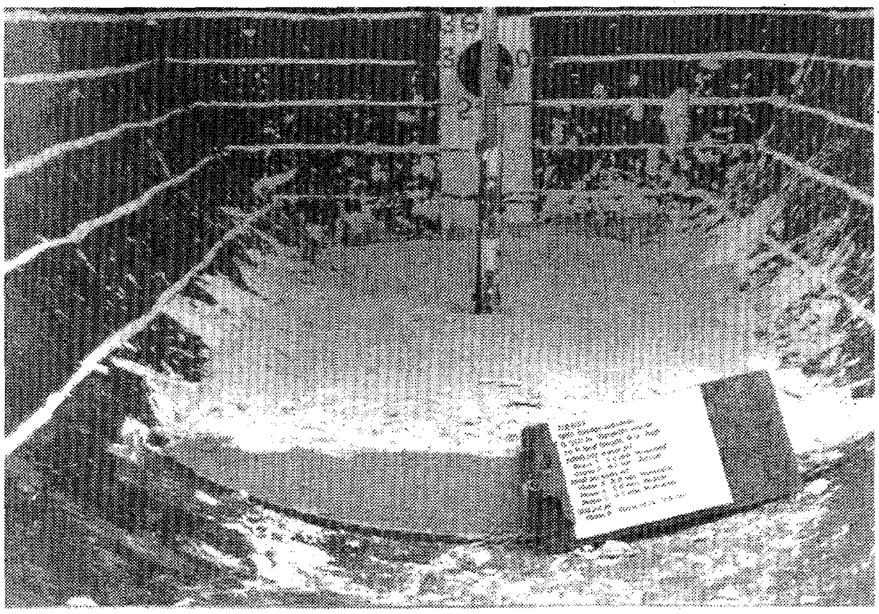

Figure 7.18 Run 3 - OHF-SS Simulant Bed Prior to Test

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 8.5 min of waterjet dislodging at an average pressure of 987±203 psi. The pressure plot, shown in Figure 7.19, showed that the pressure remained relatively constant throughout the test. At the completion of Phase 1, the fluid remaining in the horizontal-tank was pumped down to a level of ~2 in. The slurry was transferred to the supernate tank. Figure 7.20 shows the tank after the jet was stopped. Most of the 10-ft-long bed has been dislodged; however undislodged simulant remains along the far end of the tank. Some solids are visible on the sides of the tank above the liquid layer. These solids settled after jet dislodging ceased but before slurry retrieval was completed. The liquid layer is ~2-in. deep.

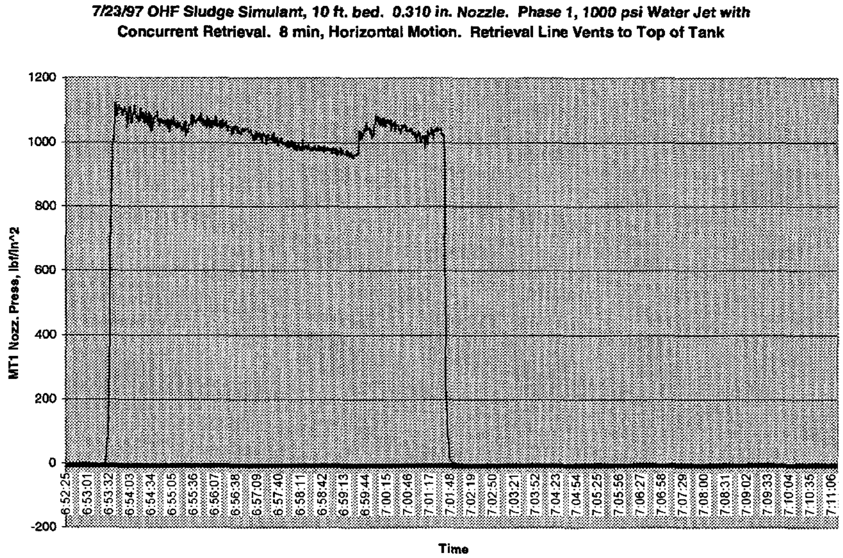

Figure 7.19 Run 3 - Waterjet Pressure During Phase 1

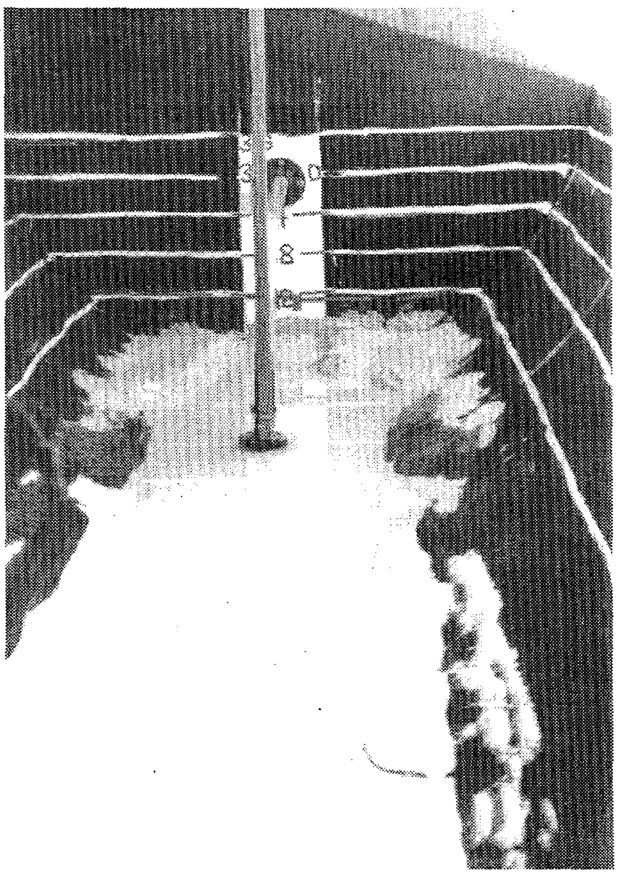

Figure 7.20 Run 3 - After Phase 1, 8.5 min of 987 psi Waterjet Spray

Phase 2 - Waterjet Dislodging and Retrieval. Phase 2 was a repeat of Phase 1. The water-addition phase was split into two parts to keep the jet spray time under 10 min duration to provide adequate photograpy of the simulant condition. Phase 2 consisted of 8.2 min of waterjet dislodging at an average pressure of 954±306 psi. The pressure plot, shown in Figure 7.21, showed that the pressure remained relatively constant throughout the test. At the completion of Phase 2, the fluid remaining in the horizontal-tank was pumped down to a level of ~2 in. The slurry was transferred to the supernate tank. Figure 7.22 shows the tank after the jet was stopped; all of the 10-ft-long bed has been dislodged. Some solids are visible on the sides of the tank above the liquid layer. These solids settled after jet dislodging ceased but before slurry retrieval was completed. The liquid layer is ~2-in. deep.

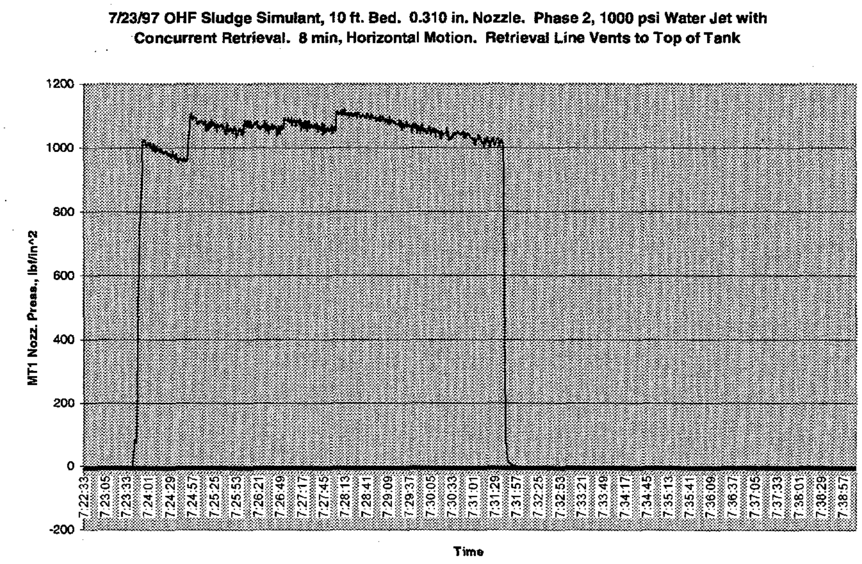

Figure 7.21 Run 3 - Waterjet Pressure During Phase 2

Phase 3 - Slurry-Jet Dislodging and Retrieval. In Phase 3, the slurry in the supernate tank was used as the dislodging fluid. The slurry supply line feeding the high-pressure pump suction was connected to the bottom of the supernate tank. This configuration provided adequate flow to the high-pressure pump feed. The retrieval line from the horizontal-tank to the supernate tank emptied into the top of the supernate tank. The pressure plot is shown in Figure 7.23. Initially the jet pressure averaged 604±231 psi; the flow was stopped and restarted and the final jet pressure averaged 850±218 psi. The condition of the horizontal-tank after completion of Phase 3 is shown in Figure 7.24. Only the ~2-in.-deep slurry remains after slurry retrieval.

Phase 4 - Slurry-Jet Dislodging and Retrieval. In Phase 4, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 916±139 psi, as shown in Figure 7.25. The condition of the horizontal-tank after completion of Phase 4 is shown in Figure 7.26. The photograph shows no obvious change from the condition at the end of Phase 3.

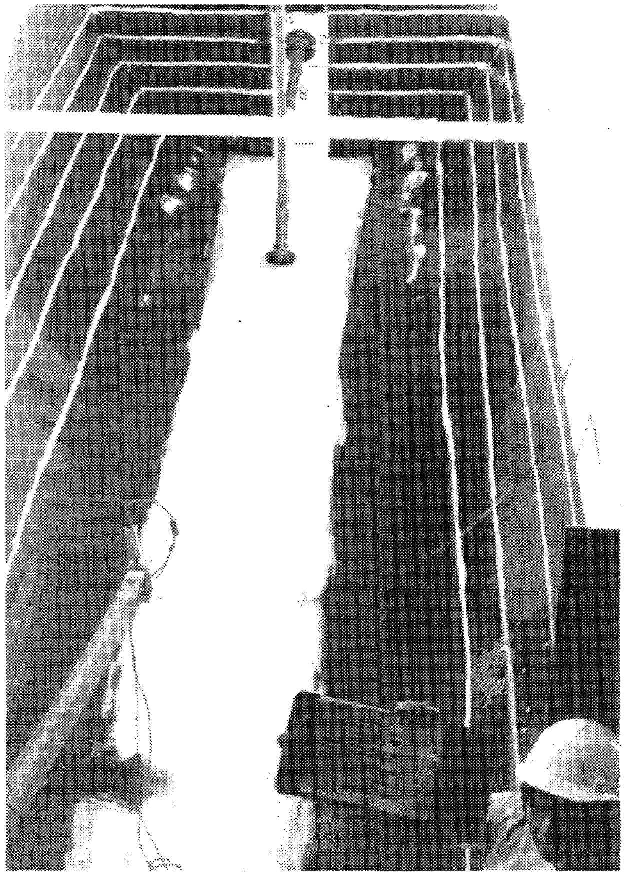

Figure 7.22 Run 3 - After Phase 2, 8.2 min of 954 psi Waterjet Spray

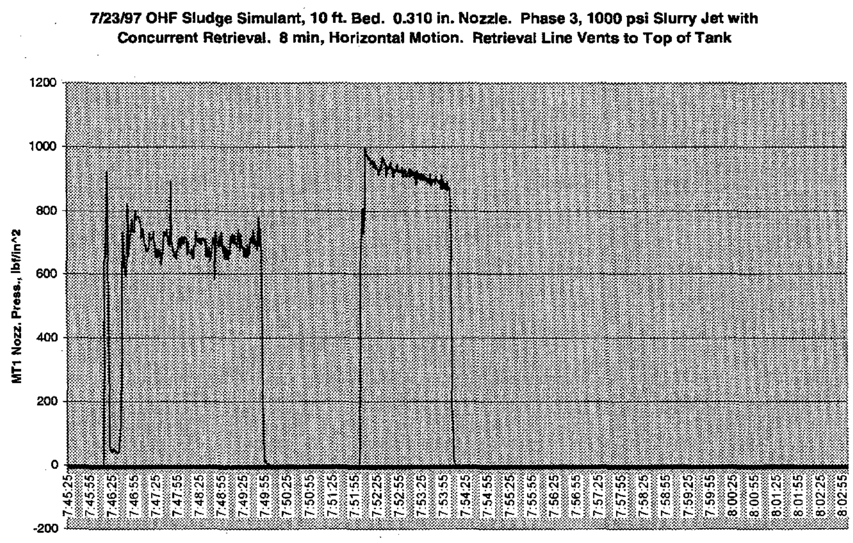

Figure 7.23 Run 3 - Slurry-Jet Pressure During Phase 3

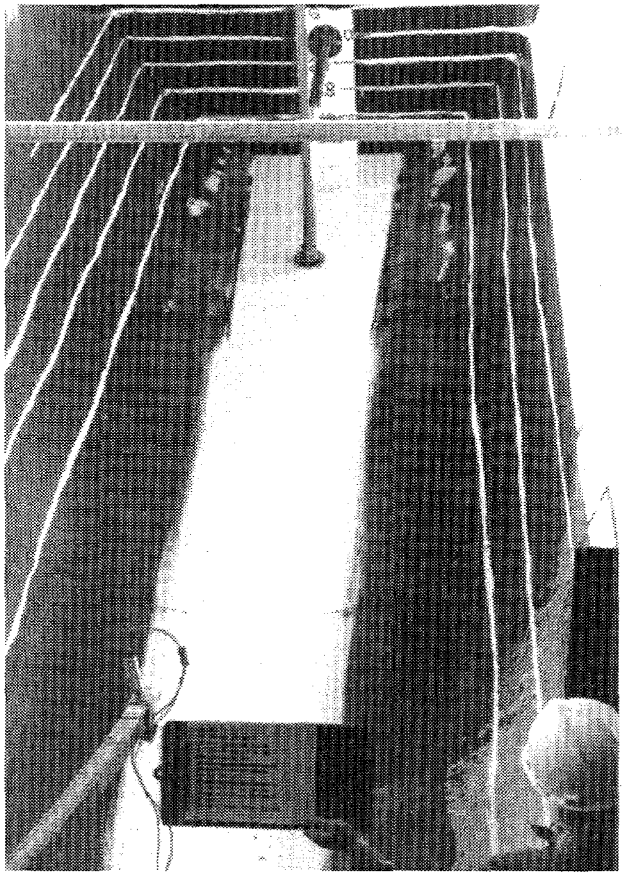

Figure 7.24 Run 3 - After Phase 3, 3.9 min of 604 psi and 2.2 min of 850 psi Waterjet Spray

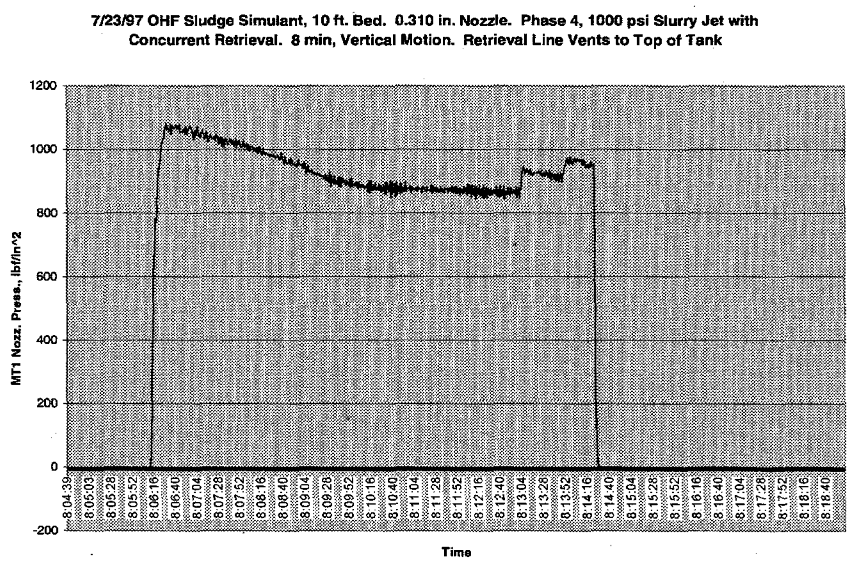

Figure 7.25 Run 3 - Waterjet Pressure During Phase 4

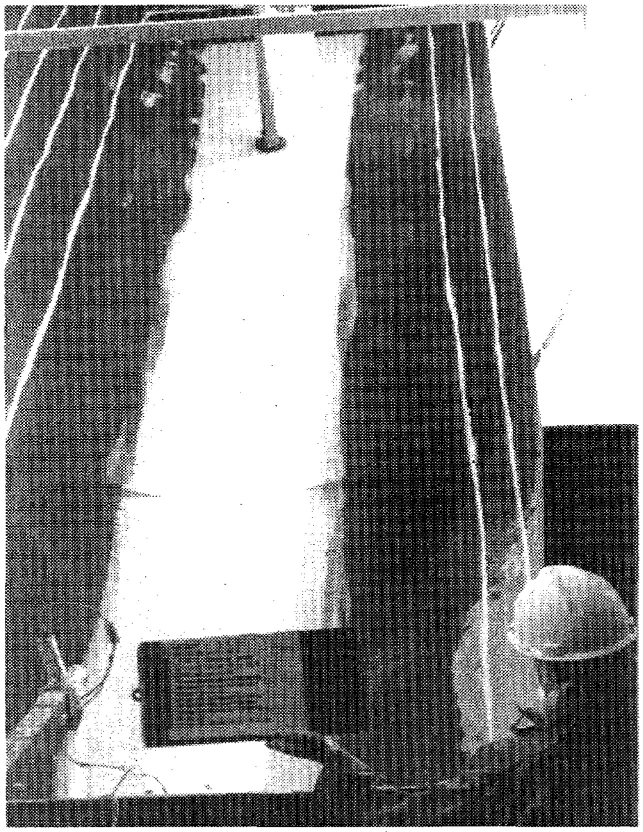

Figure 7.26 Run 3 - After Phase 4, 8.3 min of 916 psi Slurry-Jet Spray

Phase 5 - Low-Pressure Waterjet Rinse. Phase 5 consisted of 1.3 min of waterjet rinse at an average pressure of 592±199 psi. The pressure plot is shown in Figure 7.27. In Phase 5, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.28 shows the tank after completion of Phase 5. The remaining liquid is a dilute slurry; the sides of the tank are clean.

Run 3 - Mass Balance. A summary of test conditions and a mass balance for Run 3 are shown in Table 7.15. The total inventory of solids and liquids added to the horizontal-tank is shown under Horizontal-Tank Input. After Phase 1, the wt% solids based on initial water addition was 16 wt%; after Phase 2 this dropped to 8.8 wt%, near the target 10 wt%. This mass was compared to the supernate tank weight and the amount of recycled slurry to estimate the amount of retrieved slurry. The columns used in this estimate are marked with a *. About 99% of the slurry was retrieved. This compares well with an estimate of 98% for the amount of fluid remaining in the horizontal-tank based on a calculation using the height of the fluid remaining in the horizontal tank.

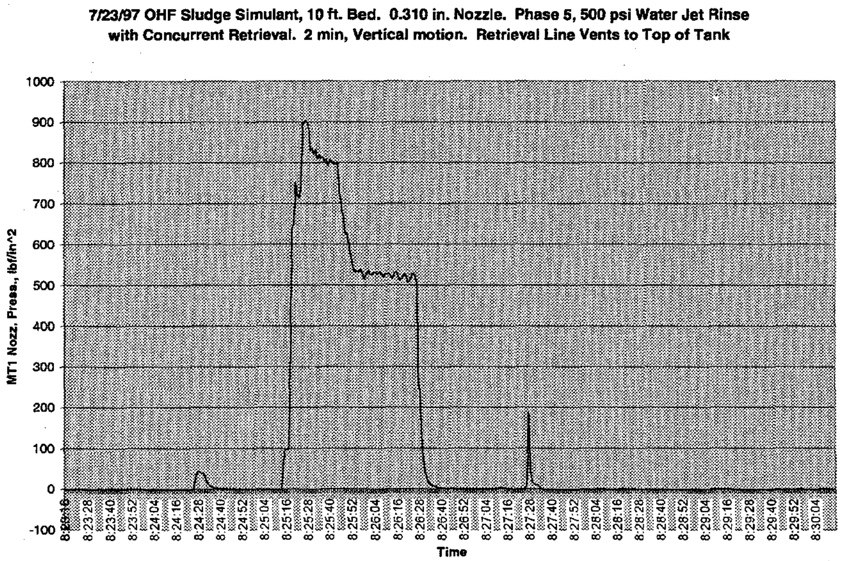

Figure 7.27 Run 3 - Waterjet Pressure During Phase 5 Waterjet Rinse

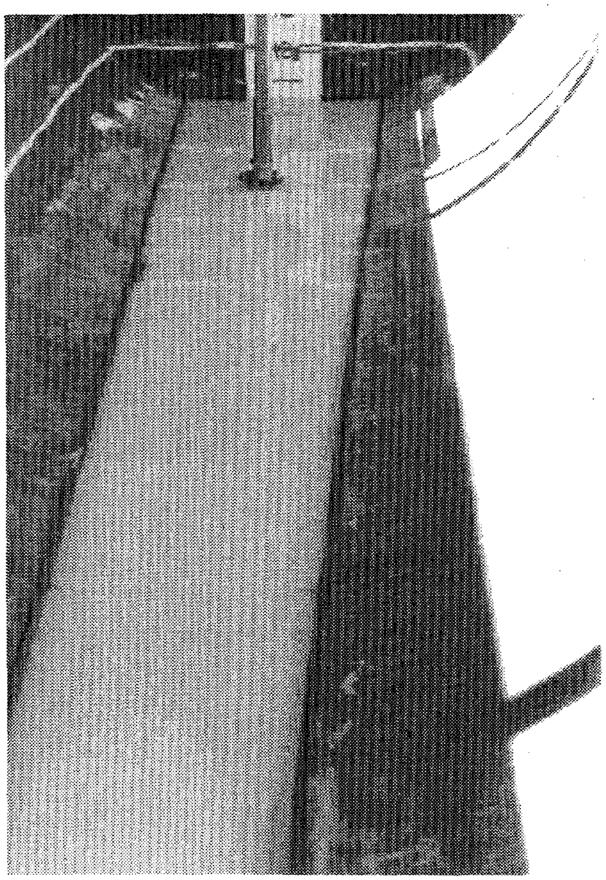

Figure 7.28 Run 3 - After Phase 5, 1.3 min of 592 psi Waterjet Rinse

Table 7.15 Run 3 - Mass Balance Between Horizontal-Tank and Supernate Tank

Phase	Horizontal-Tank Input lbm			Average wt% Solids	Slurry lbm	Super-nate Tank Weight lbm	Retrieve d Slurry lbm	Total Retrieve d Based on *-ed Columns lbm	Percent Retrieved
	Solids	Water	Total						
0	1208		1208						
1		6336	7544	16		6887*	8184	6887	91
2		6189	13733	8.8		12405*	4974	12405	90
3					3525*	11989	3741*	12621	92
4					6169*	11594	6933*	13385	97
5		753	14486	8.3		11460	935*	14320	99
Post Test	~0	350 lb remaining in horizontal-tank, estimated from 2 in. water layer							98

Run 5 - OHF-SS Simulant with 10-ft Bed, 0.310-in.-Diameter Nozzle, Supernate Layer

This run was similar to Run 3; however, the 10-ft simulant bed was covered with 6 in. of supernate for a total liquid height of 12 in. This run modeled unbalanced retrieval. The flow rate of the extendible-nozzle was greater than that of the retrieval pump; therefore, after the flow to the extendible-nozzle stopped, retrieval continued until the tank was pumped down to the prescribed supernate level. The supernate level started at 12 in. and decreased over the six phases to ~2 in. Run 5 consisted of two waterjet and three slurry-jet-dislodging and slurry retrieval phases and a final waterjet rinse.

Phase 0 - Simulant Bed. The 10-ft-long simulant bed is shown in Figure 7.29 The bed contained 1203 lb of OHF-SS simulant. The inlet to the retrieval pump was submerged in the simulant.

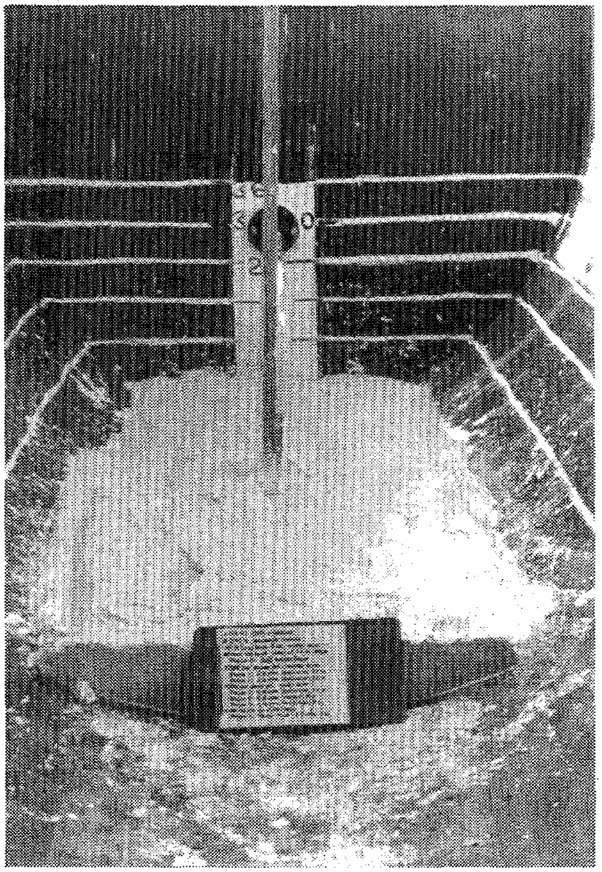

Figure 7.29 Run 5 - OHF-SS Simulant Bed Prior to Test

To simulate the supernate layer, the waterjet was operated at a low pressure to fill the horizontal tank to the prescribed water depth. The bed was not disturbed during the filling process. The supernate covered bed is shown in Figure 7.30. The liquid is up to the 12-in. line painted around the edge of the tank. The undisturbed bed is visible through the supernate layer.

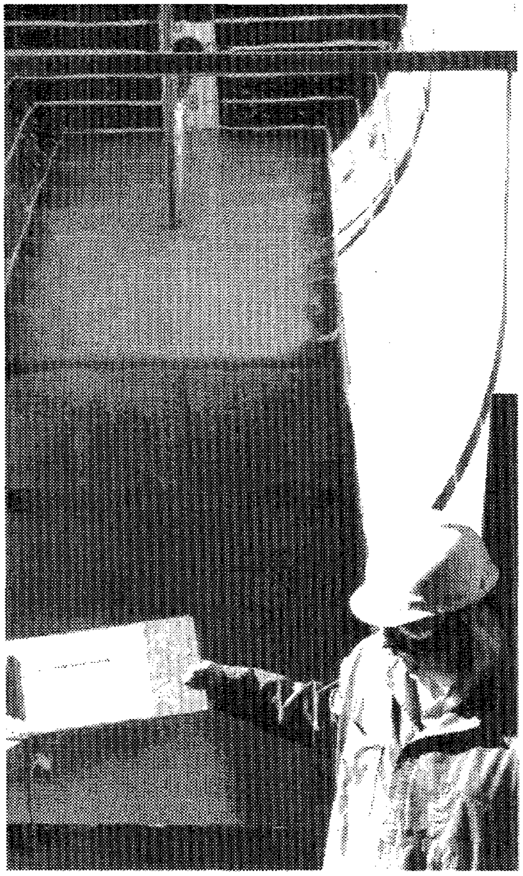

Figure 7.30 Run 5 - OHF-SS Simulant Bed Covered with Supernate

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 5.4 min of waterjet dislodging at an average pressure of 971±270 psi. The pressure plot, shown in Figure 7.31, showed that the pressure remained extremely constant throughout the test. At the completion of Phase 1, the fluid remaining in the horizontal tank was pumped down to a level of 12 in. The slurry was transferred to the supernate tank. Figure 7.32 shows the tank after the jet was stopped. The solids are well dispersed in the slurry.

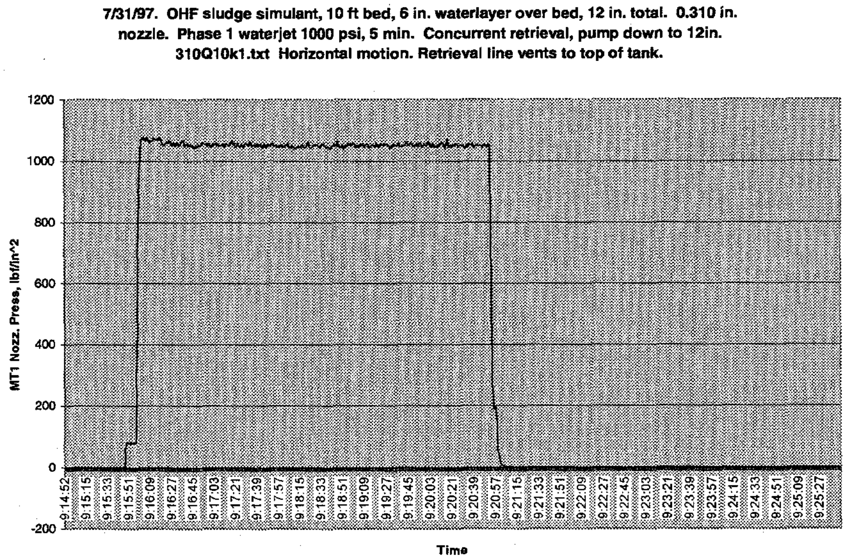

Figure 7.31 Run 5 - Waterjet Pressure During Phase 1

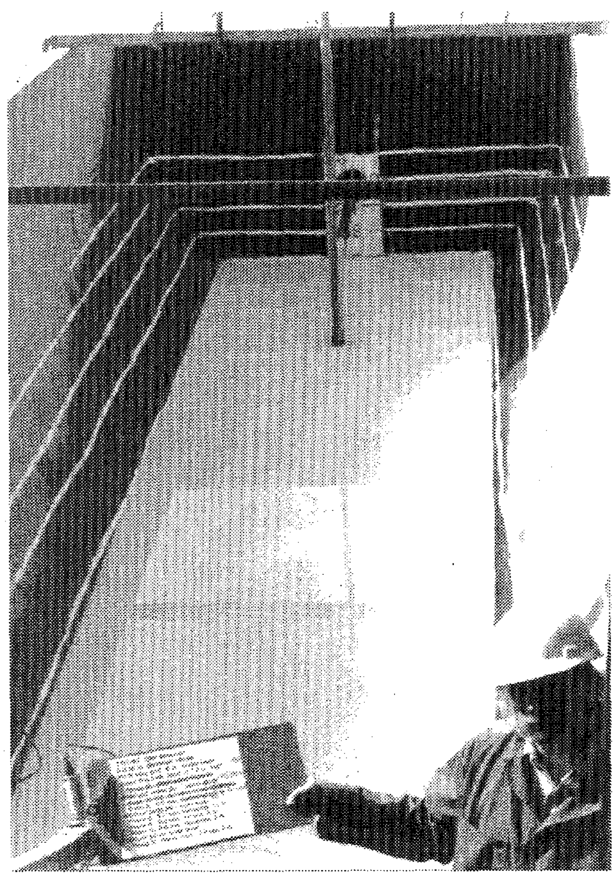

Figure 7.32 Run 5 - After Phase 1, 5.4 min of 971 psi Waterjet Spray, 12-in. Liquid Layer

Phase 2 - Waterjet Dislodging and Retrieval. Phase 2 was a repeat of Phase 1. The water-addition phase was split into two parts to keep the jet spray time under 10 min duration to provide adequate photographic documentation between phases. Phase 2 consisted of 5.2 min of waterjet dislodging at an average pressure of 996±194 psi. The pressure plot, shown in Figure 7.33, showed that the pressure remained very constant throughout the test. At the completion of Phase 2, the fluid remaining in the horizontal tank was pumped down to a level of 12 in. The slurry was transferred to the supernate tank. Figure 7.34 shows the tank after the jet was stopped; again the slurry appears to be well mixed.

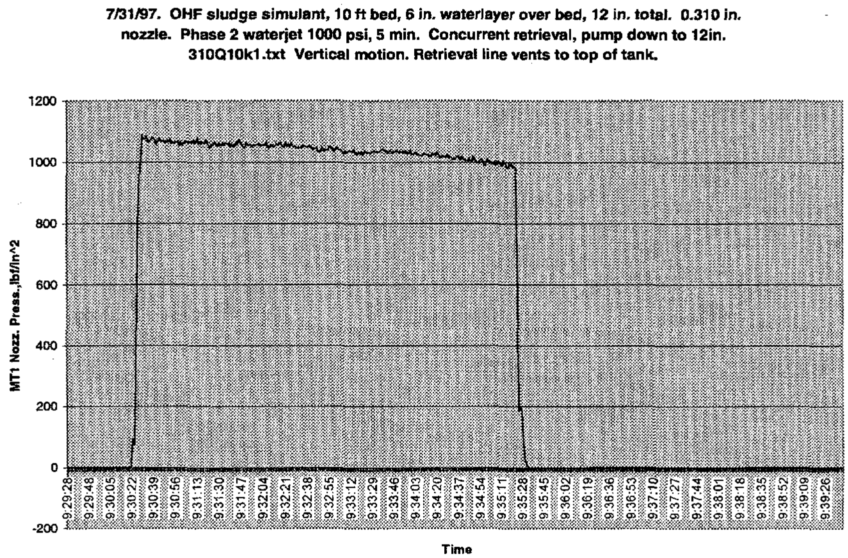

Figure 7.33 Run 5 - Waterjet Pressure During Phase 2

Phase 3 - Slurry-Jet Dislodging and Retrieval. In Phase 3, the slurry in the supernate tank was used as the dislodging fluid. The slurry supply line feeding the high-pressure pump was connected to the bottom of the supernate tank. The retrieval line from the horizontal tank to the supernate tank emptied into the top of the supernate tank. This configuration provided adequate flow to the high-pressure pump feed. The pressure plot is shown in Figure 7.35. The jet pressure averaged 1019±140 psi. The condition of the horizontal tank after completion of Phase 3 is shown in Figure 7.36. The tank was pumped to a level of 9 in. after completion of Phase 3. Liquid level was decreased with each phase to gradually uncover any undislodged solids in the tank.

Phase 4 - Slurry-Jet Dislodging and Retrieval. In Phase 4, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 956±125 psi, as shown in Figure 7.37. The condition of the horizontal tank after completion of Phase 4 is shown in Figure 7.38. At the completion of Phase 4, the tank was pumped to a level of 6 in.

Phase 5 - Slurry-Jet Dislodging and Retrieval. In Phase 5, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 983±123 psi, as shown in Figure 7.39. The condition of the horizontal tank after completion of Phase 5 is shown in Figure 7.40. The tank was pumped to a level of 2 in. at the completion of Phase 5. A few settled solids are visible at the edge of the liquid layer.

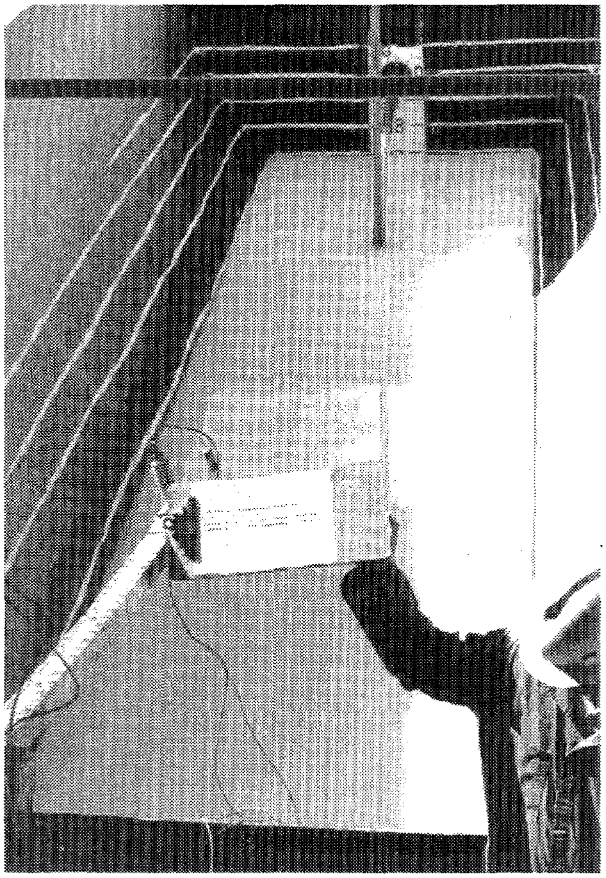

Figure 7.34 Run 5 - After Phase 2, 5.2 min of 996 psi Waterjet Spray, 12-in. Liquid Layer

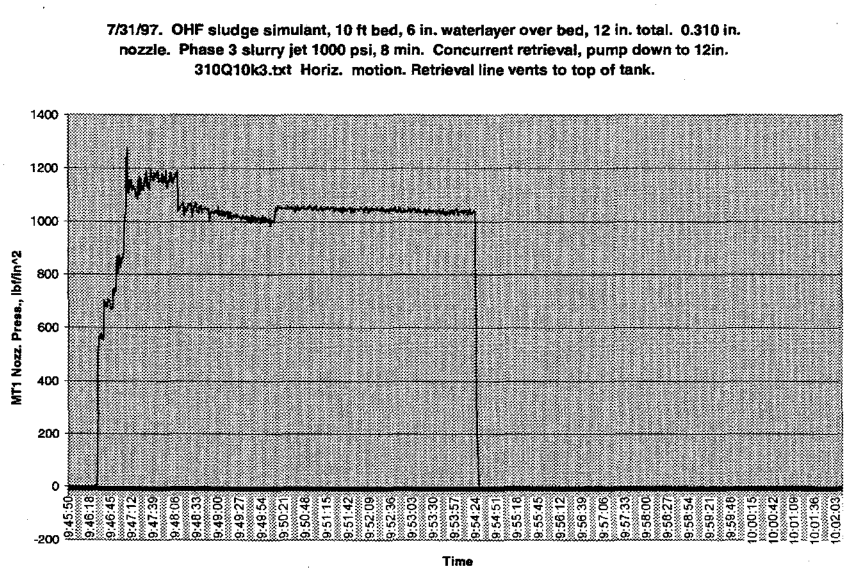

Figure 7.35 Run 5 - Slurry-Jet Pressure During Phase 3

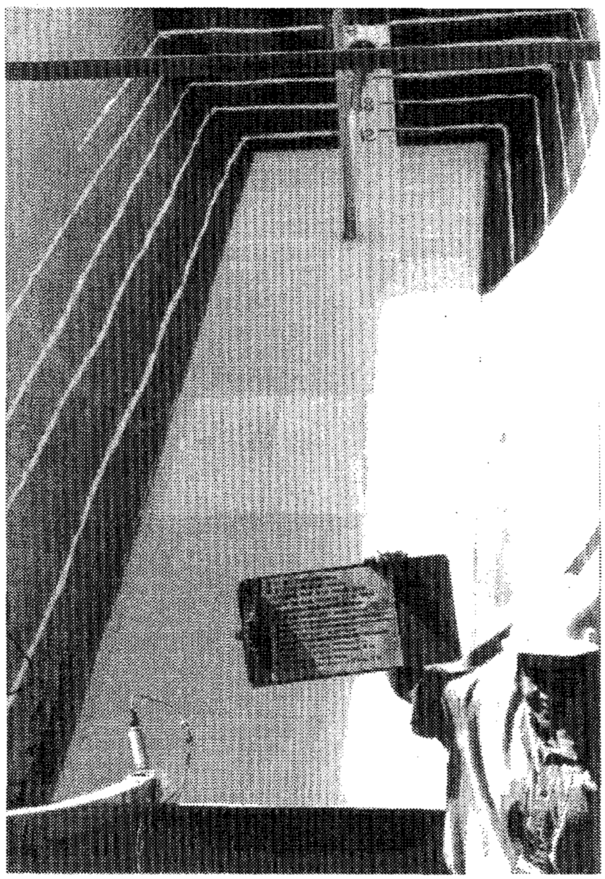

Figure 7.36 Run 5 - After Phase 3, 8.1 min of 1019 psi Slurry-Jet Spray, 9-in. Liquid Layer

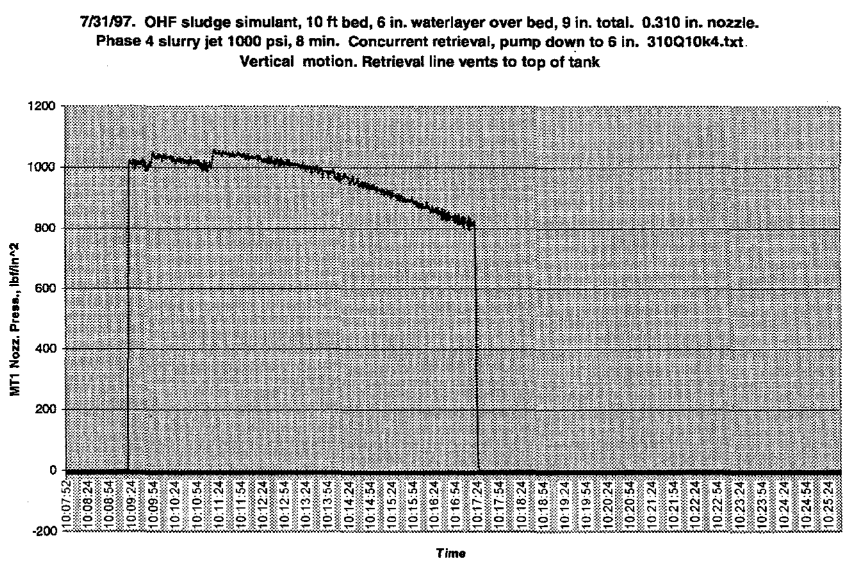

Figure 7.37 Run 5 - Waterjet Pressure During Phase 4

Figure 7.38 Run 5 - After Phase 4, 8.1 min of 956 psi Slurry-Jet Spray, 6-in. Liquid Level

Phase 6 - Low-Pressure Waterjet Rinse. Phase 6 consisted of 2.2 min of waterjet rinse at an average pressure of 516±34 psi. The pressure plot is shown in Figure 7.41. In Phase 6, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.42 shows the tank after completion of Phase 6. The remaining liquid is a dilute slurry; the sides of the tank are clean.

Run 5 - Mass Balance. A summary of test conditions and a mass balance for Run 5 are shown in Table 7.16. The total inventory of solids and liquids added to the horizontal tank is shown under Horizontal Tank Input. After Phase 1, the wt% solids based on initial water addition was 14.6 wt%; after Phase 2 this dropped to 9.8 wt%, near the target 10 wt%. This mass was compared to the supernate tank weight and the amount of recycled slurry to estimate the amount of retrieved slurry. The columns used in this estimate are marked with a *. About 9% of the slurry was retrieved. This matches the estimate of 97% for the amount of fluid remaining in the horizontal tank based on a calculation using the height of the fluid remaining in the horizontal tank.

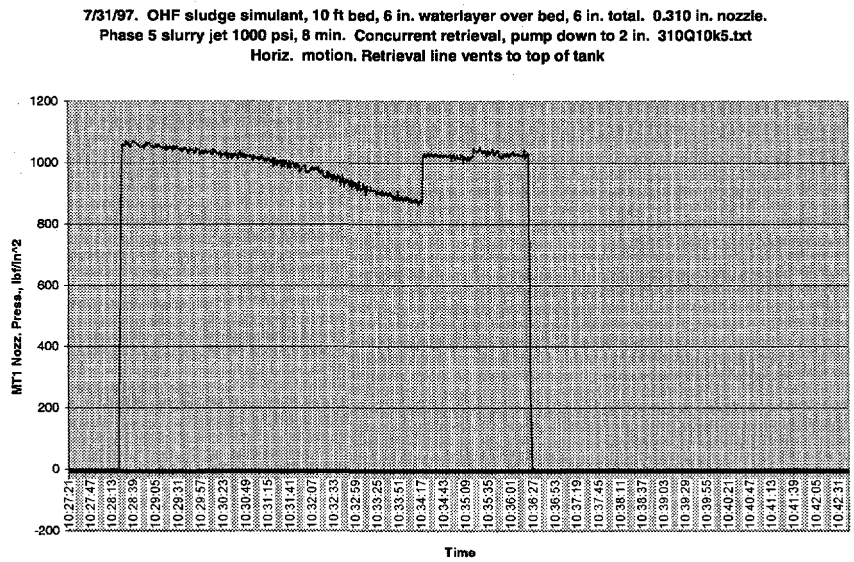

Figure 7.39 Run 5 - Waterjet Pressure During Phase 5

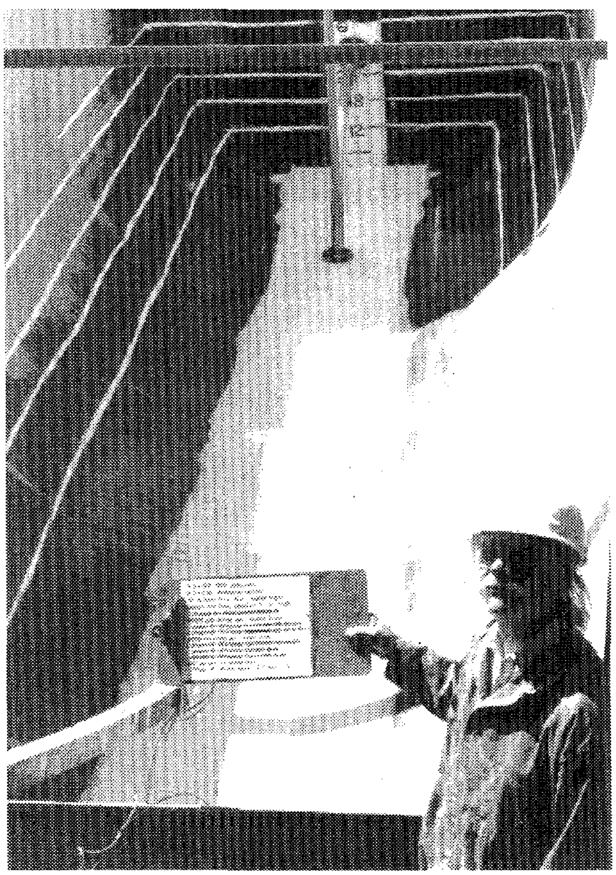

Figure 7.40 Run 5 - After Phase 5, 8.1 min of 983 psi Waterjet Spray, 2-in. Liquid Layer

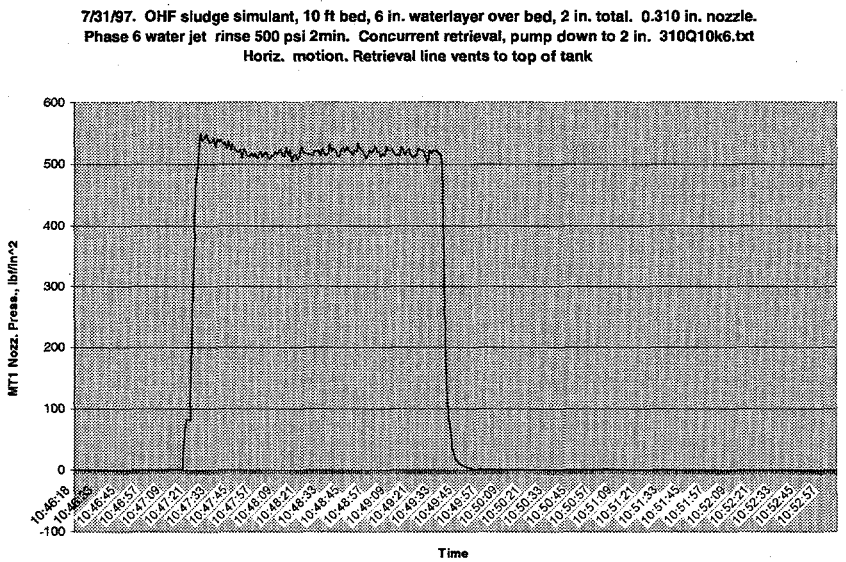

Figure 7.41 Run 5 - Waterjet Pressure During Phase 6 Waterjet Rinse

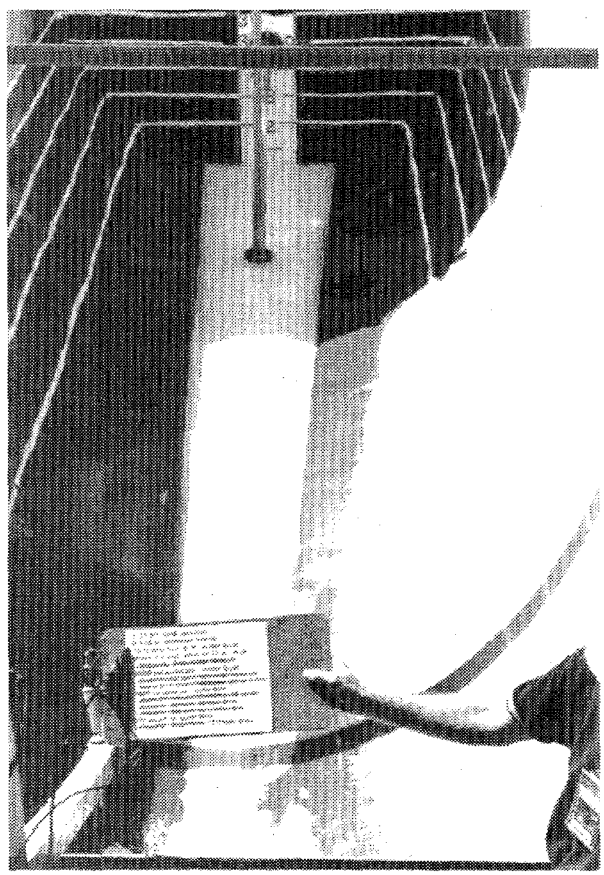

Figure 7.42 Run 5 - After Phase 6, 2.2 min of 516 psi Waterjet Rinse

Table 7.16 Run 5 - Mass Balance Between Horizontal Tank and Supernate Tank

Phase	Horizontal Tank Input lbm			Average wt% Solids	Jet Slurry lbm	Super-nate Tank Weight lbm	Retrieved Slurry lbm	Total Rerieved Based on *-ed Columns lbm	Percent Retrieved
	Solids	Water	Total						
0	1203	2924	4127						
1		4087	8214	14.6		3956*	4707	3956	32
2		4088	12302	9.8		8254*	4974	8254	67
3			12302	9.8	6676	9827*	9310	9827	80
4			12302	9.8	6647	11150*	8917	11150	91
5			12302	9.8	6521	11873*	8900	11873	97
6		1331	13633	8.8		14015	1330*	13205	97
Post Test	~0	350 lb remaining in horizontal tank, estimated from 2-in. water layer							97

Run 6 - OHF-SS Simulant with 10-ft Bed, 0.281-in.-Diameter Nozzle, Supernate Layer

This run was similar to Run 5; however, the nozzle diameter was decreased from 0.310 in. to 0.281 in. and the 10-ft simulant bed supernate layer was increased from 6 in. to 12 in. for a total liquid height of 18 in. This run modeled balanced retrieval; the flowrate of the extendible-nozzle at 1000 psi using the 0.281-in.-diameter nozzle was approximately equal to that of the retrieval pump. Therefore, the retrieval pump was stopped immediately after flow to the extendible-nozzle stopped. The supernate level started at 18 in. and decreased over the six phases to ~2 in. Run 6 consisted of one waterjet and four slurry-jet-dislodging and slurry-retrieval phases and a final waterjet rinse.

Phase 0 - Simulant Bed. The 10-ft-long simulant bed is shown in Figure 7.43 The bed contained 1261 lbm of OHF-SS simulant. The inlet to the retrieval pump was submerged in the simulant. To simulate the supernate layer, the waterjet was operated at a low pressure to fill the horizontal tank to the prescribed water depth. The bed was not disturbed during the filling process. The supernate-covered bed is shown in Figure 7.44. The liquid is up to the 18-in. line painted around the edge of the tank. The undisturbed bed is slightly visible through the supernate layer.

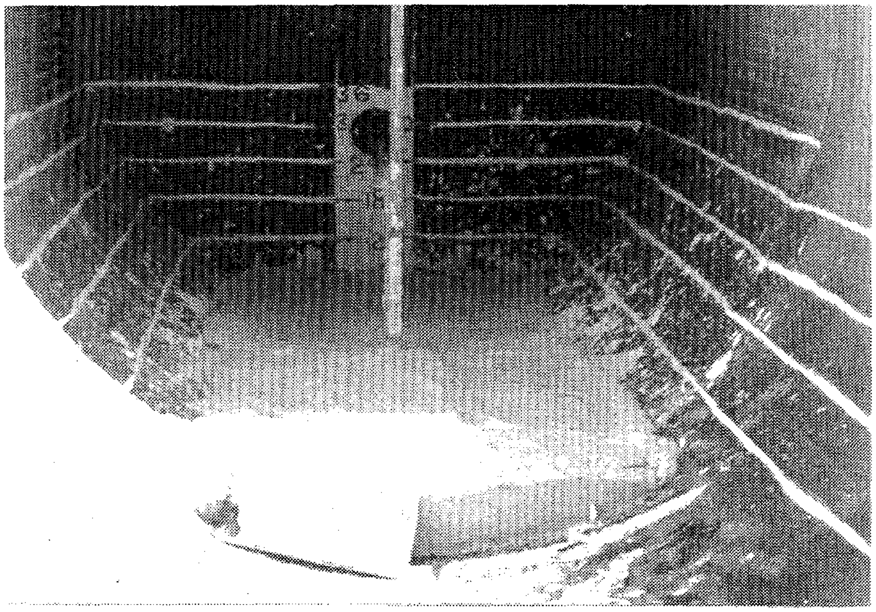

Figure 7.43 Run 6 - OHF-SS Simulant Bed Prior to Test

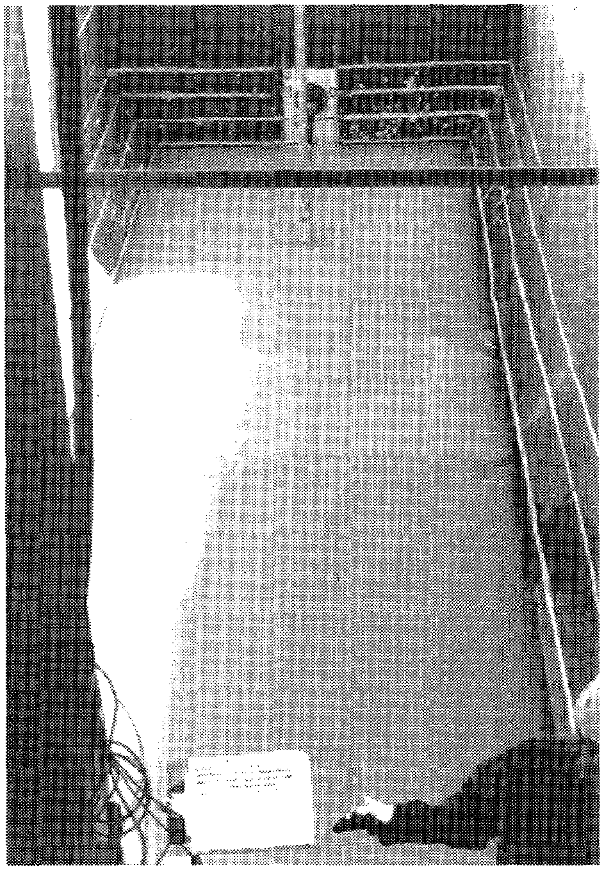

Figure 7.44 Run 6 - OHF-SS Simulant Bed Covered with Supernate

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 5.3 min of waterjet dislodging at an average pressure of 1019±226 psi. The pressure plot, shown in Figure 7.45, showed that the pressure remained extremely constant throughout the test. At the completion of Phase 1 the fluid remaining in the horizontal tank was pumped down to a level of 18 in. The slurry was transferred to the supernate tank. Figure 7.46 shows the tank after the jet was stopped. The solids are well dispersed in the slurry.

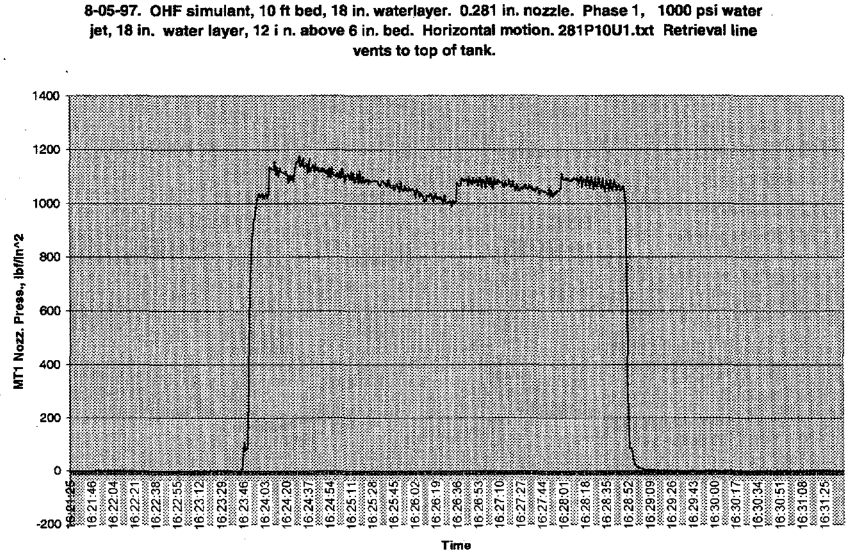

Figure 7.45 Run 6 - Waterjet Pressure During Phase 1

Phase 2 - Waterjet Dislodging and Retrieval. In Phase 2, the slurry in the supernate tank was used as the dislodging fluid. The slurry supply line feeding the high-pressure pump was connected to the bottom of the supernate tank. The retrieval line from the horizontal tank to the supernate tank emptied into the top of the supernate tank. With an 18-in.-deep supernate layer, only one waterjet dislodging phase was required to provide the desired dilution. Phase 2 consisted of 5.1 min of waterjet dislodging at an average pressure of 1076 psi. The pressure plot, shown in Figure 7.47, was taken from the computer screen print; no data file was available for this phase. The pressure trace starts with a spike at 1050 psi at 1 min and then from 2 to 6 min becomes relatively constant at 1100 psi. Another signal trace is also shown on the plot. At the completion of Phase 2, the fluid remaining in the horizontal tank was pumped down to a level of 12 in. The slurry was transferred to the supernate tank. Figure 7.48 shows the tank after the jet was stopped; again the slurry appears to be well mixed.

Phase 3 - Slurry-Jet Dislodging and Retrieval. In Phase 3, the slurry in the supernate tank was used as the dislodging fluid. The pressure plot is shown in Figure 7.49. The jet pressure averaged 1049±138 psi. The condition of the horizontal tank after completion of Phase 3 is shown in Figure 7.50. The tank was pumped to a level of 9 in. after completion of Phase 3.

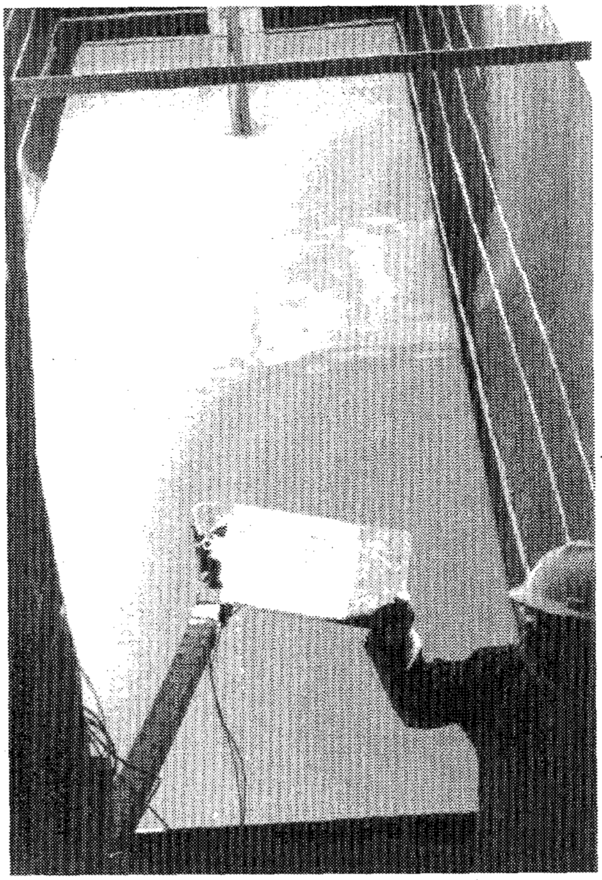

Figure 7.46 Run 6 - After Phase 1, 5.3 min of 1019 psi Waterjet Spray, 18-in. Liquid Layer

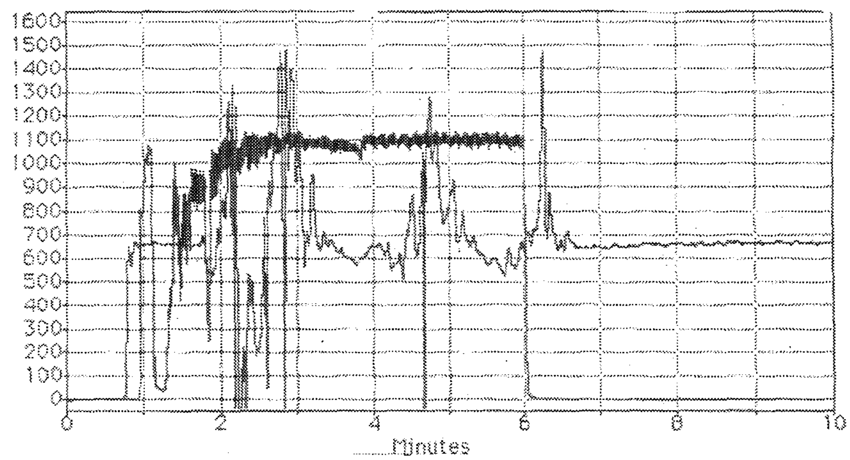

Figure 7.47 Run 6 - Waterjet Pressure During Phase 2

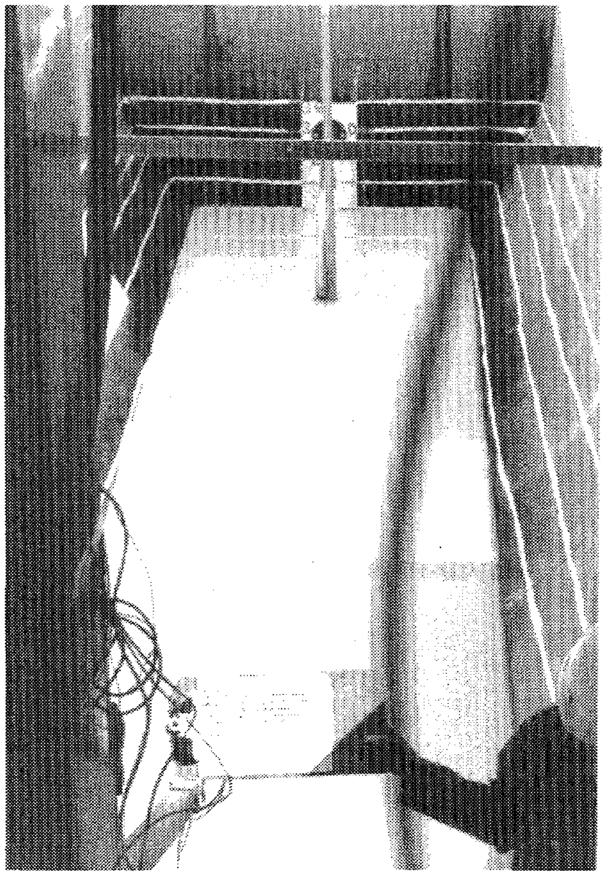

Figure 7.48 Run 6 - After Phase 2, 5.1 min of 1076 psi Waterjet Spray, 12-in. Liquid Layer

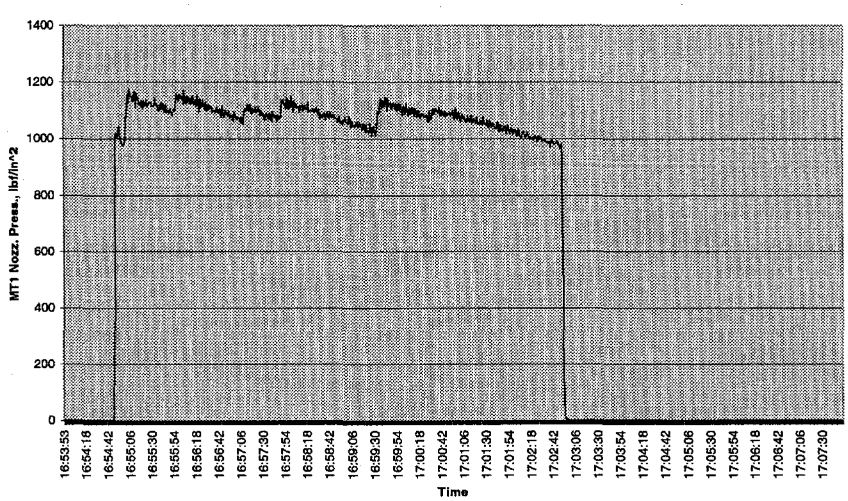

Figure 7.49 Run 6 - Slurry-Jet Pressure During Phase 3

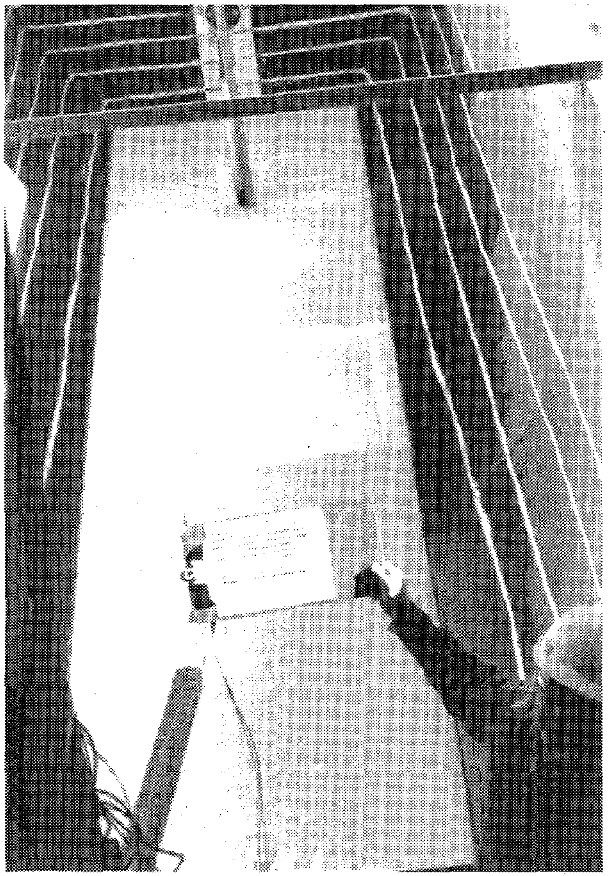

Figure 7.50 Run 6 - After Phase 3, 8.2 min of 1049 psi Slurry-Jet Spray, 9-in. Liquid Layer

Phase 4 - Slurry-Jet Dislodging and Retrieval. In Phase 4, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 1067±142 psi, as shown in Figure 7.51. The condition of the horizontal tank after completion of Phase 4 is shown in Figure 7.52. At the completion of Phase 4, the tank was pumped to a level of 6 in.

Phase 5 - Slurry-Jet Dislodging and Retrieval. In Phase 5, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 1081±90 psi, as shown in Figure 7.53. The condition of the horizontal tank after completion of Phase 5 is shown in Figure 7.54. The tank was pumped to a level of 2 in. at the completion of Phase 5. A few settled solids are visible at the edge of the liquid layer.

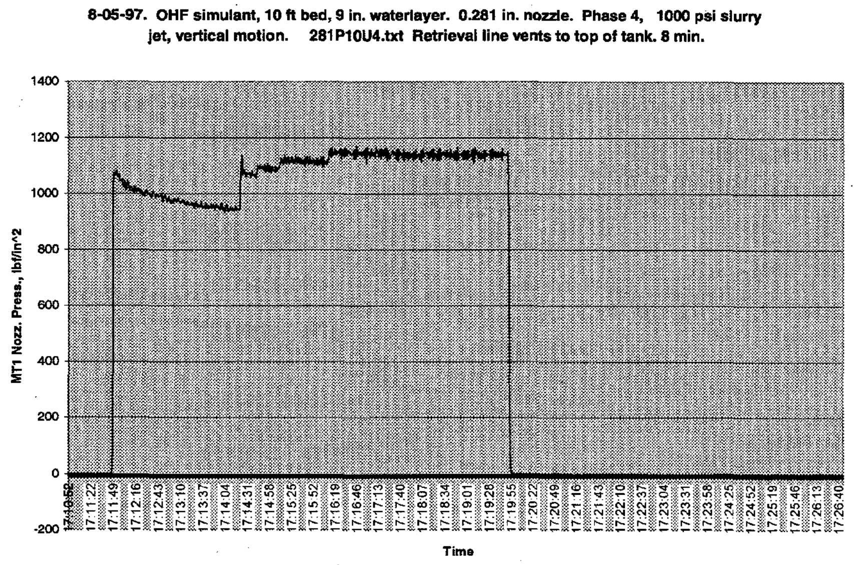

Figure 7.51 Run 6 - Waterjet Pressure During Phase 4

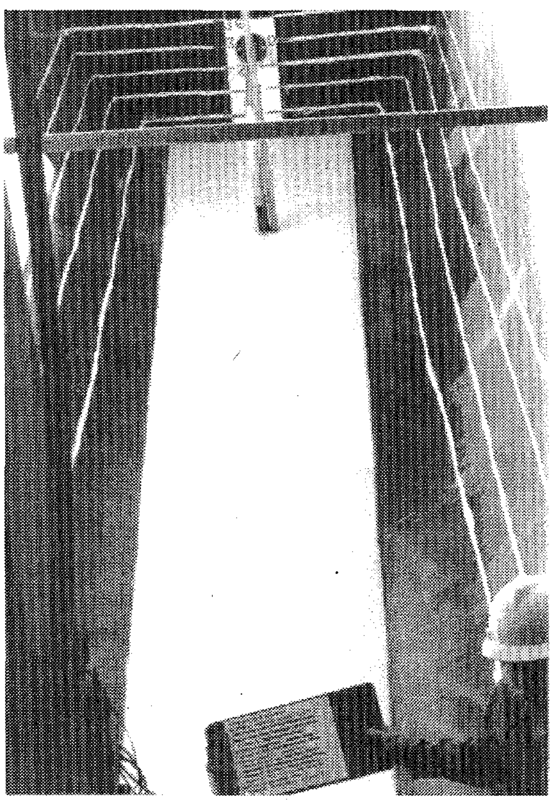

Figure 7.52 Run 6 - After Phase 4, 8.2 min of 1067 psi Slurry-Jet Spray, 6-in. Liquid Level

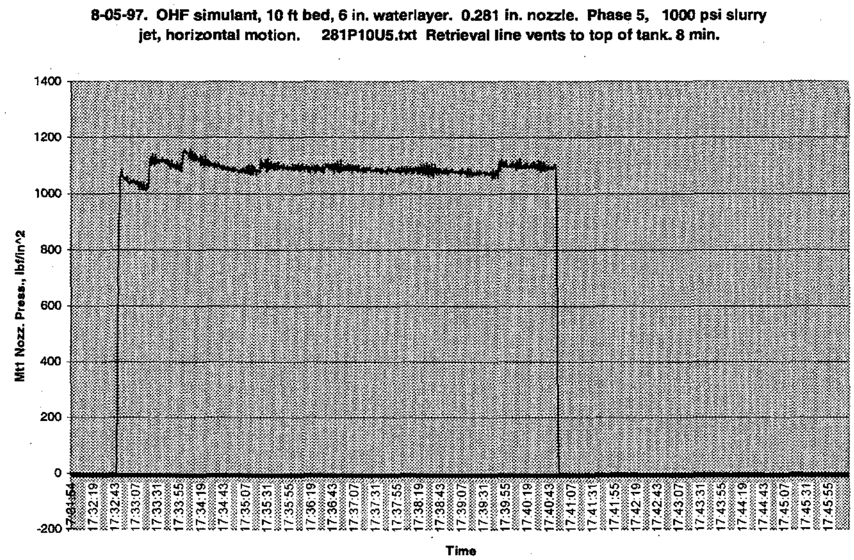

Figure 7.53 Run 6 - Waterjet Pressure During Phase 5

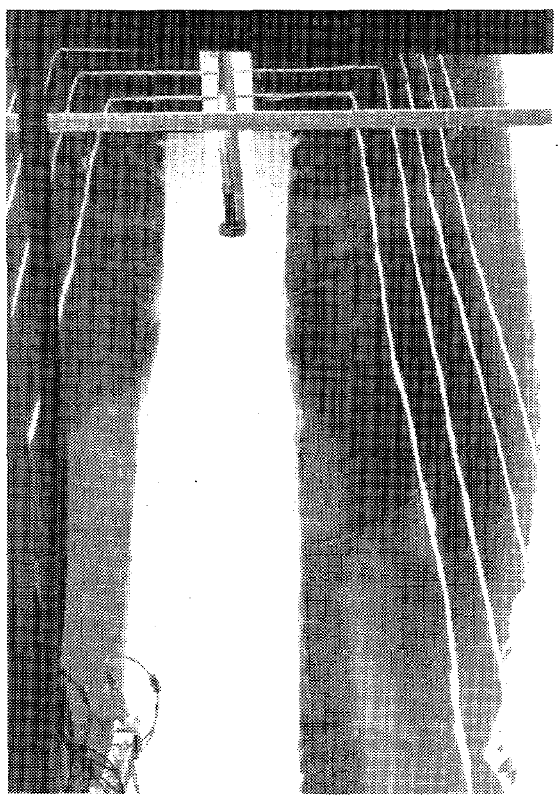

Figure 7.54 Run 6 - After Phase 5, 8.1 min of 1081 psi Waterjet Spray, 2-in. Liquid Layer

Phase 6 - Low-Pressure Waterjet Rinse. Phase 6 consisted of 2.2 min of waterjet rinse at an average pressure of 631±67 psi. The pressure plot is shown in Figure 7.55. In Phase 6, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.56 shows the tank after completion of Phase 6. The remaining liquid is a dilute slurry; the sides of the tank are clean.

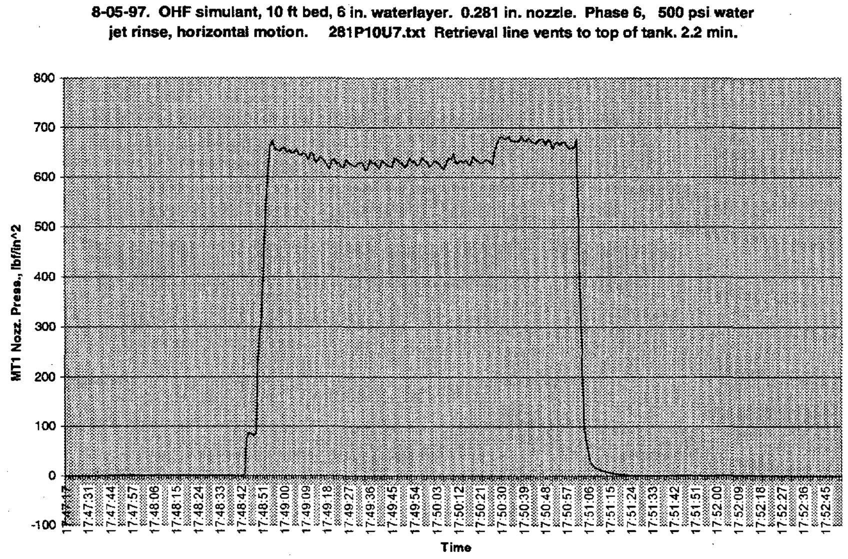

Figure 7.55 Run 6 - Waterjet Pressure During Phase 6 Waterjet Rinse

Phase 7 - Post Test. After completion of Phase 6, the fluid was drained from the tank and the tank photographed. The solids deposited in the tank during draining are shown in Figure 7.57. The solids at the nozzle end of the tank were not within the range of the extendible-nozzle. It is limited to angles greater than the 30 degree cone from the vertical.

Run 6 - Mass Balance. A summary of test conditions and a mass balance for Run 6 are shown in Table 7.17. The total inventory of solids and liquids added to the horizontal tank is shown under Horizontal Tank Input. After Phase 1, the wt% solids based on initial water addition was 10.9 wt%, near the target 10 wt%. This mass was compared to the supernate tank weight and the amount of recycled slurry to estimate the amount of retrieved slurry. The columns used in this estimate are marked with an *. About 98% of the slurry was retrieved. This compares well with an estimate of 97% for the amount of fluid remaining in the horizontal tank based on a calculation using the height of the fluid remaining in the horizontal tank.

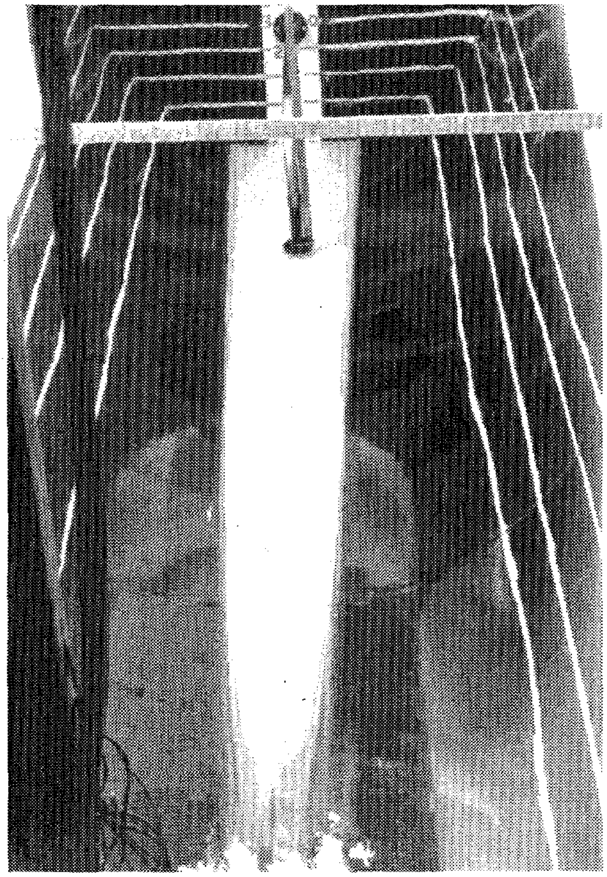

Figure 7.56 Run 6 - After Phase 6, 2.2 min of 631 psi Waterjet Rinse

Comparisons Between OHF-SS Runs

Direct comparisons between the OHF-SS runs can be made to evaluate the effect of simulant bed length, and the presence or absence of a supernate layer. The data from all the OHF-SS simulant runs is summarized in Table 7.18. All of the runs successfully dislodged and retrieved slurry from the horizontal tank. Based on mass balance, retrieval rates were all 97% or greater.

Simulant Bed Length. Run 1 and Run 3 can be directly compared. Run 1 was completed with a 5-ft simulant bed; Run 3 was completed with a 10-ft simulant bed. Based on mass balance, the runs successfully retrieved 97% and 99% of the slurry, respectively. When compared to the amount remaining in the tank, the Run 3 with larger inventory has the potential to retrieve a greater percent of the slurry. Both runs were completed with no solid chunks remaining in the tank. Run 1 was completed employing 8 min of 987 psi water spray and 8 min of 184 psi slurry spray. Run 3 was completed employing 16.7 min of ~970 psi water spray and 14.4 min of ~820 psi slurry spray.

Supernate Layer. Run 3 and Run 5 can be compared. Run 3 was completed with an exposed simulant bed; Run 5 was completed with a 12-in.-deep supernate layer. Run 3 retrieved 99% of the slurry based on mass balance; Run 5 retrieved 97% of the slurry based on mass balance.

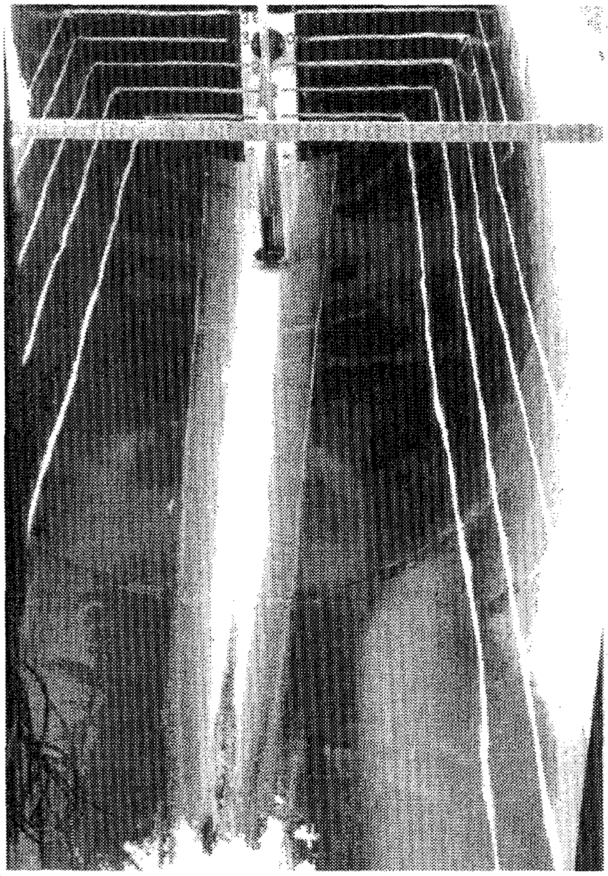

Figure 7.57 Run 6 - Solids Remaining in Tank After Slurry Drained at End of Phase 6

Table 7.17 Run 6 - Mass Balance Between Horizontal Tank and Supernate Tank

Phase	Horizontal Tank Input lbm			Average wt% Solids	Jet Slurry lbm	Super-nate Tank Weight lbm	Retrieved Slurry lbm	Total Retrieved Based on *-ed columns lbm	Percent Retrieved
	Solids	Water	Total						
0	1261	7129	8390						
1		3188	11578	10.9		3139*	3990	3139	27
2			11578	10.9		6976*		6976	60
3			11578	10.9	5236	8603*	7549	8603	74
4			11578	10.9	5257	9867*	8003	9867	85
5			11578	10.9	5315	10875*	7271	10875	94
6		1126	12704	9.9		12457*	11431	12457	98
Post Test	~0	350 lb remaining in horizontal tank, estimated from 2 in. water layer							97

Table 7.18 Performance Comparison Between OHF-SS Runs

Run	Nozzle Diameter in.	Simulant Bed Length ft	Supernate Level in.	Water Spray		Slurry Spray		Percent Retrieved Based On	
				min	psi	min	psi	Mass Balance	Fraction Remaining
1	0.310	5	2	7.7	987	8.2	184	97	95
3	0.310	10	2	16.7	971	14.4	528	99	98
5	0.310	10	12	10.6	983	24.3	986	97	97
6	0.281	10	18	5.3	1019	29.6	1067	98	97

7.6.2 OHF-HS Simulant Tests

Three tests were conducted using simulant OHF-HS, the sludge simulant with shear strength five times that of the sludge simulant designed to match rheological properties of OHF sludge. The differences between the tests are shown in Table 7.12. The first two tests were conducted using the 0.310-in.-diameter nozzle; the last test used the 0.281-in.-diameter nozzle. All tests were evaluated dislodging a 5-ft-long bed. The first test was conducted with no supernate layer; the last two tests were conducted with 12-in.-deep supernate layers. The first two tests were conducted with the retrieval pump 5 ft from the end of the tank, simulating the ORNL configuration of multiple-riser deployment. The last test was conducted with the retrieval pump inlet near the extendible-nozzle, simulating single-riser deployment.

Run 2 - OHF-HS Simulant with 5-ft Bed, 0.310-in.-Diameter Nozzle, No Supernate Layer

This run was similar to Run 1; however, OHF-HS simulant was dislodged instead of OHF-SS simulant. This run modeled unbalanced retrieval. The flow rate of the extendible-nozzle was greater than that of the retrieval pump. Therefore, after the flow to the extendible-nozzle stopped, retrieval continued until the tank was pumped down and the retrieval pump inlet was exposed. Run 2 consisted of two waterjet and two slurry-jet-dislodging and slurry-retrieval phases and a final waterjet rinse.

Phase 0 - Simulant Bed. The 5-ft-long simulant bed is shown in Figure 7.58. The bed contained 700 lbm of OHF-HS simulant.

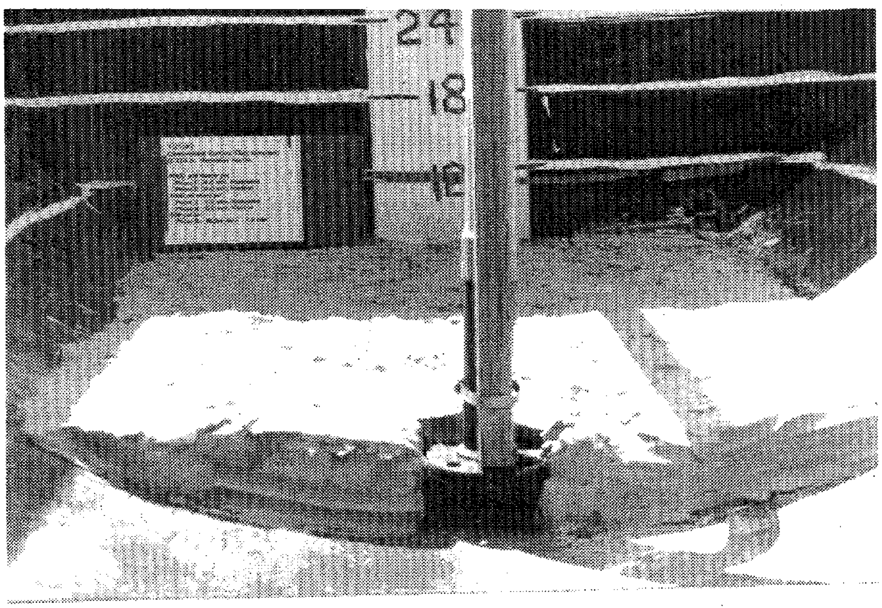

Figure 7.58 Run 2 - OHF-HS Simulant Bed Prior to Test

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 8.0 min of waterjet dislodging at an average pressure of 1016 psi. The pressure plot, shown in Figure 7.59, was taken from the computer screen print; no data file was available for this phase. The pressure trace starts at 1 min and continues to decrease with a series of four incremental increases. Another signal trace is also shown on the plot. At the completion of Phase 1, the fluid remaining in the horizontal tank was pumped down to a level of ~2 in. The slurry was transferred to the supernate tank. Figure 7.60 shows the tank after the jet was stopped. Several large blocks of clay simulant remain in the path of the jet. These blocks are similar in size to the blocks of clay used to make this simulant bed.

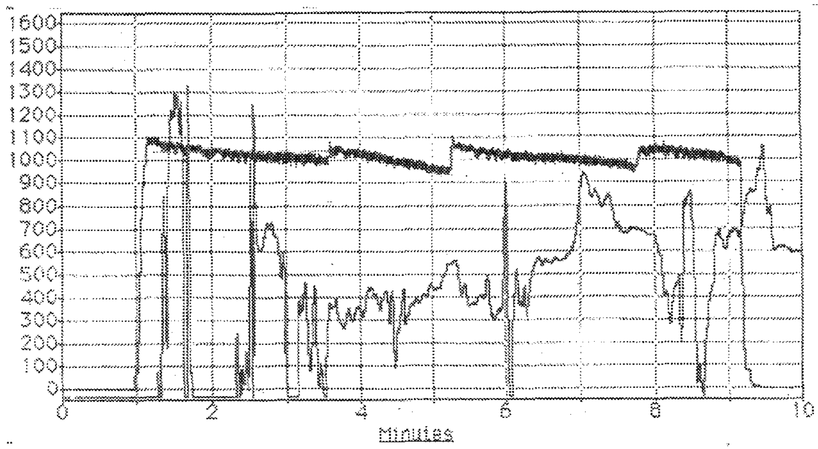

Figure 7.59 Run 2 - Waterjet Pressure During Phase 1

Phase 2 - Waterjet Dislodging and Retrieval. Phase 2 was a second waterjet dislodging run. Phase 2 consisted of 8.5 min of waterjet dislodging at an average pressure of 970 ± 203 psi. The pressure plot, shown in Figure 7.61, consists of four pressure cycles. At the completion of Phase 2, the fluid remaining in the horizontal tank was pumped down to a level of ~2 in. The slurry was transferred to the supernate tank. Figure 7.62 shows the tank after the jet was stopped. Simulant chunks are visible along the end of the tank. However, much of the blocks present at the end of Phase 1 have been eroded.

Phase 3 - Slurry-Jet Dislodging and Retrieval. In Phase 3, the slurry in the supernate tank was used as the dislodging fluid. Both the slurry line feeding the high-pressure pump and the retrieval line from the horizontal tank were connected to the bottom of the supernate tank. This configuration starved the high-pressure pump feed; therefore, the jet pressure averaged 91±112 psi as shown in Figure 7.63. The initial pressure of >500 psi occurred at start up. The phase was completed at this lower-than-desired jet pressure. The condition of the horizontal tank after completion of Phase 3 is shown in Figure 7.64. The tank was pumped to a level of ~2 in. after completion of Phase 3. Most solids have been turned into slurry; a few chunks remain at the end of the tank.

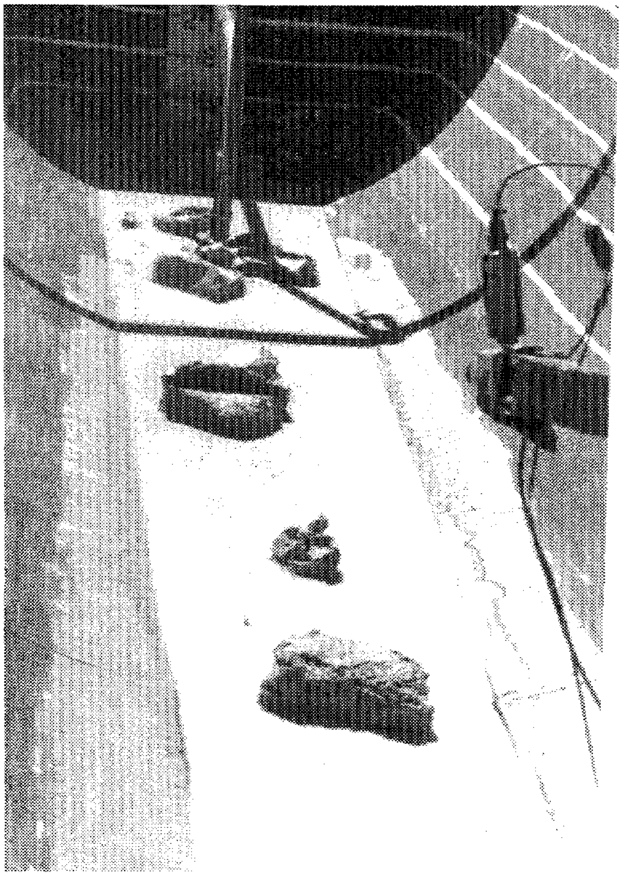

Figure 7.60 Run 2 - After Phase 1, 8.0 min of 1016 psi Waterjet Spray

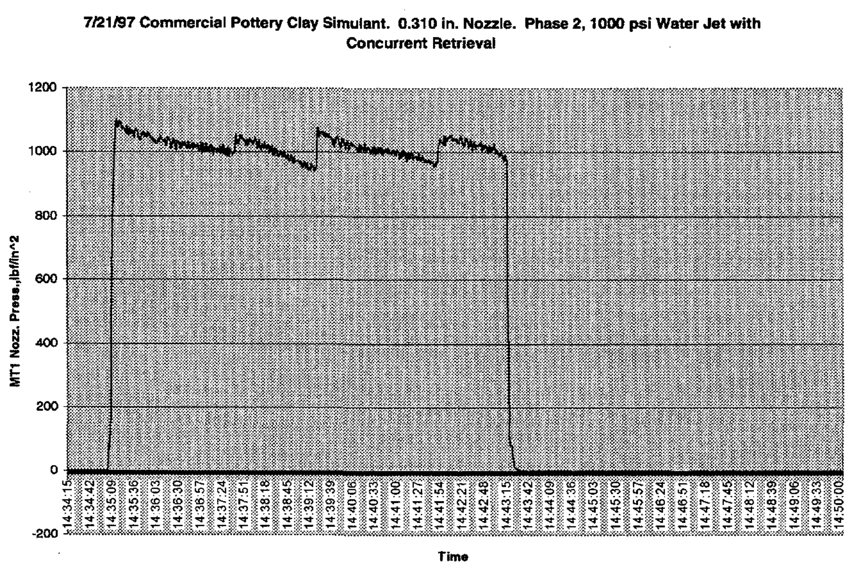

Figure 7.61 Run 2 - Waterjet Pressure During Phase 2

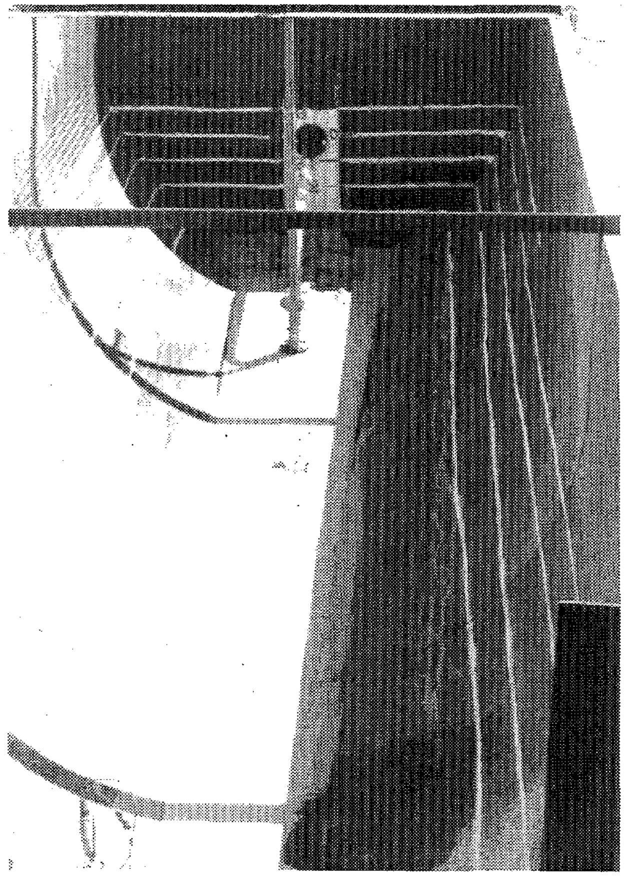

Figure 7.62 Run 2 - After Phase 2, 8.5 min of 970 psi Waterjet Spray

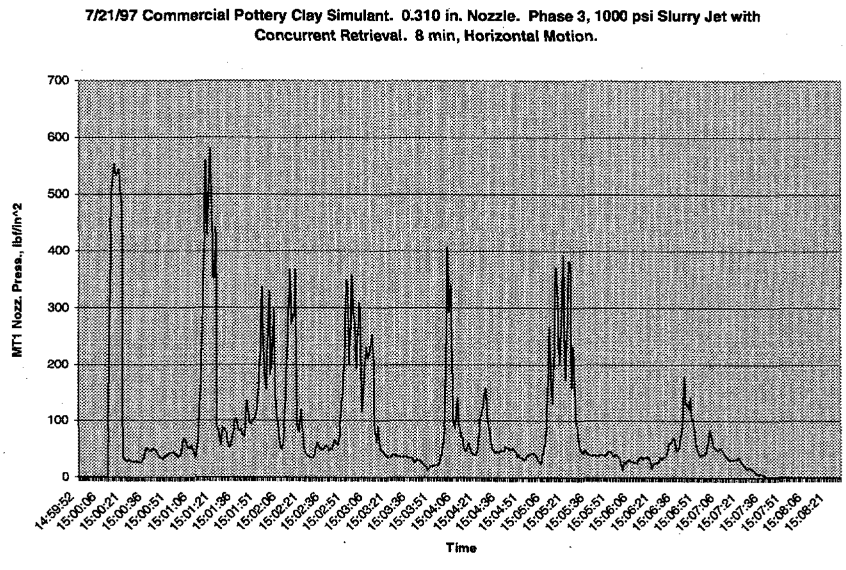

Figure 7.63 Run 2 - Slurry-Jet Pressure During Phase 3

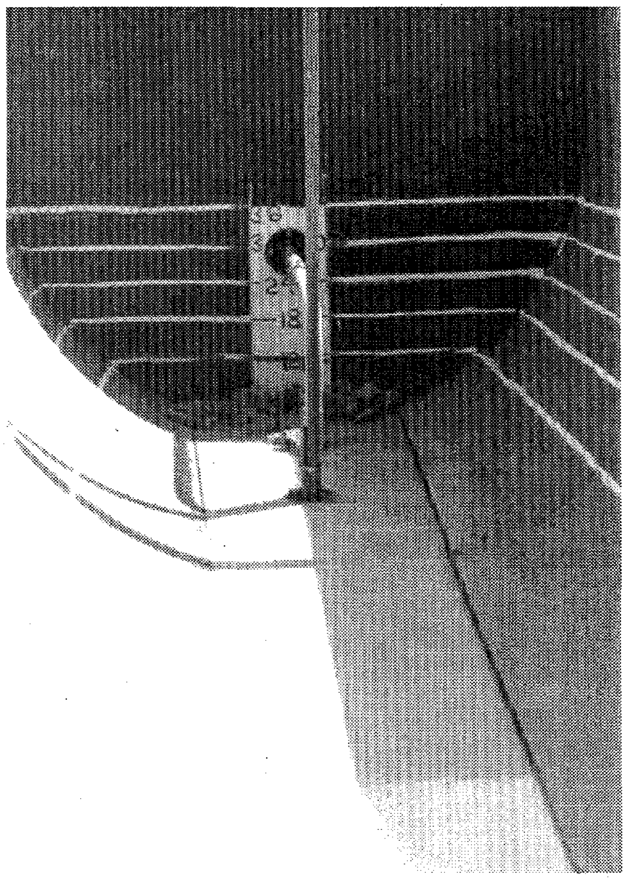

Figure 7.64 Run 2 - After Phase 3, 8.0 min of 911 psi Slurry-Jet Spray

Phase 4 - Slurry-Jet Dislodging and Retrieval. Prior to the start of Phase 4, the piping was reconfigured to route the retrieval line from the horizontal tank to empty into the top of the supernate tank. The slurry line feeding the high-pressure pump remained connected to the bottom of the supernate tank. In Phase 4, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 864±262 psi, as shown in Figure 7.65. The condition of the horizontal tank after completion of Phase 4 is shown in Figure 7.66. At the completion of Phase 4 the tank was pumped to a level of ~2 in. The solids have been dislodged from the end of the tank; they are now closer to the retrieval pump inlet.

Phase 5 - Low-Pressure Waterjet Rinse. Phase 5 consisted of 2.2 min of waterjet rinse at an average pressure of 532±22 psi. The pressure plot is shown in Figure 7.67. In Phase 5, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.68 shows the tank after completion of Phase 5. The remaining liquid is a dilute slurry with a few clay chunks behind the retrieval pump; the sides of the tank are clean. After the end of the test, the solids remaining in the tank were removed and weighed. The total weight of solids remaining was 66 lbm.

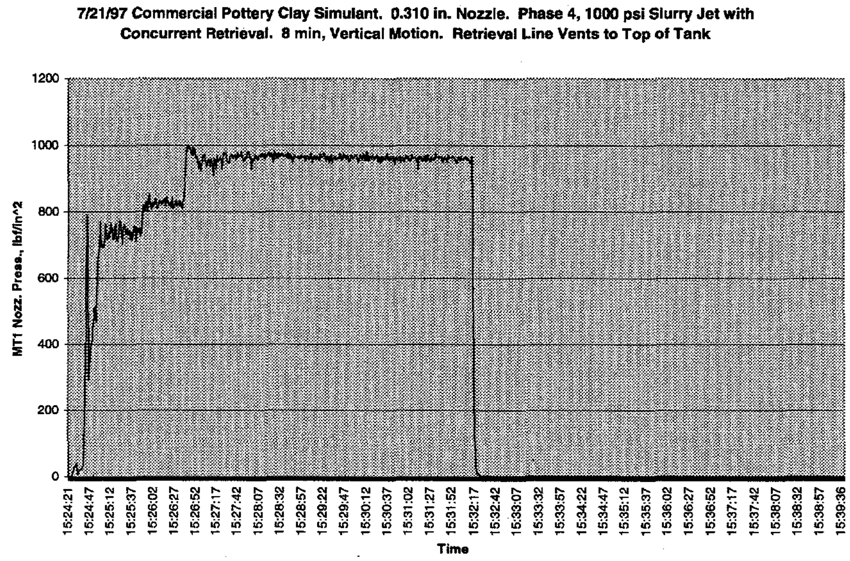

Figure 7.65 Run 2 - Waterjet Pressure During Phase 4

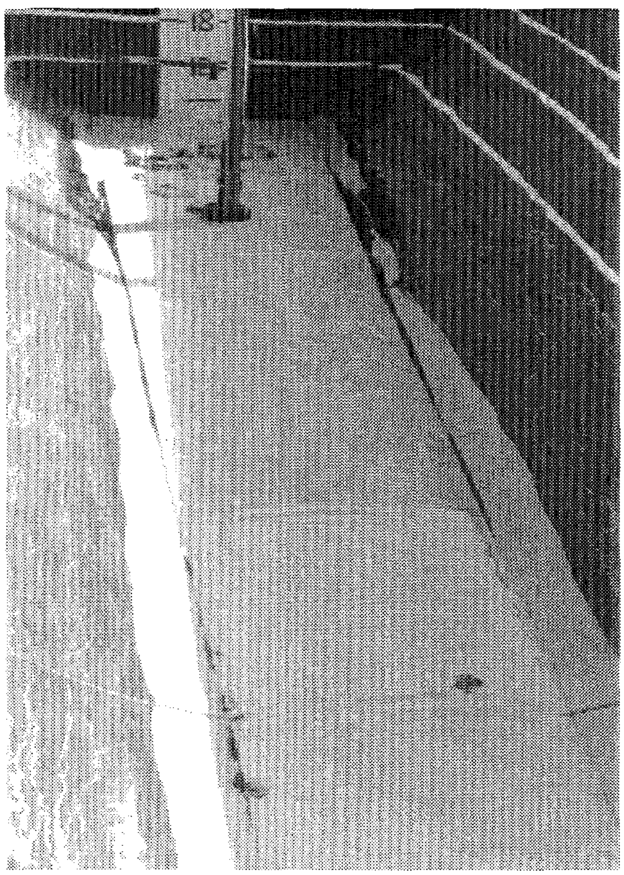

Figure 7.66 Run 2 - After Phase 4, 8.2 min of 864 psi Slurry-Jet Spray

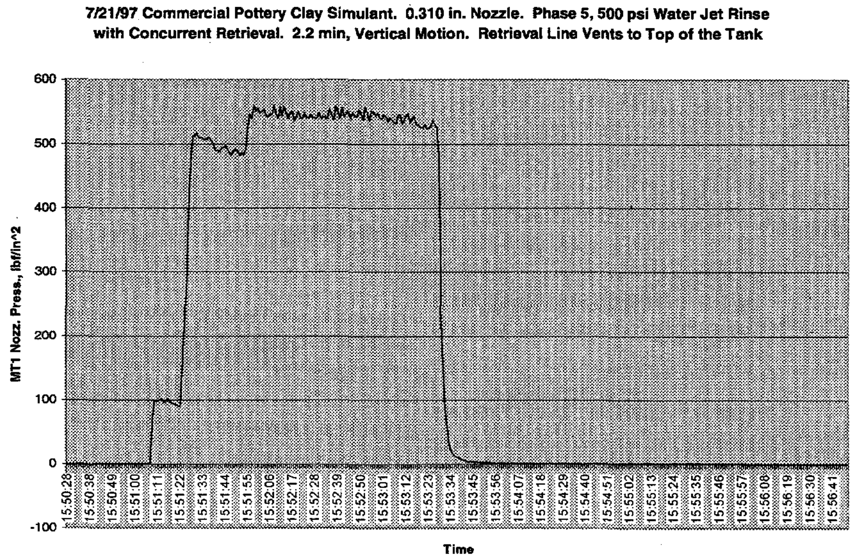

Figure 7.67 Run 2 - Waterjet Pressure During Phase 5

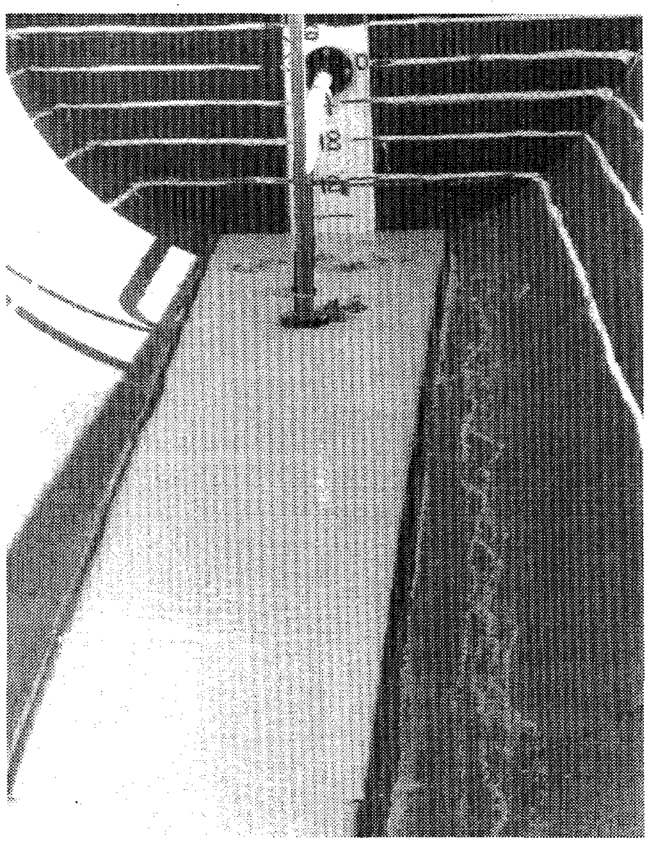

Figure 7.68 Run 2 - After Phase 5, 2.2 min of 532 psi Waterjet Rinse

Run 2 - Mass Balance. A summary of test conditions and a mass balance for Run 2 are shown in Table 7.19. The total inventory of solids and liquids added to the horizontal tank is shown under Horizontal Tank Input. After Phase 1, the wt% solids based on initial water addition was 10.3 wt%, near the target of 10 wt%. This mass was compared to the supernate tank weight and the amount of recycled slurry to estimate the amount of retrieved slurry. The columns used in this estimate are marked with an *. About 96% of the slurry was retrieved. This compares well with an estimate of 97% for the amount of fluid remaining in the horizontal tank based on a calculation using the height of the fluid remaining in the horizontal tank.

Table 7.19 Run 2 - Mass Balance Between Horizontal Tank and Supernate Tank

Phase	Horizontal Tank Input lbm			Average wt% Solids	Jet Slurry lbm	Super-nate Tank Weight lbm	Retrieved Slurry lbm	Total Retrieved Based on *-ed Columns lbm	Percent Retrieved
	Solids	Water	Total						
1	700	6056	6756	10.4		5031*		5031	74
2		6263	13019	5.4		10868*	5541	10868	83
3			13019	5.4		10883*	12741	10883	84
4			13019	5.4	5522*	10600	7380*	12741	81
5			14262	4.9		11809	923*	13665	96
Post Test	66	416 lbm	416 lbm remaining in horizontal tank, estimated from 2 in. water layer (350 lbm) + 66 lbm solids						97

Run 4 - OHF-HS Simulant with 5-ft Bed, 0.310-in.-Diameter Nozzle, Supernate Layer

This run was similar to Run 2; however, the 5-ft simulant bed was covered with 6 in. of supernate for a total liquid height of 12 in. This run modeled unbalanced retrieval. The flow rate of the extendible-nozzle was greater than that of the retrieval pump. Therefore, after the flow to the extendible-nozzle stopped, retrieval continued until the tank was pumped down to the prescribed supernate level. The supernate level started at 12 in. and decreased over the five phases to ~2 in. Run 4 consisted of one waterjet and three slurry-jet-dislodging and slurry retrieval phases and a final waterjet rinse.

Phase 0 - Simulant Bed. The 5-ft-long simulant bed is shown in Figure 7.69. The bed contained 700 lbm of OHF-HS simulant. To simulate the supernate layer, the waterjet was operated at a low pressure to fill the horizontal tank to the prescribed water depth. The bed was not disturbed during the filling process. The supernate covered bed is shown in Figure 7.70. The liquid is up to the 12-in. line painted around the edge of the tank. The undisturbed bed is visible through the supernate layer.

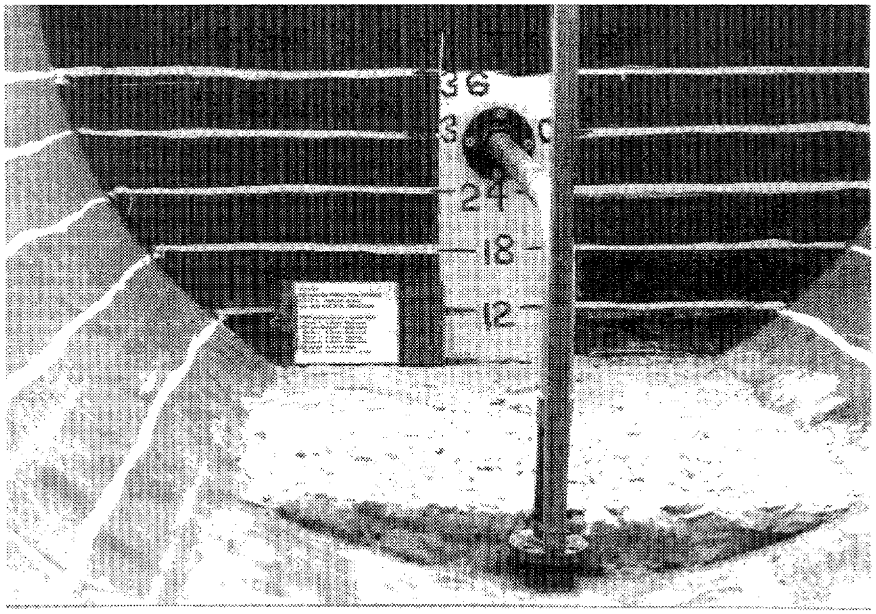

Figure 7.69 Run 4 - OHF-HS Simulant Bed Prior to Test

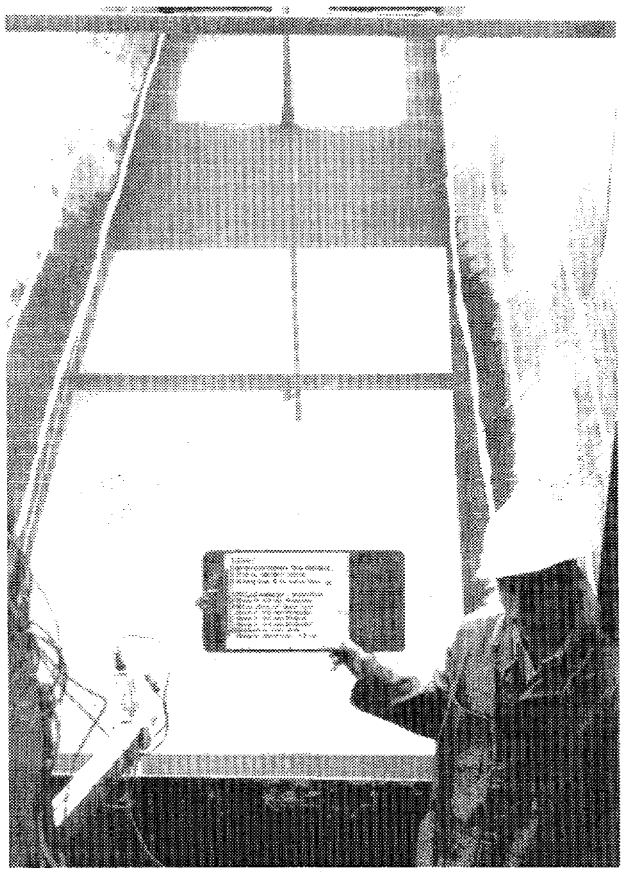

Figure 7.70 Run 4 - OHF-HS Simulant Covered with Supernate

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 4.9 min of waterjet dislodging at an average pressure of 992±311 psi. The pressure plot, shown in Figure 7.71, showed that the pressure remained constant throughout the test. At the completion of Phase 1, the fluid remaining in the horizontal tank was pumped down to a level of 12 in. The slurry was transferred to the supernate tank. Figure 7.72 shows the tank after the jet was stopped. The solids are well dispersed in the slurry; no solid chunks are visible beneath the 12-in. supernate layer.

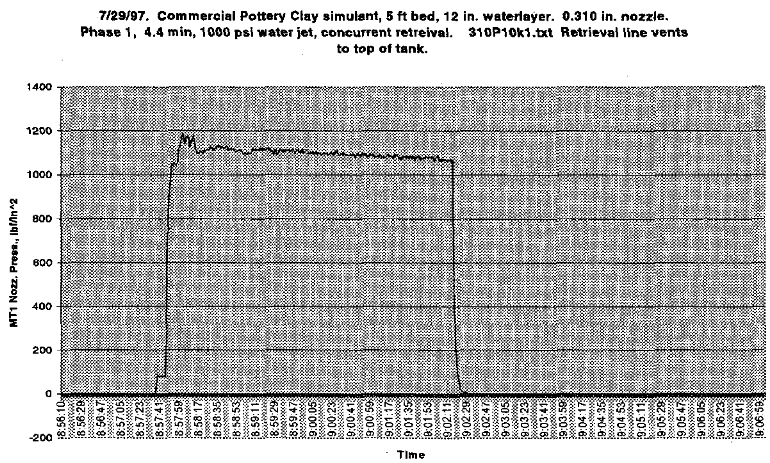

Figure 7.71 Run 4 - Waterjet Pressure During Phase 1

Phase 2 - Waterjet Dislodging and Retrieval. In Phase 2, the slurry in the supernate tank was used as the dislodging fluid. The slurry line feeding the high-pressure pump suction was connected to the bottom of the supernate tank. This configuration provided adequate flow to the high-pressure pump feed to sustain high-pressure operation. The retrieval line from the horizontal tank to the supernate tank empties into the top of the supernate tank. Phase 2 consisted of 8.1 min of waterjet dislodging at an average pressure of 964 psi. The pressure plot, shown in Figure 7.73, was relatively constant. At the completion of Phase 2 the fluid remaining in the horizontal tank was pumped down to a level of 6 in. The slurry was transferred to the supernate tank. Figure 7.74 shows the tank after the jet was stopped. Two small simulant chunks are visible in front of the jet and more chunks are piled along the end of the tank.

Phase 3 - Slurry-Jet Dislodging and Retrieval. Phase 3 was a repeat of Phase 2; the slurry in the supernate tank was used as the dislodging fluid. The pressure plot is shown in Figure 7.75. The jet pressure averaged 1040±129 psi. The condition of the horizontal tank after completion of Phase 3 is shown in Figure 7.76. The tank was pumped to a level of ~2 in. after completion of Phase 3. Several large chunks remain centered in the tank. Settled solids are visible along the edges of the supernate layer.

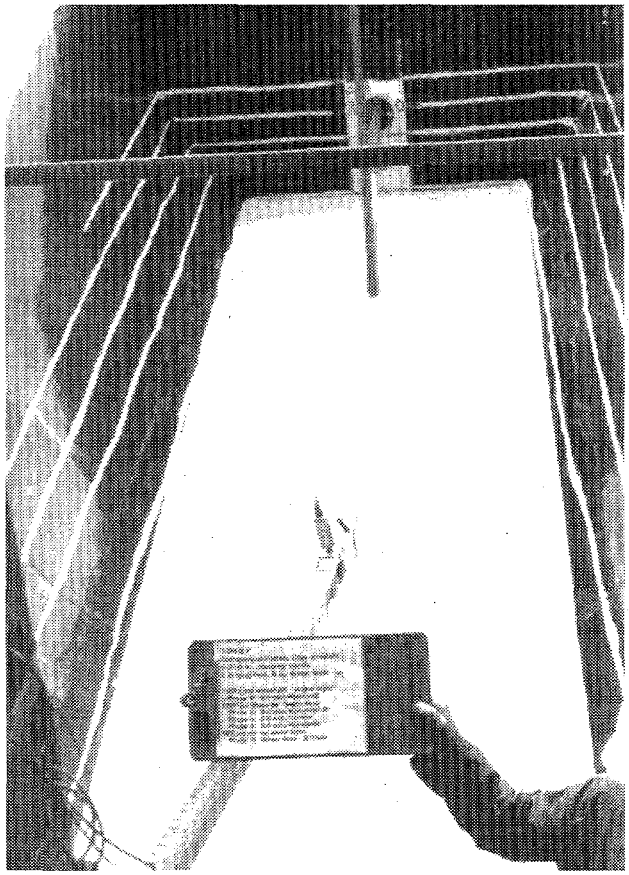

Figure 7.72 Run 4 - After Phase 1, 4.9 min of 992 psi Waterjet Spray, 12-in. Liquid Layer

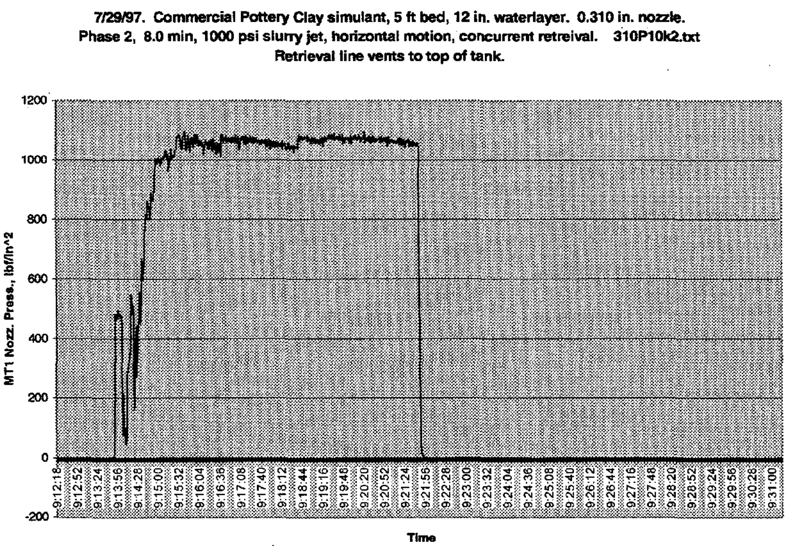

Figure 7.73 Run 4 - Waterjet Pressure During Phase 2

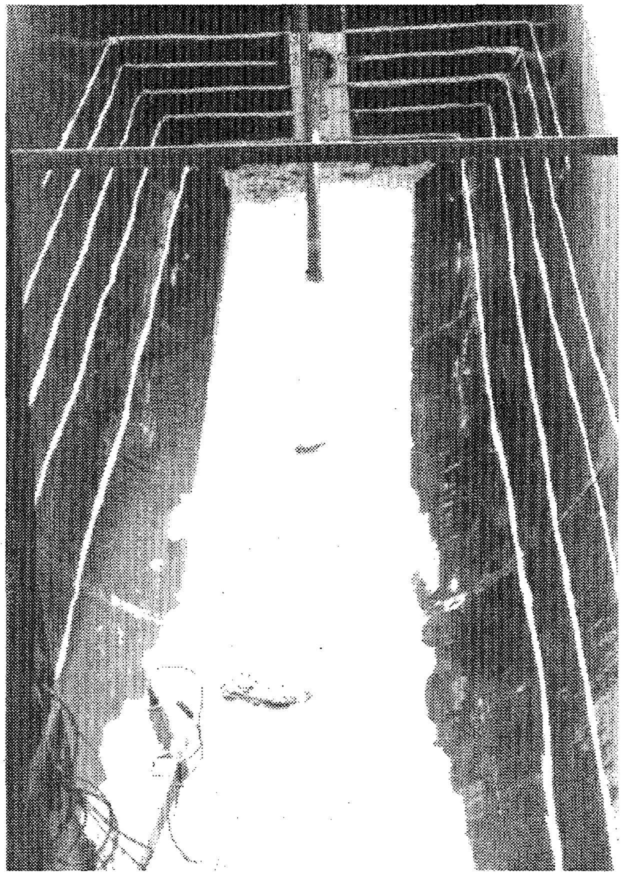

Figure 7.74 Run 4 - After Phase 2, 8.1 min of 964 psi Waterjet Spray, 6-in. Liquid Layer

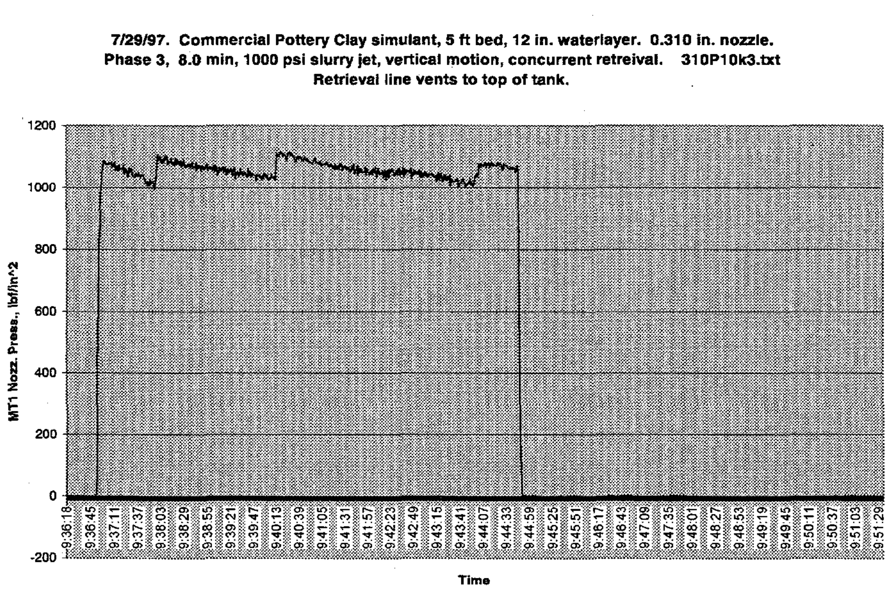

Figure 7.75 Run 4 - Slurry-Jet Pressure During Phase 3

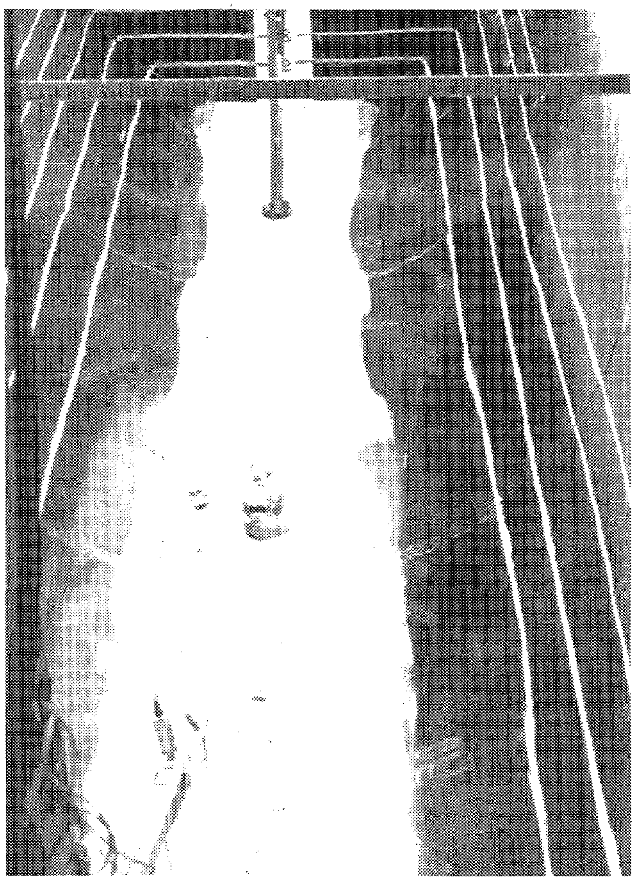

Figure 7.76 Run 4 - After Phase 3, 8.0 min of 1040 psi Slurry-Jet Spray

Phase 4 - Slurry-Jet Dislodging and Retrieval. In Phase 4, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 993±116 psi, as shown in Figure 7.77. The condition of the horizontal tank after completion of Phase 4 is shown in Figure 7.78. At the completion of Phase 4, the tank was pumped to a level of ~2 in. No solid chunks are visible; settled solids are visible along the sides of the tank above the supernate layer.

Phase 5 - Low-Pressure Waterjet Rinse. Phase 5 consisted of 2.2 min of waterjet rinse at an average pressure of 396±42 psi. The pressure plot is shown in Figure 7.79. In Phase 5, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.80 shows the tank after completion of Phase 5. The remaining liquid is a dilute slurry; the sides of the tank are clean. After the end of the test, the solids remaining in the tank were removed and weighed. The solids, shown in Figure 7.81, weighed 1.8 lbm.

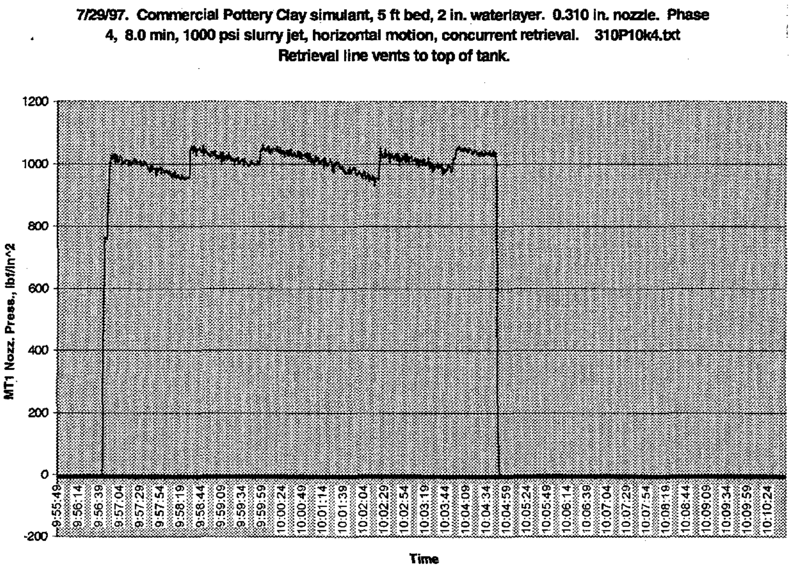

Figure 7.77 Run 4 - Waterjet Pressure During Phase 4

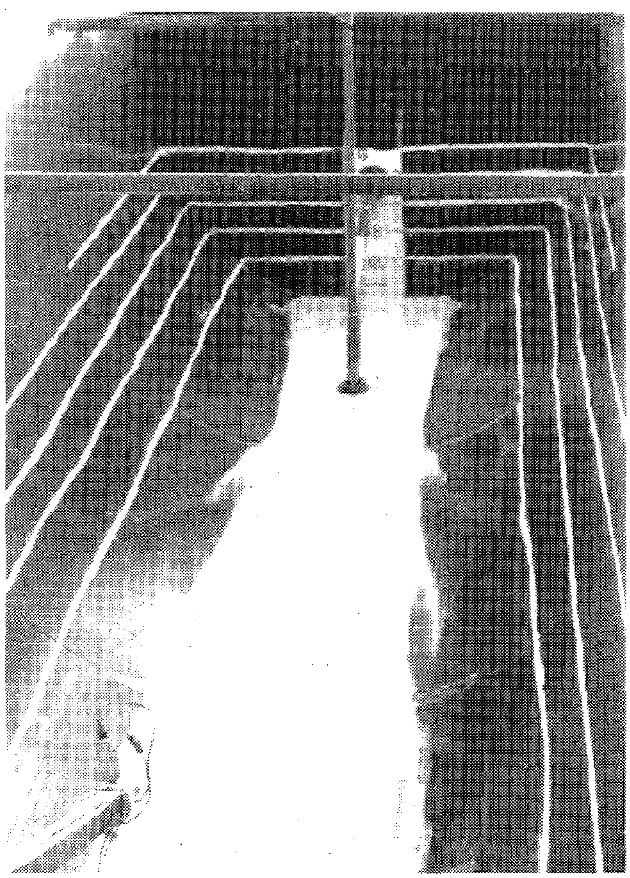

Figure 7.78 Run 4 - After Phase 4, 8.2 min of 993 psi Slurry-Jet Spray

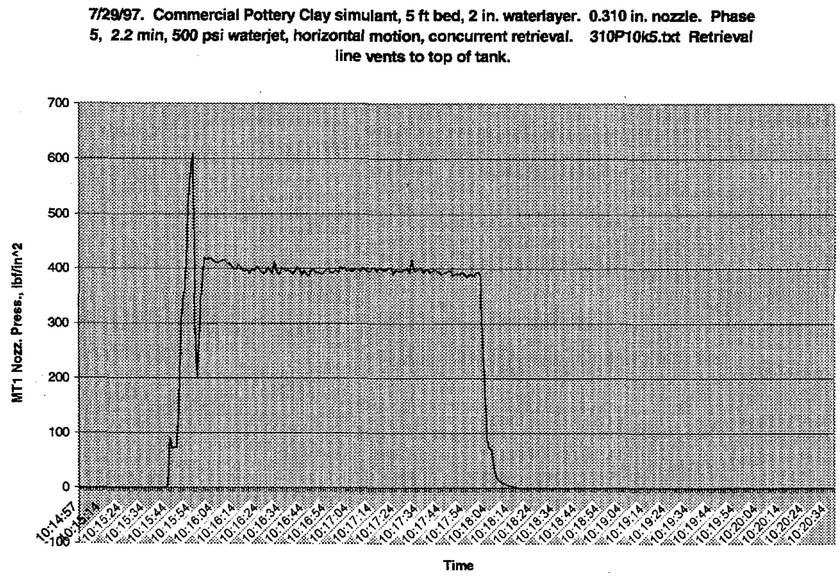

Figure 7.79 Run 4 - Waterjet Pressure During Phase 5

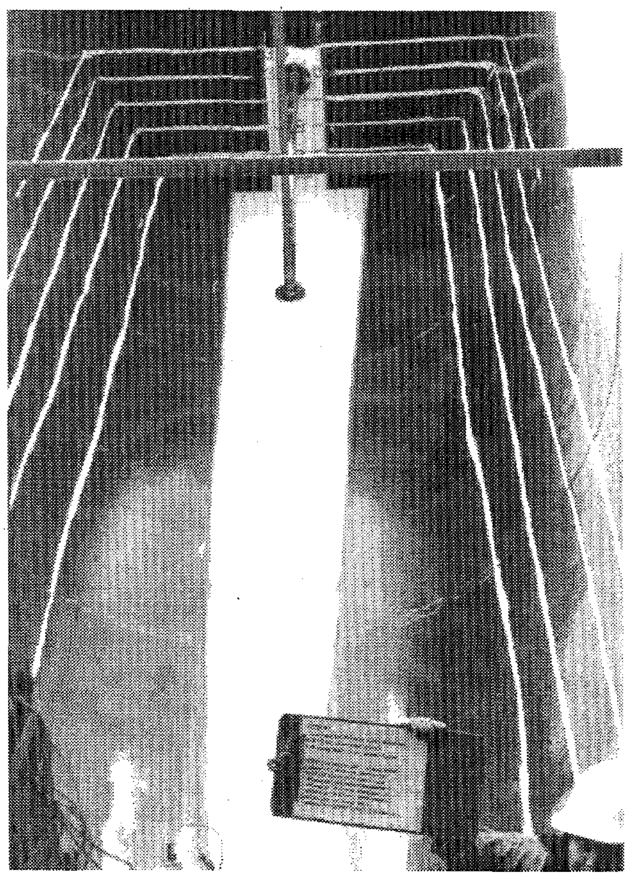

Figure 7.80 Run 4 - After Phase 5, 2.2 min of 396 psi Waterjet Rinse

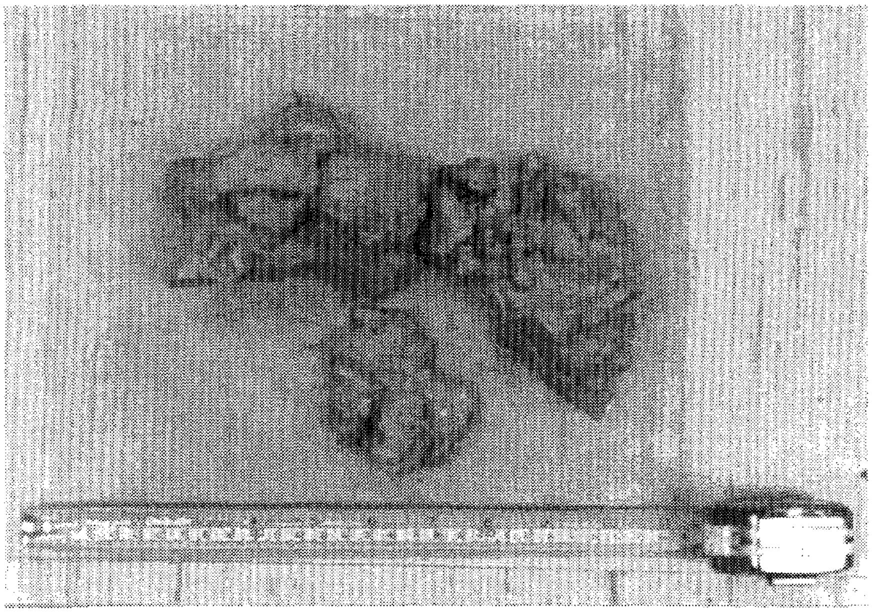

Figure 7.81 Run 4 - Solids Removed from Tank After Test

Run 4 - Mass Balance. A summary of test conditions and a mass balance for Run 4 are shown in Table 7.20. The total inventory of solids and liquids added to the horizontal tank is shown under Horizontal Tank Input. The initial quantity of water used for the supernate layer was calculated based on the volume of the tank; no data for Phase 0 was available. After Phase 1, the wt% solids based on initial water addition was 5.4 wt%; obtaining 10 wt% solids with a 12-in.-liquid layer was not attainable. This mass was compared to the supernate tank weight and the amount of recycled slurry to estimate the amount of retrieved slurry. The columns used in this estimate are marked with an *. Based on the estimate of initial supernate volume, >100% of the slurry was calculated to be removed. The estimate of 98% for the amount of fluid remaining in the horizontal tank based on a calculation using the height of the fluid remaining in the horizontal tank seems plausible.

Table 7.20 Run 4 - Mass Balance Between Horizontal Tank and Supernate Tank

Phase	Horizontal Tank Input lbm			Average wt% Solids	Jet Slurry lbm	Super-nate Tank Weight lbm	Retrieved Slurry lbm	Total Retrieved Based on *-ed columns lbm	Percent Retrieved
	Solids	Water	Total						
0	700	8535[(a)]	9235						
1		3703	12938	5.4		3456	4569*	4569	35
2			12938	5.4	6057*	6501	10564*	9076	70
3			12938	5.4	6473*	7076	8905*	11508	89
4			12938	5.4	6532*	6875	7609*	12585	97
5		1155	14093	5.0		9686	1730*	14315	>100
Post Test	2	352 lbm	352 lbm remaining in horizontal tank, estimated from 2 in. water layer (350 lbm) + 2 lbm solids						98

(a) Amount of water estimated based on the calculated volume of a 12-in.-deep supernate layer.

Run 9 - Single-Riser Retrieval, OHF-HS Simulant with 5-ft Bed, 0.281-in.-Diameter Nozzle, Supernate Layer

Run 9 was the only run to model single-riser retrieval. The retrieval line was attached to the tank end near the extendible-nozzle, as shown in Figure 7.82. Also the smallest nozzle diameter, 0.281 in., was tested. This run modeled balanced retrieval; the flow rate of the extendible-nozzle at 1000 psi using the 0.281-in.-diameter nozzle was approximately equal to that of the retrieval pump. Therefore, the retrieval pump was stopped immediately after flow to the extendible-nozzle stopped. The supernate level started at 12 in. and decreased over the five phases to ~2 in. Run 9 consisted of one waterjet and three slurry-jet-dislodging and slurry retrieval phases and a final waterjet rinse.

Phase 0 - Simulant Bed. The 5-ft-long simulant bed is shown in Figure 7.83. The bed contained 700 lbm of OHF-HS simulant. To simulate the supernate layer, the waterjet was operated at a low pressure to fill the horizontal tank to the prescribed water depth. The bed was not disturbed during the filling process. The supernate covered bed is shown in Figure 7.84. The liquid is up to the 12-in. line painted around the edge of the tank. The undisturbed bed is visible through the supernate layer.

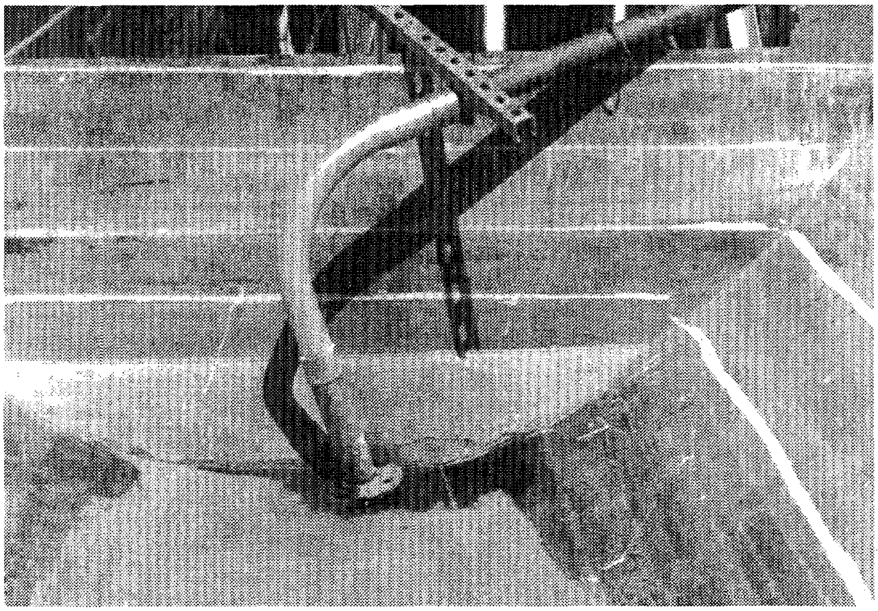

Figure 7.82 Run 9 - Retrieval Pump Inlet Configuration at Nozzle End of Tank

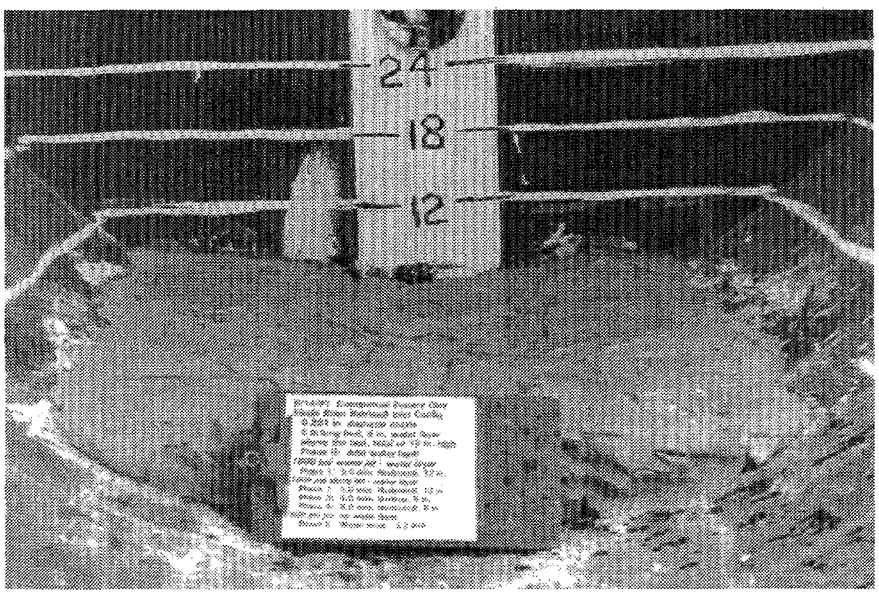

Figure 7.83 Run 9 - OHF-HS Simulant Bed Prior to Test, Retrieval Pump at Nozzle End of Tank

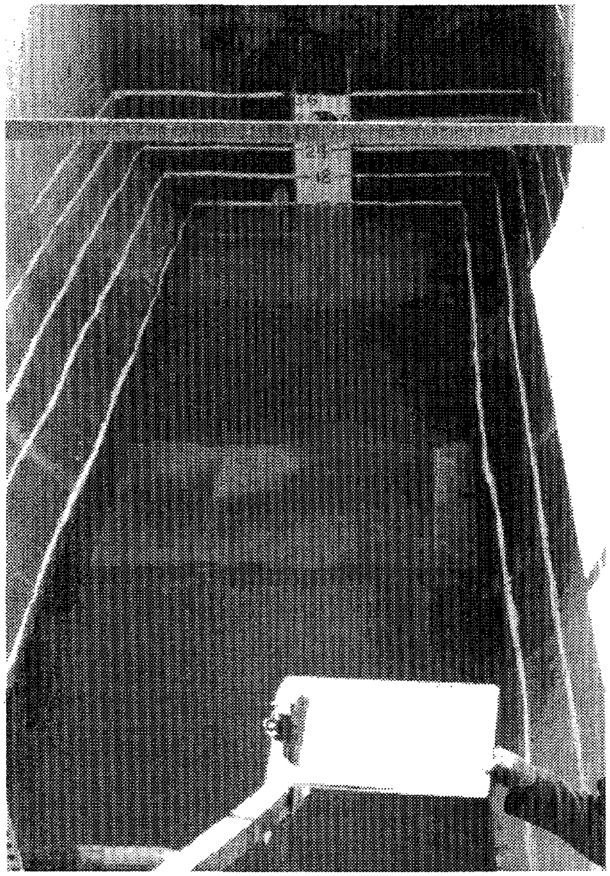

Figure 7.84 Run 9 - OHF-HS Simulant Covered with Supernate, Retrieval Pump at Nozzle End of Tank

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 5.0 min of waterjet dislodging at an average pressure of 1140±29 psi. The pressure plot, shown in Figure 7.85, showed that the pressure remained relatively constant throughout the test. At the completion of Phase 1, the fluid remaining in the horizontal tank was pumped down to a level of 12 in. The slurry was transferred to the supernate tank. Figure 7.86 shows the tank after the jet was stopped. The solids are well dispersed in the slurry; no solid chunks are visible beneath the 12-in. supernate layer.

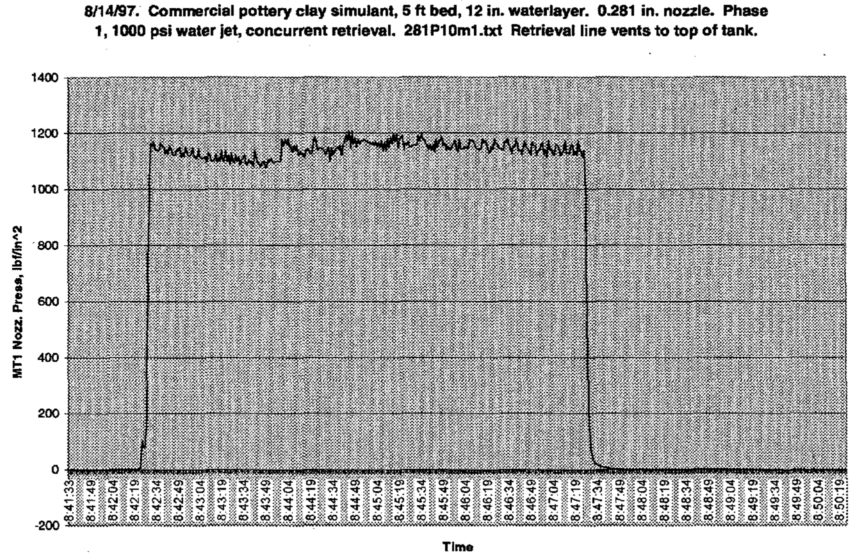

Figure 7.85 Run 9 - Waterjet Pressure During Phase 1

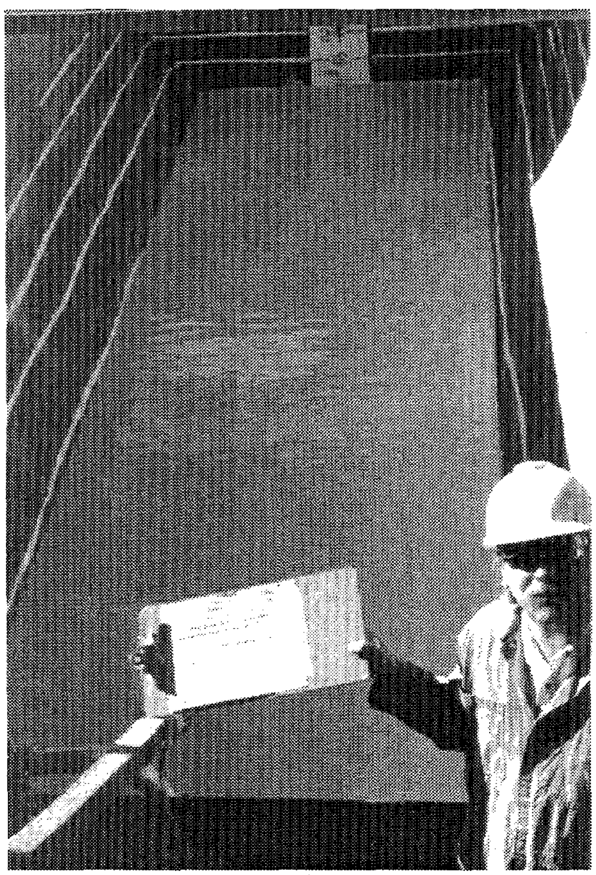

Figure 7.86 Run 9 - After Phase 1, 5.0 min of 1140 psi Waterjet Spray, 12-in. Liquid Layer

Phase 2 - Waterjet Dislodging and Retrieval. In Phase 2, the slurry in the supernate tank was used as the dislodging fluid. The slurry line feeding the high-pressure pump suction was connected to the bottom of the supernate tank. This configuration provided adequate flow to the high-pressure pump feed to sustain high-pressure operation. The retrieval line from the horizontal tank to the supernate tank empties into the top of the supernate tank. Phase 2 consisted of 8.0 min of waterjet dislodging at an average pressure of 1160±32 psi. The pressure plot, shown in Figure 7.87, was relatively constant. At the completion of Phase 2, the fluid remaining in the horizontal tank was pumped down to a level of 9 in. The slurry was transferred to the supernate tank. Figure 7.88 shows the tank after the jet was stopped. The slurry is well mixed, although simulant chunks are visible piled up at the end of the tank.

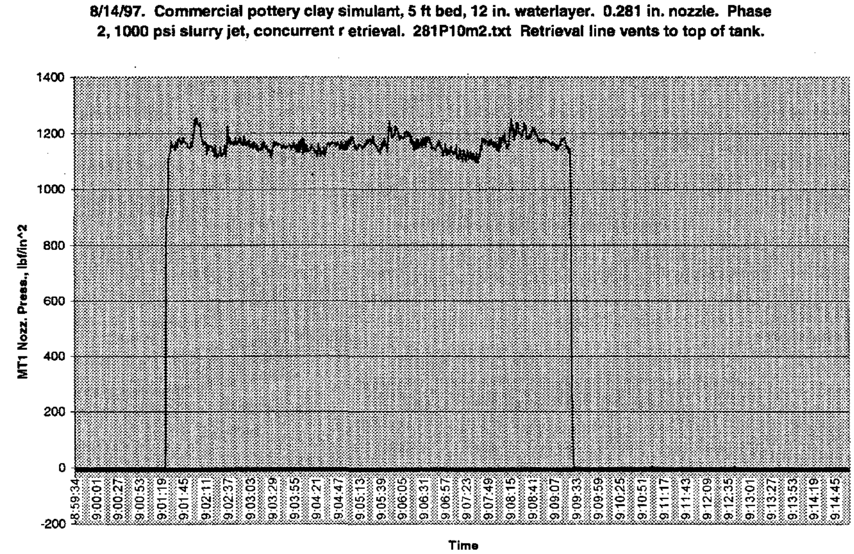

Figure 7.87 Run 9 - Waterjet Pressure During Phase 2

Phase 3 - Slurry-Jet Dislodging and Retrieval. Phase 3 was a repeat of Phase 2; the slurry in the supernate tank was used as the dislodging fluid. The pressure plot is shown in Figure 7.89. The jet pressure averaged 1160±34 psi. The condition of the horizontal tank after completion of Phase 3 is shown in Figure 7.90. The tank was pumped to a level of 6 in. after completion of Phase 3. The solids piled at the end of the tank have been dislodged.

Phase 4 - Slurry-Jet Dislodging and Retrieval. In Phase 4, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 1151±33 psi, as shown in Figure 7.91. The condition of the horizontal tank after completion of Phase 4 is shown in Figure 7.92. At the completion of Phase 4, the tank was pumped to a level of ~4 in. The horizontal tank sloped toward the far end; therefore with the retrieval pump at the extendible-nozzle end of the tank, the fluid depth was increased. Two small solid chunks are visible; settled solids are visible along the sides of the tank above the supernate layer.

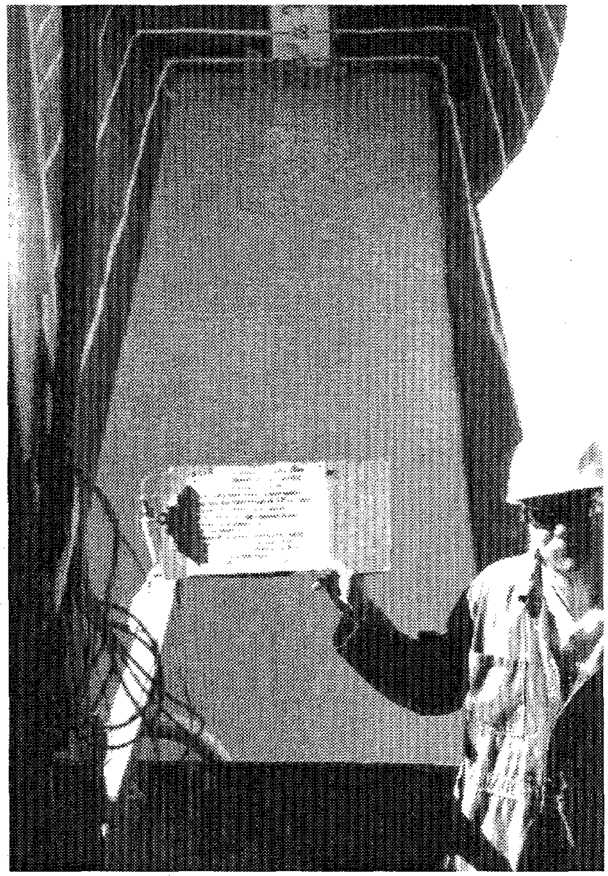

Figure 7.88 Run 9 - After Phase 2, 8.0 min of 1160 psi Slurry-Jet Spray, 9-in. Liquid Layer

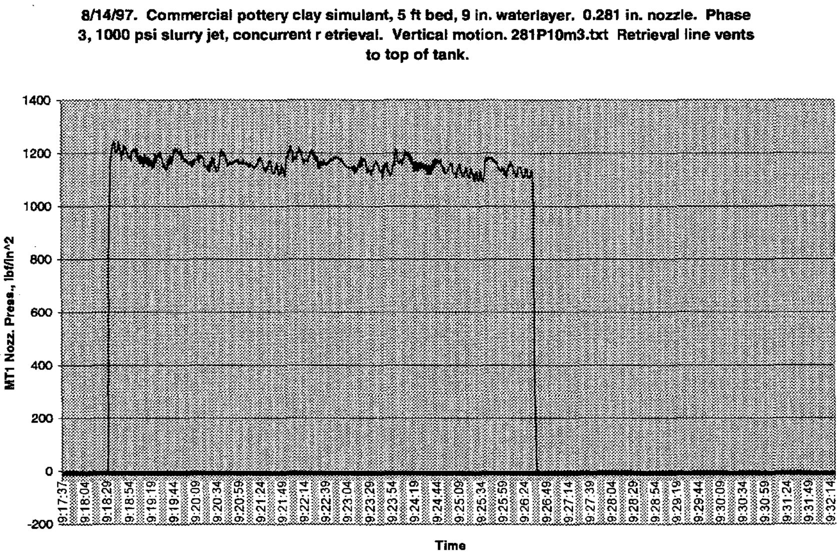

Figure 7.89 Run 9 - Slurry-Jet Pressure During Phase 3

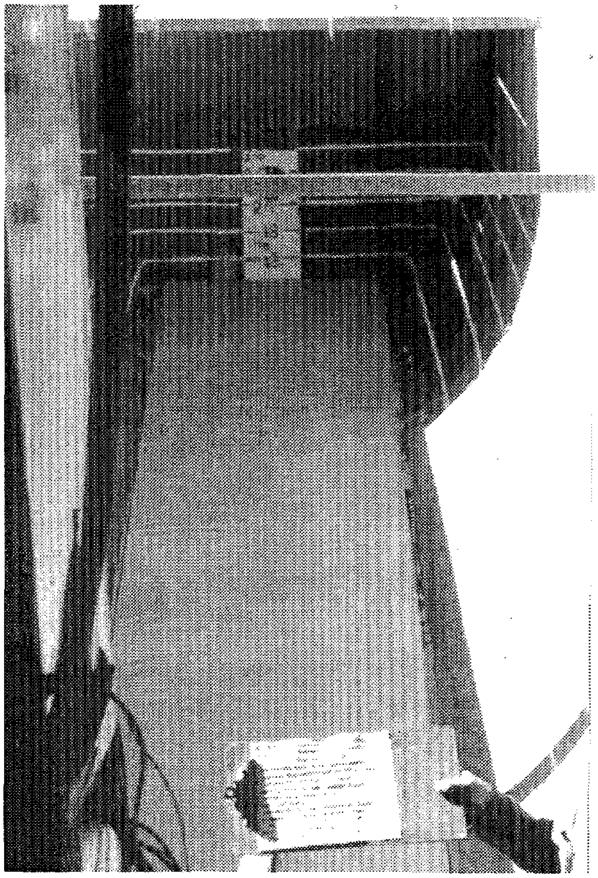

Figure 7.90 Run 9 - After Phase 3, 8.0 min of 1160 psi Slurry-Jet Spray, 6-in. Liquid Layer

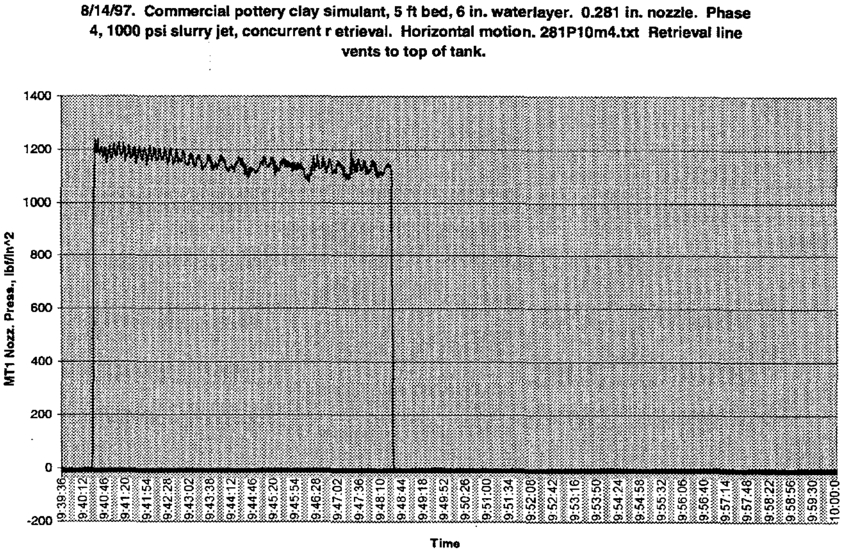

Figure 7.91 Run 9 - Waterjet Pressure During Phase 4

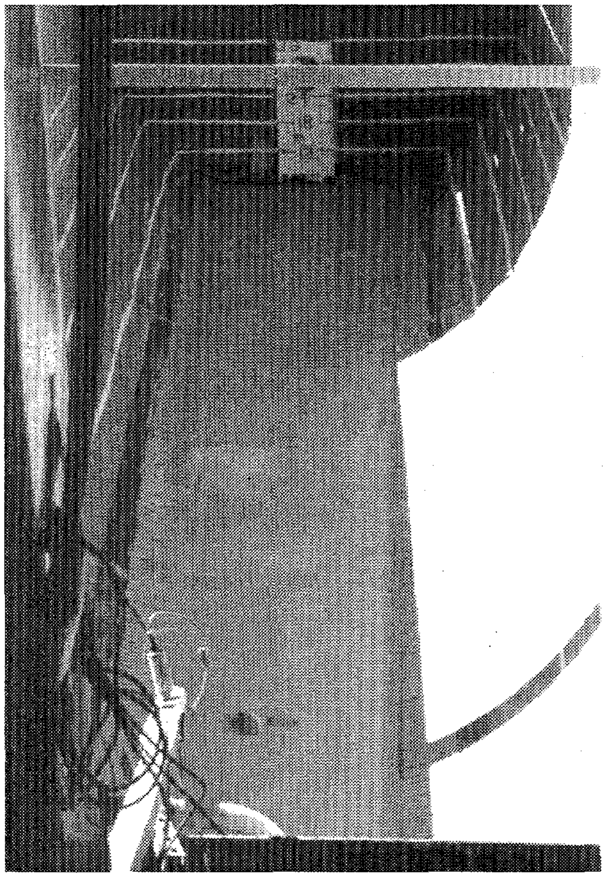

Figure 7.92 Run 9 - After Phase 4, 8.0 min of 1151 psi Slurry-Jet Spray, ~4-in. Liquid Layer

Phase 5 - Low-Pressure Waterjet Rinse. Phase 5 consisted of 2.3 min of waterjet rinse at an average pressure of 526±44 psi. The pressure plot is shown in Figure 7.93. In Phase 5, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.94 shows the tank after completion of Phase 5. The remaining liquid is a dilute slurry; the sides of the tank are clean. After the end of the test, the solids remaining in the tank were removed and weighed. The solids, shown in Figure 7.95, weighed 18 lbm.

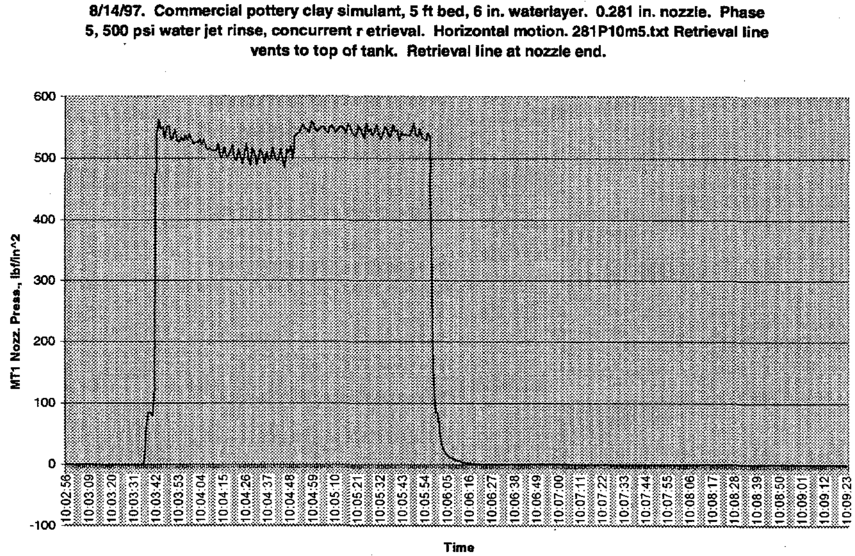

Figure 7.93 Run 9 - Waterjet Pressure During Phase 5

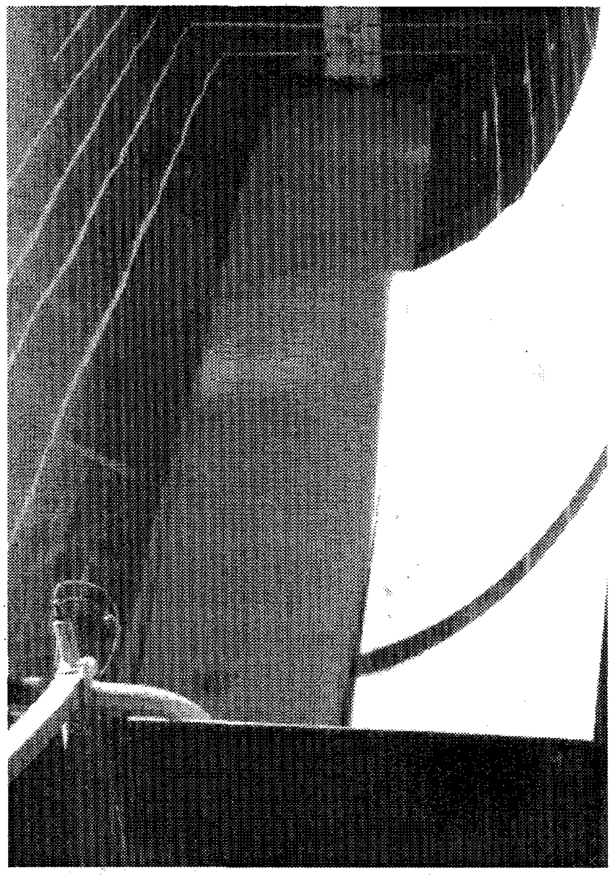

Figure 7.94 Run 9 - After Phase 5, 2.3 min of 526 psi Waterjet Rinse

Figure 7.95 Run 9 - Container of Solids Collected from Tank Floor After Tank Drained

Run 9 - Mass Balance. A summary of test conditions and a mass balance for Run 9 are shown in Table 7.21. The total inventory of solids and liquids added to the horizontal tank is shown under Horizontal Tank Input. After Phase 1, the wt% solids based on initial water addition was 9.1 wt%, near the target 10 wt%. This mass was compared to the supernate tank weight and the amount of recycled slurry to estimate the amount of retrieved slurry. The columns used in this estimate are marked with an *. About 93% of the slurry was retrieved. This compares with the estimate of 96% for the amount of fluid remaining in the horizontal tank based on a calculation using the height of the fluid remaining in the horizontal tank.

Table 7.21 Run 9 - Mass Balance Between Horizontal Tank and Supernate Tank

Phase	Horizontal Tank Input lbm			Average wt% Solids	Jet Slurry lbm	Super-nate Tank Weight lbm	Retrieved Slurry lbm	Total Retrieved Based on *-ed columns lbm	Percent Retrieved
	Solids	Water	Total						
0	700	3648	4348						
1		3364	7712	9.1		2980*	3197	2980	39
2			7712	9.1	5503	4505*	7289	4505	58
3			7712	9.1	5612	5460*	8284	5460	78
4			7712	9.1	5690	6549*	8437	6549	85
5		1111	8823	7.9		8162*	1261	8162	93
Post Test	2	368 lbm	368 lbm remaining in horizontal tank, estimated from 2 in. water layer (350 lbm) + 18 lbm solids						96

Comparisons Between OHF-HS Runs

Direct comparisons between the OHF-HS Runs 2 and 4 can be made to evaluate the presence or absence of supernate layer and between Runs 4 and 9 to evaluate the effect of the location of the retrieval pump suction. The data from all the OHF-SS simulant runs is summarized in Table 7.22. All of the runs successfully dislodged and retrieved slurry from the horizontal tank. Based on mass balance, retrieval rates for Runs 2 and 4 were all greater than 96%.

Supernate Layer. Run 2 and Run 4 can be compared. Run 2 was completed with an exposed simulant bed; Run 4 was completed with a 12-in.-deep supernate layer. Run 2 retrieved 96% of the slurry based on mass balance; Run 4 retrieved 98% of the slurry based on the fraction remaining and more than 100% based on mass balance. Based on examination of the photos taken at the end of each phase, sludge chunks were more apt to be present when no supernate layer was present. This can be observed by comparing the photos for Phase 1 and Phase 2 for Runs 2 and 4.

Retrieval Inlet Location. Run 4 and Run 9 can be compared although a 0.310-in.-diameter nozzle was used during Run 4 and a 0.281-in.-diameter nozzle was used during Run 9. The jet dislodging patterns were employed differently for the two runs. During runs with the retrieval inlet far from the nozzle, it was easy to push solids toward the pump inlet. With the retrieval pump inlet near the nozzle, water flow patterns must be induced to propel slurry to the retrieval pump inlet. This was done by aiming the jet directly at the back wall of the tank or aiming the jet along the side of the tank. These results are qualitative.

Table 7.22 Performance Comparison Between OHF-HS Runs

Run	Nozzle Diameter in.	Simulant Bed Length ft	Retrieval Inlet ft from Tank End	Supernate Level in.	Water Spray		Slurry Spray		Percent Retrieved Based On	
					min	psi	min	psi	Mass Balance	Fraction Remaining
2	0.310	5	5	2	16.5	992	16.2	887	96	97
4	0.310	5	5	12	4.9	1092	24.3	999	>100	98
9	0.281	5	22	12	5.0	1140	24.0	1157	93	96

7.6.3 Challenging Simulant Tests

Two tests were conducted with simulants developed to "challenge" the extendible-nozzle system. The kaolin/plaster/sand simulant included two sizes of sand. The purpose of the sand was to determine how much of the sand could be mobilized during the dislodging and be retrieved by the retrieval pump. Another simulant, hard pan, had a shear strength of 150 kPa, 60 times the OHF-SS simulant shear strength. This simulant was designed to evaluate whether the extendible-nozzle could readily dislodge higher shear strength solids. The two challenging simulant tests are summarized in Table 7.12. Both tests were conducted using the 0.281-in.-diameter nozzle, a 5-ft-long bed, and a 12-in.-deep supernate layer.

Run 7 - Kaolin/Plaster/Sand Simulant with 5-ft Bed, 0.281-in.-Diameter Nozzle, Supernate Layer

This run was similar to Run 4 with a 0.281-in.-diameter nozzle instead of the 0.310-in.-diameter nozzle and to Run 9 with the retrieval pump inlet 5 ft from the end of the tank (multiple-riser configuration) instead of 22 ft from the end of the tank (single-riser configuration). This run modeled balanced retrieval. The flow rate of the extendible-nozzle at 1000 psi using the 0.281-in.-diameter nozzle was approximately equal to that of the retrieval pump. Therefore, the retrieval pump was stopped immediately after flow to the extendible-nozzle stopped. The supernate level started at 12 in. and decreased over five phases to ~2 in. Run 7 consisted of one waterjet and three slurry-jet-dislodging and slurry-retrieval phases and a final waterjet rinse.

Phase 0 - Simulant Bed. The 5-ft-long simulant bed is shown in Figure 7.96. The bed contained 621 lbm of kaolin/plaster/sand simulant. To simulate the supernate layer, the waterjet was operated at a low pressure to fill the horizontal tank to the prescribed water depth. The bed was not disturbed during the filling process. The supernate covered bed is shown in Figure 7.97. The liquid is up to the 12-in. line painted around the edge of the tank. The undisturbed bed is visible through the supernate layer.

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 4.9 min of waterjet dislodging at an average pressure of 1081±47 psi. The pressure plot, shown in Figure 7.98, showed that the pressure remained relatively constant throughout the test. At the completion of Phase 1, the fluid remaining in the horizontal tank was pumped down to a level of 12 in. The slurry was transferred to the supernate tank. Figure 7.99 shows the tank after the jet was stopped. The solids are well dispersed in the slurry.

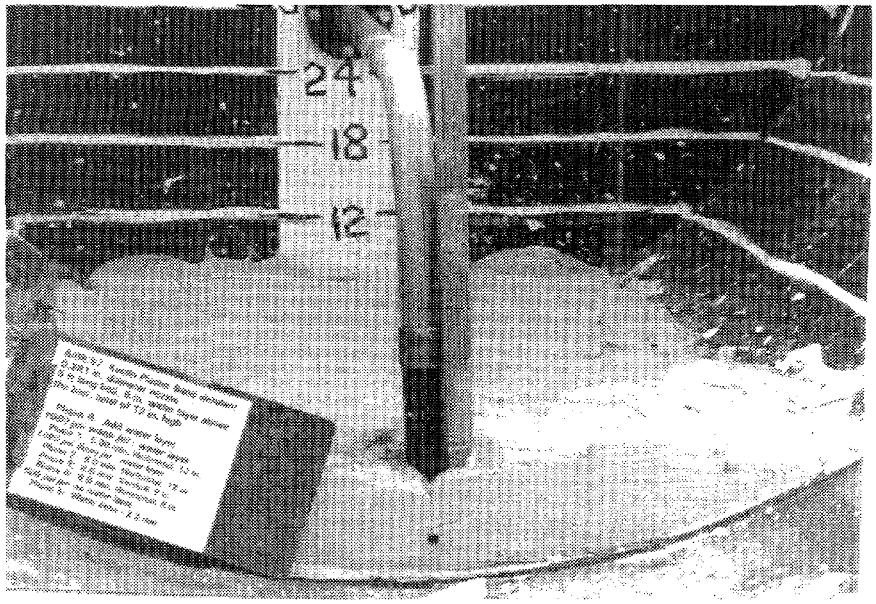

Figure 7.96 Run 7 - Kaolin/Plaster/Sand Simulant Bed Prior to Test

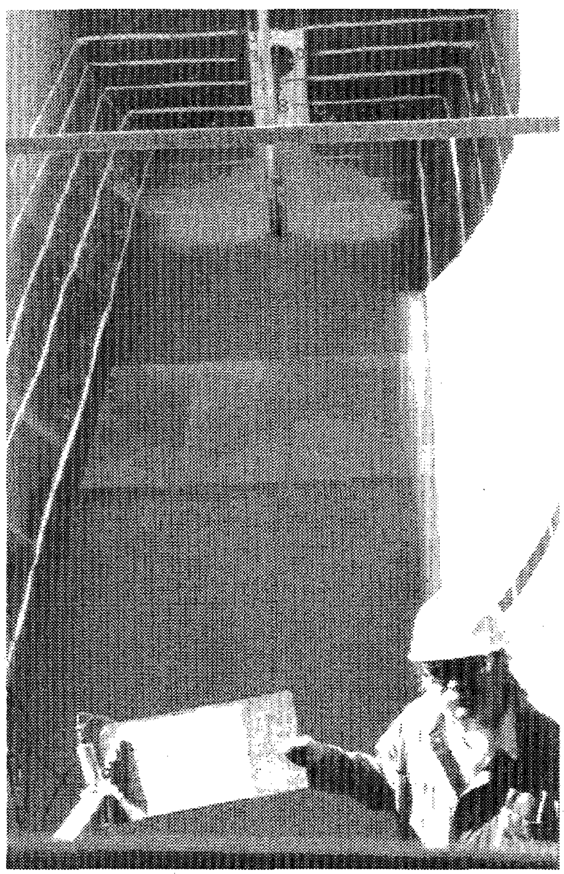

Figure 7.97 Run 7 - Kaolin/Plaster/Sand Simulant Covered with Supernate

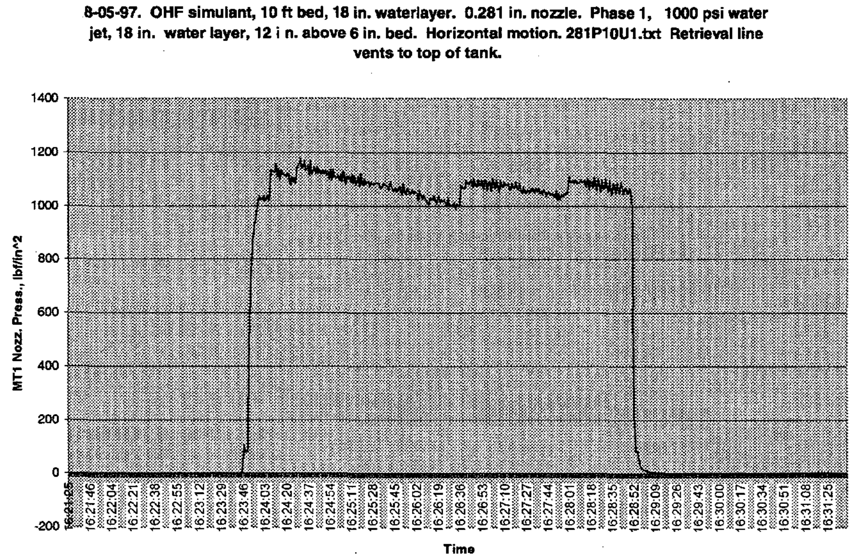

Figure 7.98 Run 7 - Waterjet Pressure During Phase 1

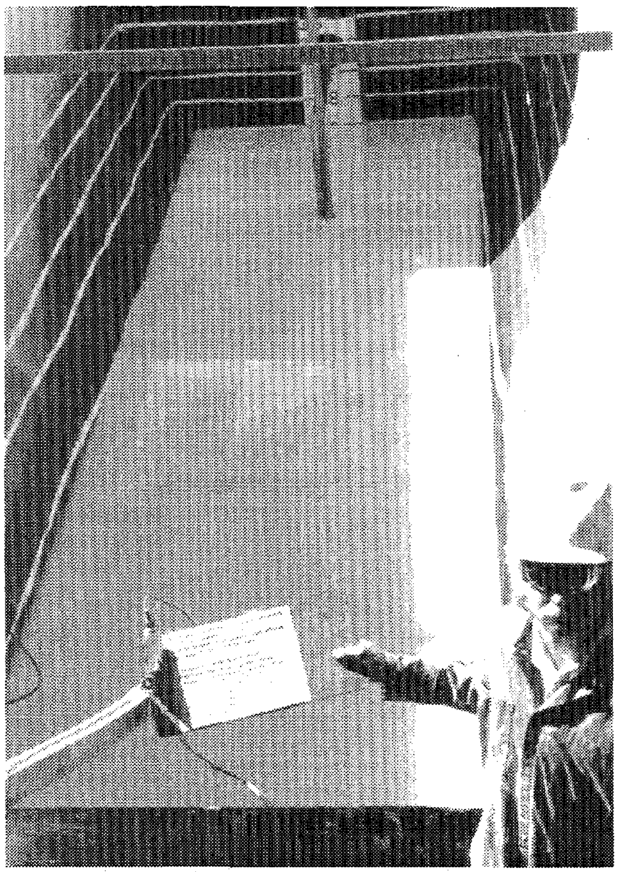

Figure 7.99 Run 7 - After Phase 1, 4.9 min of 1081 psi Waterjet Spray, 12-in. Liquid Layer

Phase 2 - Waterjet and Slurry-Jet Dislodging and Retrieval. Due to miscommunication, Phase 2 was initiated as a waterjet, but switched to a slurry jet (the planned condition) after 2.8 min of spray. In the slurry-jet configuration, the slurry in the supernate tank was used as the dislodging fluid. The slurry line feeding the high-pressure pump suction was connected to the bottom of the supernate tank. This configuration provided adequate flow to the high-pressure pump feed to sustain high-pressure operation. The retrieval line from the horizontal tank to the supernate tank empties into the top of the supernate tank. Phase 2 consisted of 2.8 min of waterjet at 1064±17 psi and 8.0 min of slurry-jet dislodging at an average pressure of 666±202 psi. The pressure plots for the relatively constant waterjet and erratic slurry jet, are shown in Figures 7.100 and 7.101, respectively. Some slugs of simulant in the pump suction line caused the pressure fluctuations. At the completion of Phase 2, the fluid remaining in the horizontal tank was pumped down to a level of 9 in. The slurry was transferred to the supernate tank. Figure 7.102 shows the tank after the jet was stopped; the slurry was well mixed.

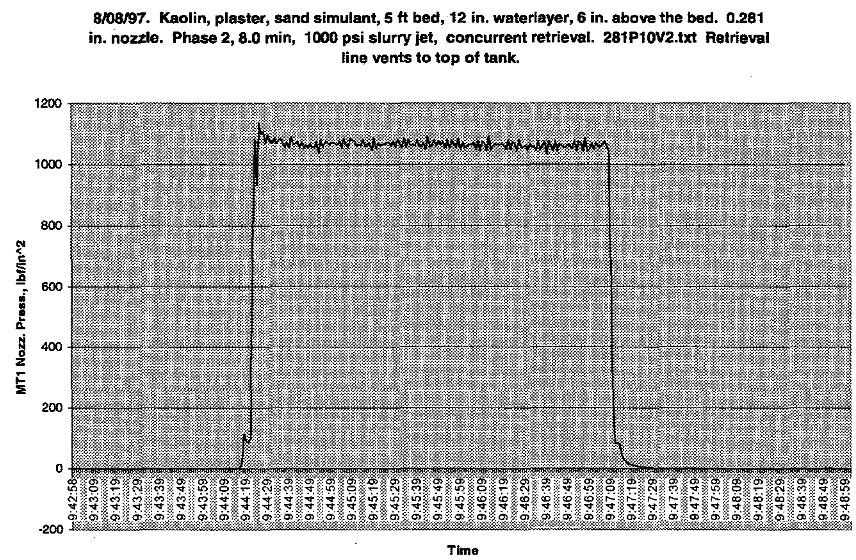

Figure 7.100 Run 7 - Waterjet Pressure During Phase 2

Phase 3 - Slurry-Jet Dislodging and Retrieval. In Phase 3, the slurry in the supernate tank was used as the dislodging fluid; the slurry-jet cycle lasted 7.8 min. The pressure plot is shown in Figure 7.103. The jet pressure averaged 1130±26 psi. The condition of the horizontal tank after completion of Phase 3 is shown in Figure 7.104. The tank was pumped to a level of 6 in. after completion of Phase 3. The slurry appears to be well mixed.

Phase 4 - Slurry-Jet Dislodging and Retrieval. In Phase 4, the slurry in the supernate tank was used as the dislodging fluid; the slurry-jet cycle lasted 8.0 min. The jet pressure averaged 1075±47 psi, as shown in Figure 7.105. The condition of the horizontal tank after completion of Phase 4 is shown in Figure 7.106. At the completion of Phase 4, the tank was pumped to a level of ~2 in. Settled solids are visible along the sides of the tank above the supernate layer.

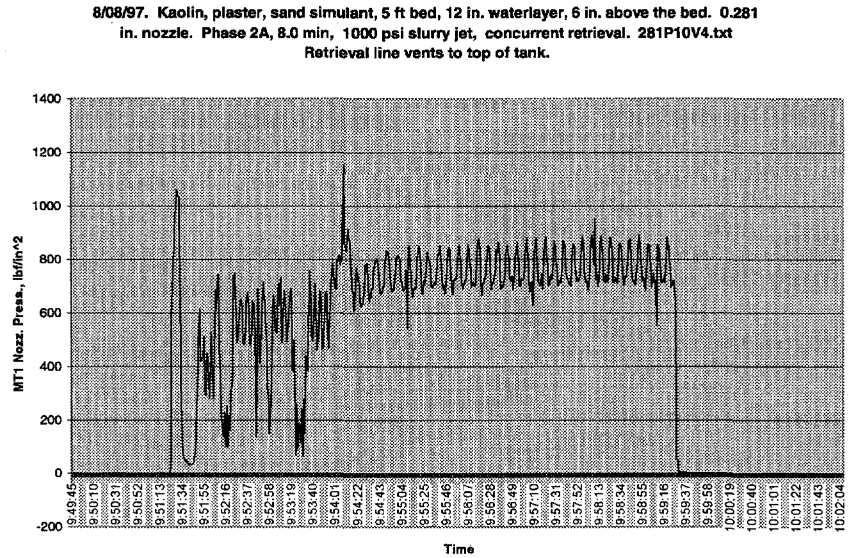

Figure 7.101 Run 7 - Slurry-Jet Pressure During Phase 2A

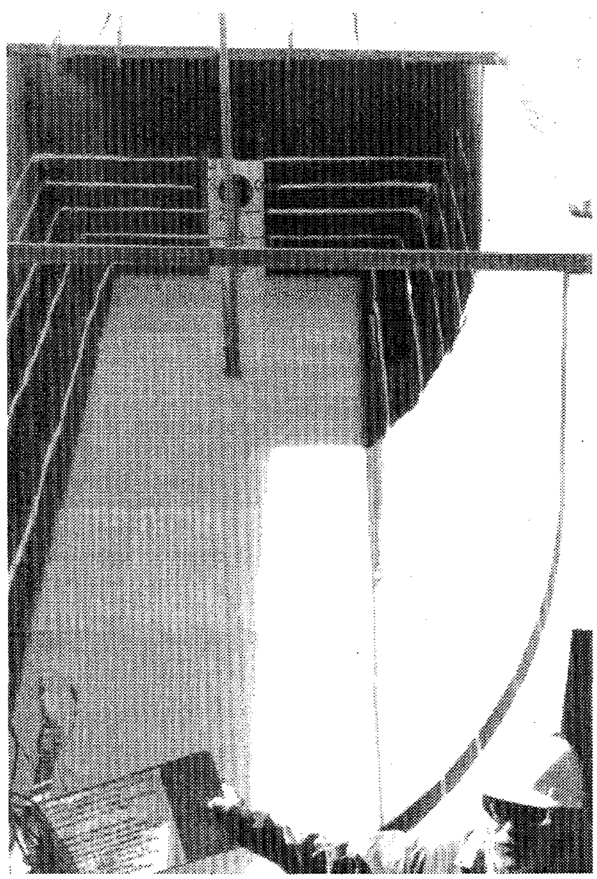

Figure 7.102 Run 7 - After Phase 2A, 8.0 min of 666 psi Slurry-Jet Spray, 9-in. Liquid Layer

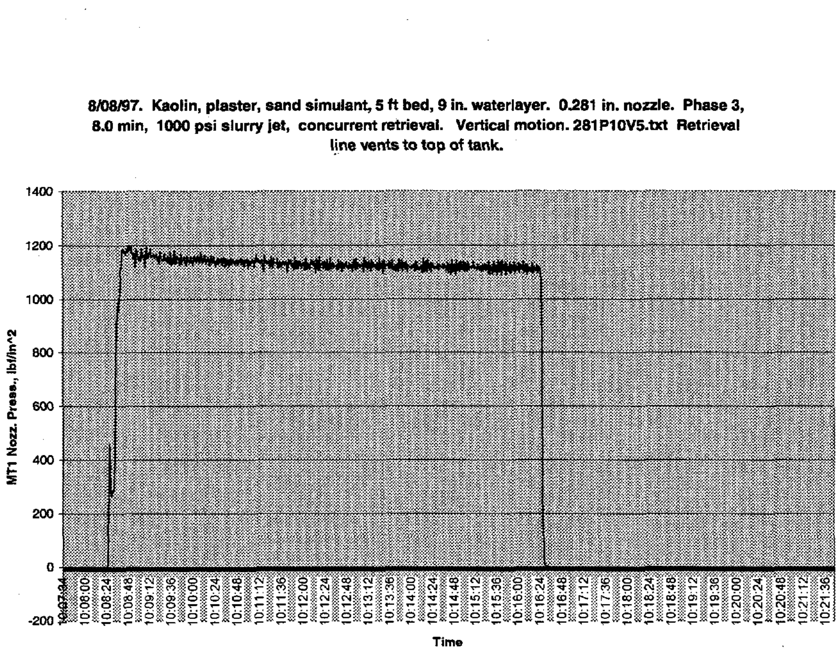

Figure 7.103 Run 7 - Slurry-Jet Pressure During Phase 3

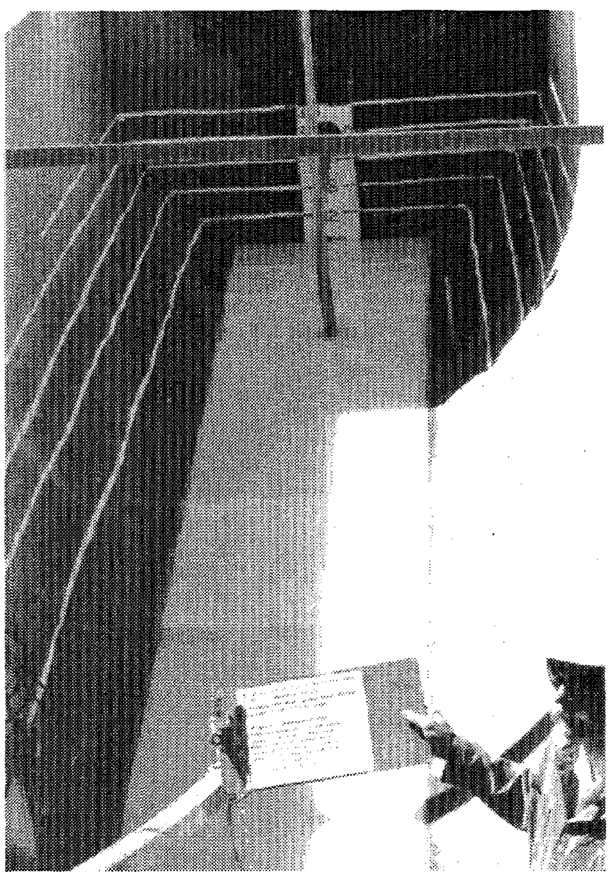

Figure 7.104 Run 7 - After Phase 3, 7.8 min of 1130 psi Slurry-Jet Spray, 6-in. Liquid Layer

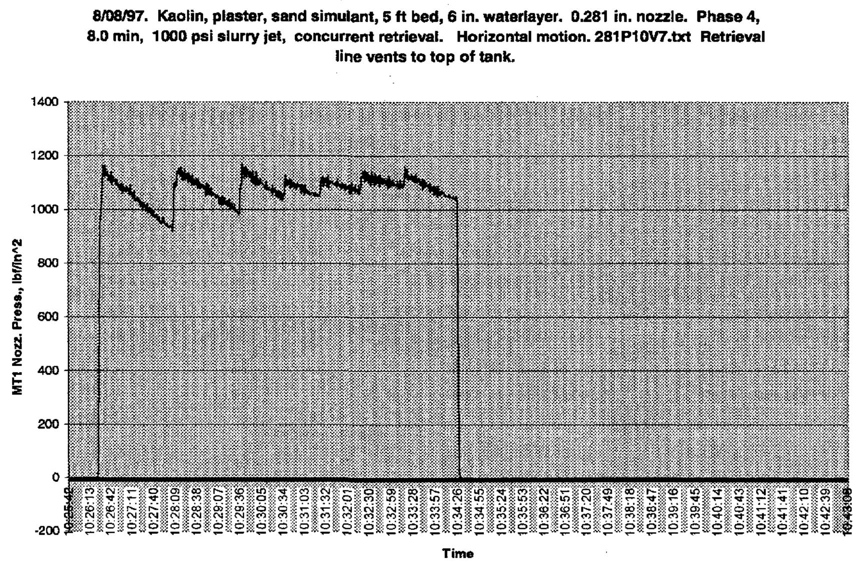

Figure 7.105 Run 7 - Waterjet Pressure During Phase 4

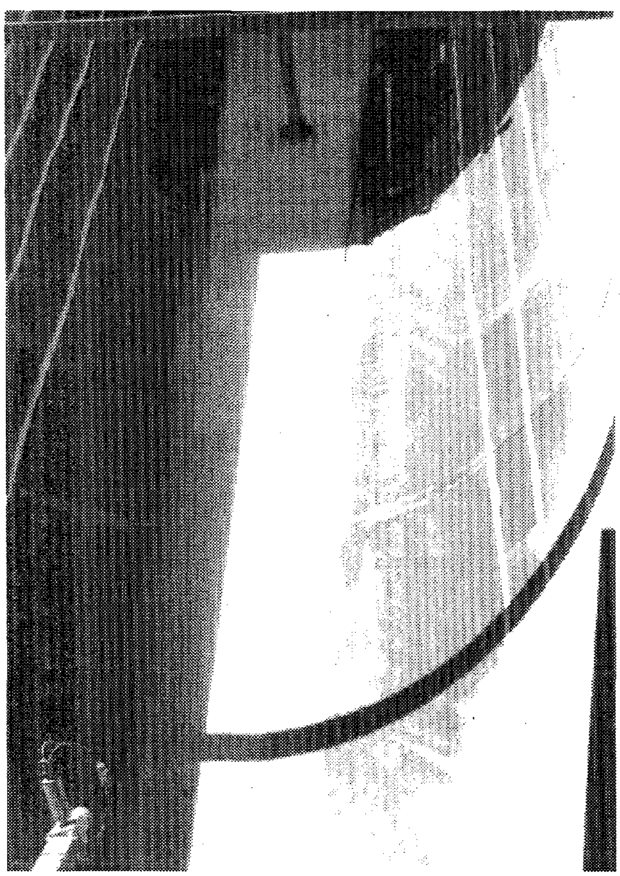

Figure 7.106 Run 7 - After Phase 4, 8.0 min of 1075 psi Slurry-Jet Spray, 2-in. Liquid Layer

Phase 5 - Low-Pressure Waterjet Rinse. Phase 5 consisted of 2.2 min of waterjet rinse at an average pressure of 521±15 psi. The pressure plot is shown in Figure 7.107. In Phase 5, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.108 shows the tank after completion of Phase 5. The remaining liquid is a dilute slurry; the sides of the tank are clean. After the end of the test, the fluid was drained and the solids remaining in the tank were removed. A representative sample of the solids is shown in Figure 7.109. The total solids removed weighed 16 lbm.

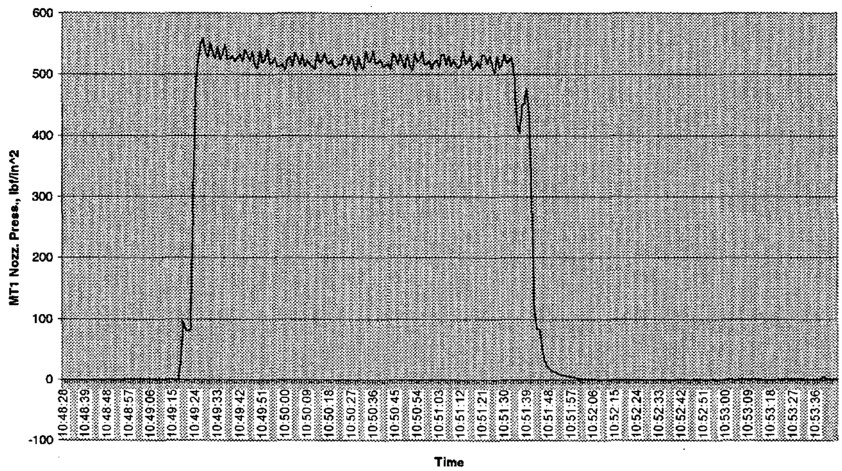

Figure 7.107 Run 7 - Waterjet Pressure During Phase 5

Run 7 - Mass Balance. A summary of test conditions and a mass balance for Run 7 are shown in Table 7.23. The total inventory of solids and liquids added to the horizontal tank is shown under Horizontal Tank Input. After Phase 2, the wt% solids based on initial water addition was 6.8 wt%; obtaining 10 wt% solids with a 12-in.-liquid layer was not achievable. This mass was compared to the supernate tank weight and the amount of recycled slurry to estimate the amount of retrieved slurry. The columns used in this estimate are marked with an *. Based on the estimate of initial supernate volume, >100% of the slurry was calculated to be removed. The estimate of 96% for the amount of fluid remaining in the horizontal tank based on a calculation using the height of the fluid remaining in the horizontal tank seems plausible.

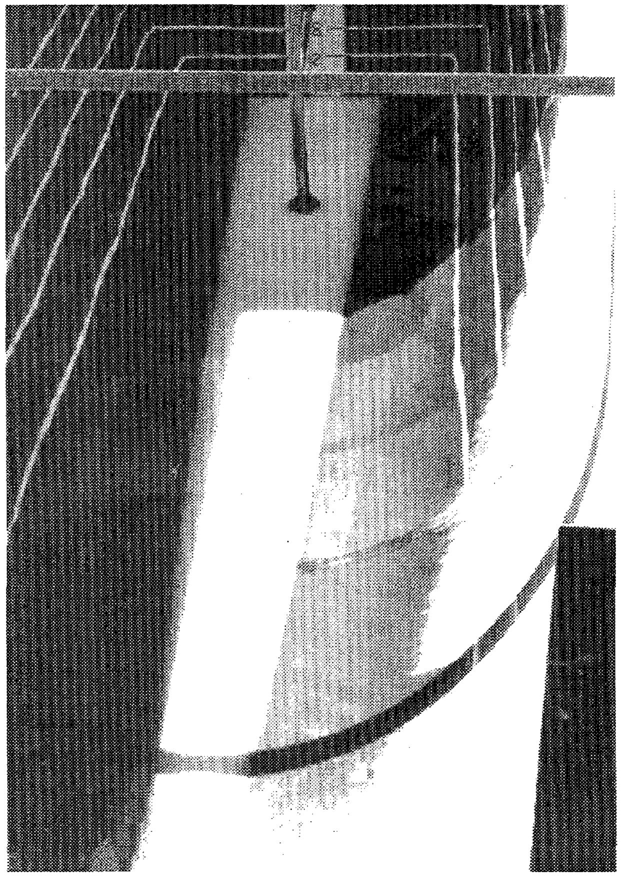

Figure 7.108 Run 7 - After Phase 5, 2.2 min of 521 psi Waterjet Rinse

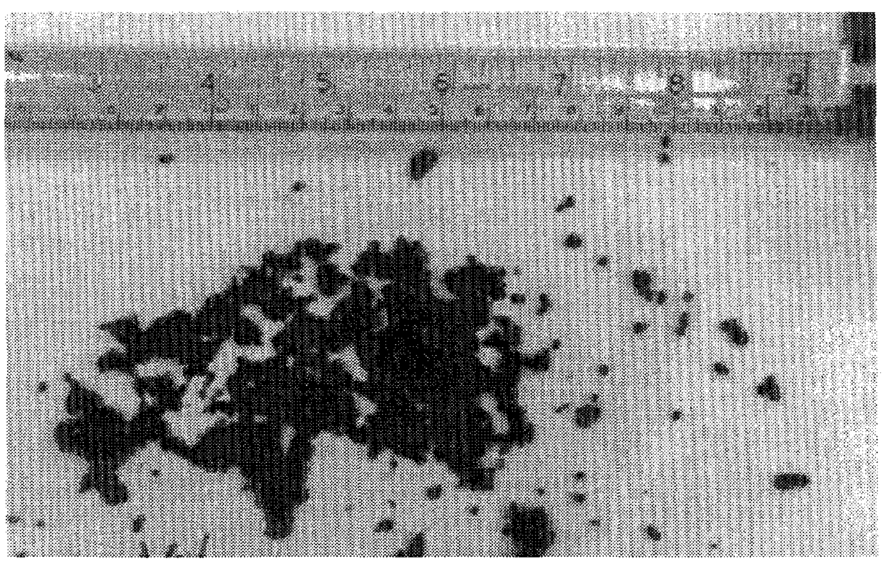

Figure 7.109 Run 7 - Solids Removed from the Horizontal Tank In Front of Retrieval Pump Inlet

Table 7.23 Run 7 - Mass Balance Between Horizontal Tank and Supernate Tank

Phase	Horizontal Tank Input lbm			Average wt% Solids	Jet Slurry lbm	Super-nate Tank Weight lbm	Retrieved Slurry lbm	Total Retrieved Based on *-ed Columns lbm	Percent Retrieved
	Solids	Water	Total						
0	621	3476	4097						
1		3237	7334	8.5		2996*	3849	2996	41
2		1819	9153	6.8		4950*	2046	4950	54
2A			9153	6.8	3795	6111*	5677	6111	67
3			9153	6.8	5307	7325*	7586	7325	80
4			9153	6.8	5214	8771*	7152	8771	96
5		1063	10216	6.1		10180 *	1477	10180	99
Post Test	16	366 lbm	366 lbm remaining in horizontal tank, estimated from 2 in. water layer (350 lbm) + 16 lbm solids						96

Run 8 - Hard Pan Simulant with 5-ft Bed, 0.281-in.-Diameter Nozzle, Supernate Layer

This run was the same as Run 7 using the hard pan simulant and was similar to Run 4 with a 0.281-in.-diameter nozzle instead of the 0.310-in.-diameter nozzle and to Run 9 with the retrieval pump inlet 5 ft from the end of the tank instead of 22 ft from the end of the tank. This run modeled balanced retrieval. The flow rate of the extendible-nozzle at 1000 psi using the 0.281-in.-diameter nozzle was approximately equal to that of the retrieval pump. Therefore, the retrieval pump was stopped immediately after flow to the extendible-nozzle stopped. The supernate level started at 12 in. and decreased over five phases to ~2 in. Run 8 consisted of one waterjet and three slurry-jet-dislodging and slurry -retrieval phases and a final waterjet rinse.

Phase 0 - Simulant Bed. The 5-ft-long simulant bed is shown in Figure 7.110. The bed contained 605 lbm of hard pan simulant. To simulate the supernate layer, the waterjet was operated at a low pressure to fill the horizontal tank to the prescribed water depth. The bed was not disturbed during the filling process. The supernate covered bed is shown in Figure 7.111. The liquid is up to the 12-in. line painted around the edge of the tank. The undisturbed bed is visible through the supernate layer.

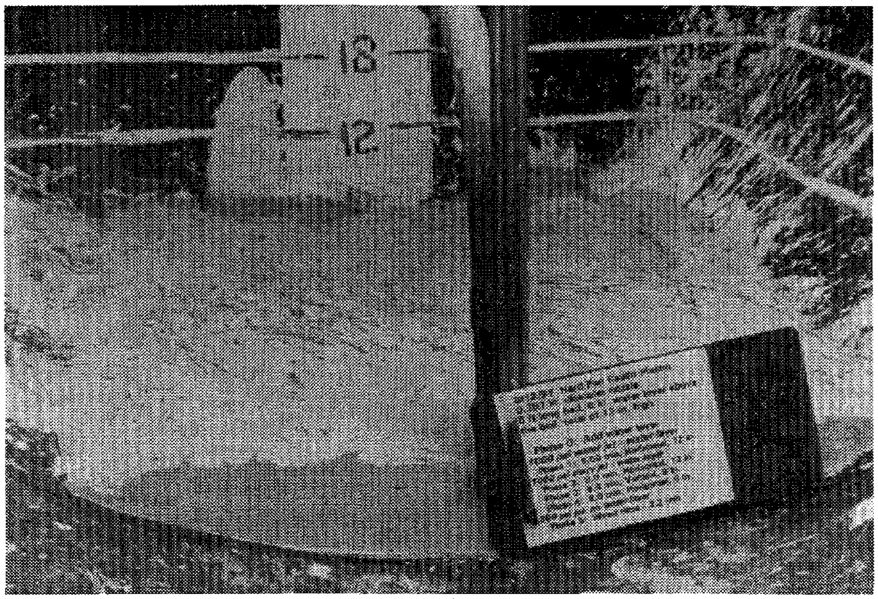

Figure 7.110 Run 8 - Hard Pan Simulant Bed Prior to Test

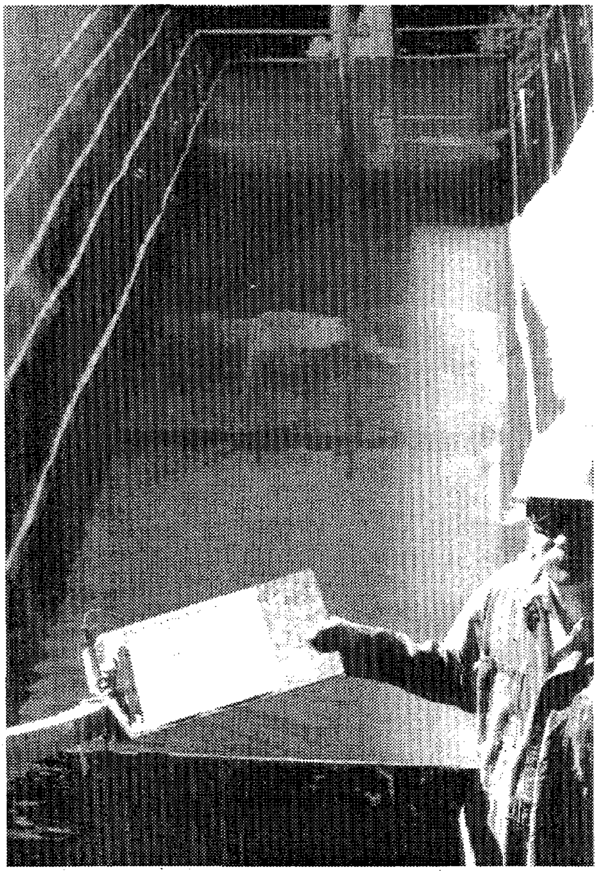

Figure 7.111 Run 8 - Hard Pan Simulant Covered with Supernate

Phase 1 - Waterjet Dislodging and Retrieval. Phase 1 consisted of 5.2 min of waterjet dislodging at an average pressure of 1106±145 psi. The pressure plot, shown in Figure 7.112, showed that the pressure remained relatively constant throughout the test. At the completion of Phase 1, the fluid remaining in the horizontal tank was pumped down to a level of 12 in. The slurry was transferred to the supernate tank. Figure 7.113 shows the tank after the jet was stopped. Some solids are visible in a pile by the end of the tank. The slurry does not appear to be fully mixed.

Phase 2 - Slurry-Jet Dislodging and Retrieval. In Phase 2, the slurry in the supernate tank was used as the dislodging fluid; the slurry-jet cycle lasted 8.4 min. The slurry line feeding the high-pressure pump suction was connected to the bottom of the supernate tank. This configuration provided adequate flow to the high-pressure pump feed to sustain high-pressure operation. The retrieval line from the horizontal tank to the supernate tank empties into the top of the supernate tank. Phase 2 consisted of 8.4 min of waterjet spray at a pressure of 1125±201 psi. The pressure plot is shown in Figure 7.114. The pressure became relatively constant after a rather erratic start likely due to air entrainment in the pump suction line. At the completion of Phase 2, the fluid remaining in the horizontal tank was pumped down to a level of 9 in. The slurry was transferred to the supernate tank. Figure 7.115 shows the tank after the jet was stopped; the slurry was well mixed. One small chunk is visible to the left behind the retrieval pump inlet.

Phase 3 - Slurry-Jet Dislodging and Retrieval. In Phase 3, the slurry in the supernate tank was used as the dislodging fluid; the Slurry-Jet cycle lasted 8.0 min. The pressure plot is shown in Figure 7.116. The jet pressure averaged 1177±121 psi. The condition of the horizontal tank after completion of Phase 3 is shown in Figure 7.117. The tank was pumped to a level of 6 in. after completion of Phase 3. The slurry appears to be well mixed; however, with the lower liquid level, solids are now visible at the end of the tank to the right behind the retrieval pump inlet.

Phase 4 - Slurry-Jet Dislodging and Retrieval. In Phase 4, the slurry in the supernate tank was used as the dislodging fluid. The jet pressure averaged 1143±121 psi and was relatively constant as shown in Figure 7.118. The condition of the horizontal tank after completion of Phase 4 is shown in Figure 7.119. At the completion of Phase 4, the tank was pumped to a level of ~2 in. Settled solids are visible along the sides of the tank above the supernate layer. Chunks of simulant are piled around the inlet to the retrieval pump.

Phase 5 - Low-Pressure Waterjet Rinse. Phase 5 consisted of 2.0 min of waterjet rinse at an average pressure of 535±126 psi. The pressure plot is shown in Figure 7.120. In Phase 5, water from the hydrant was used as the rinse fluid. During the rinse phase, clean water was used to push the remaining solids along the tank floor to the inlet to the retrieval pump. Figure 7.121 shows the tank after completion of Phase 5. Several large chunks align along the center of the tank. The remaining liquid is a dilute slurry; the sides of the tank are clean. After the end of the test, the fluid was drained and the solids remaining in the tank were removed. The solids collected are shown in Figure 7.122. The total solids removed weighed 34.9 lbm. The solids were rather large diameter ovals, ~6 in. x 10 in.

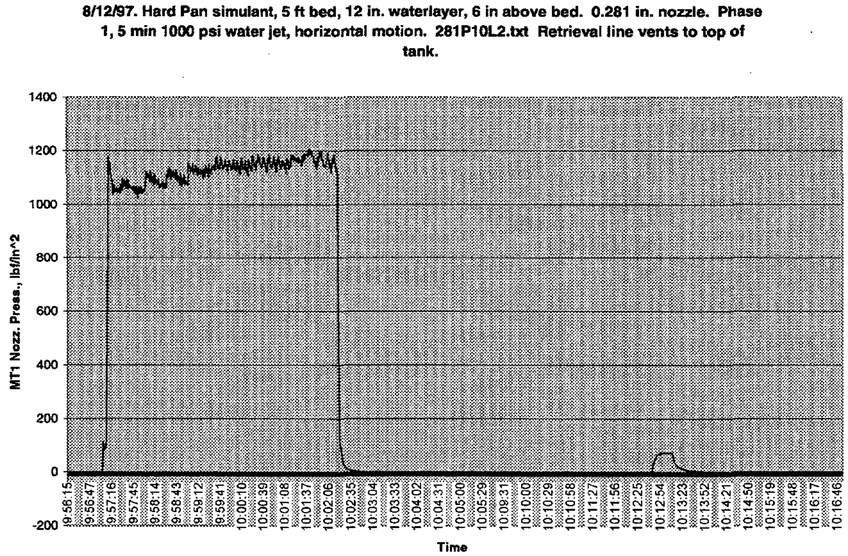

Figure 7.112 Run 8 - Waterjet Pressure During Phase 1

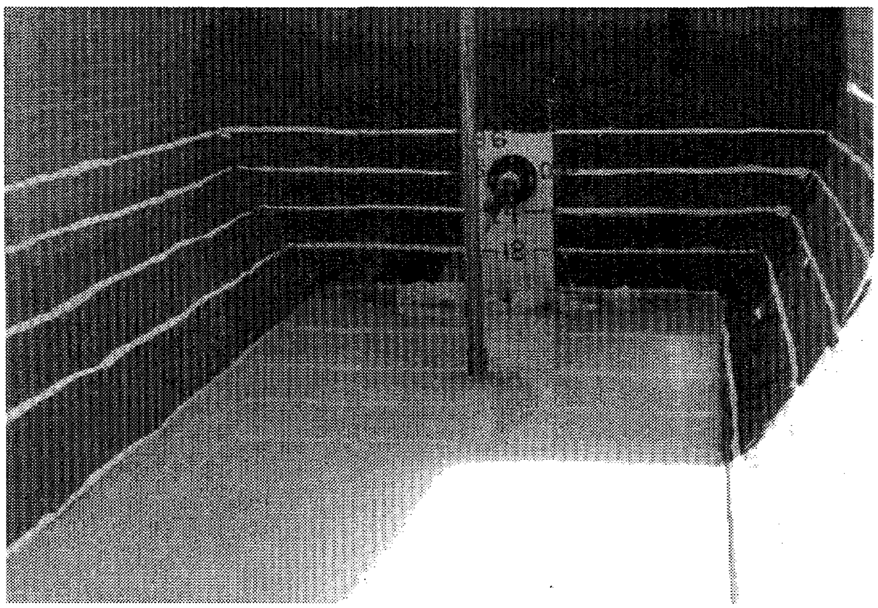

Figure 7.113 Run 8 - After Phase 1, 5.2 min of 1106 psi Waterjet Spray, 12-in. Liquid Layer

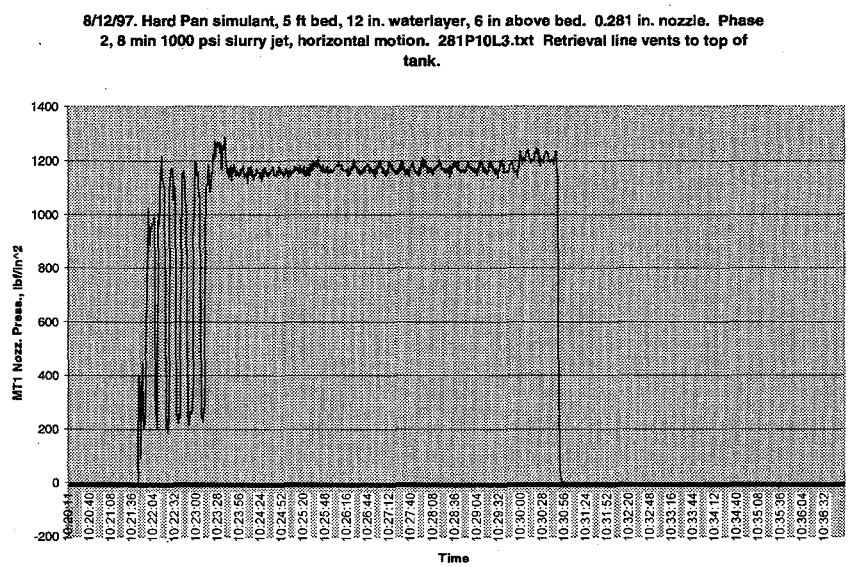

Figure 7.114 Run 8 - Waterjet Pressure During Phase 2

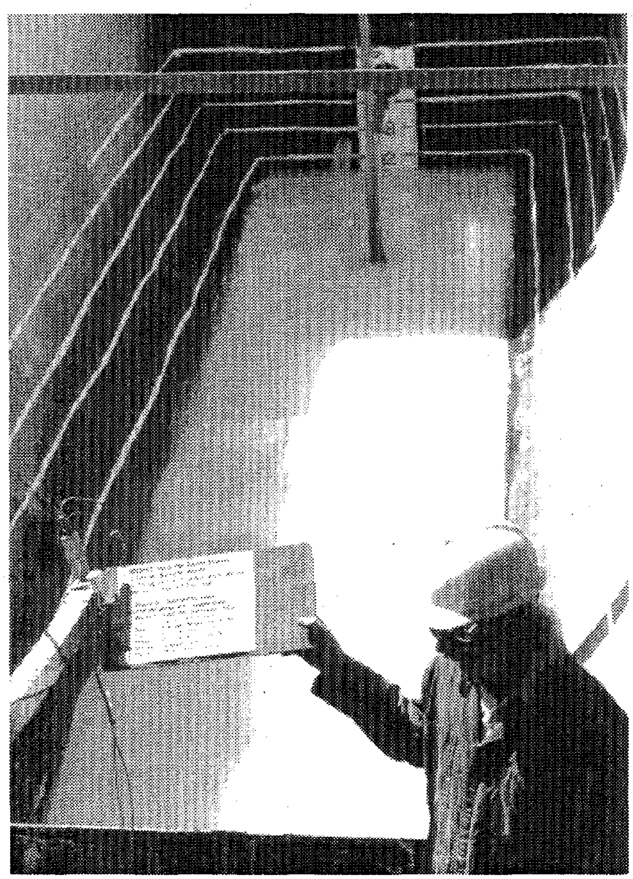

Figure 7.115 Run 8 - After Phase 2, 8.4 min of 1125 psi Slurry-Jet Spray, 9-in. Liquid Layer

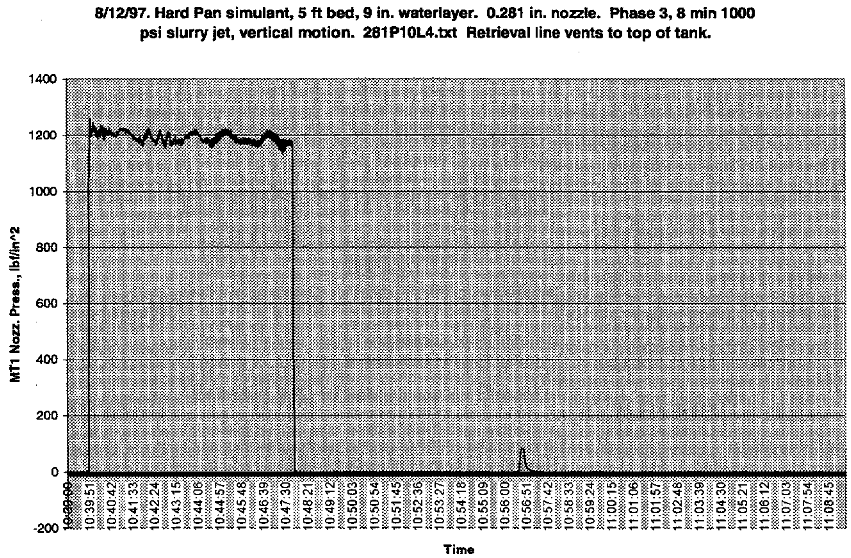

Figure 7.116 Run 8 - Slurry-Jet Pressure During Phase 3

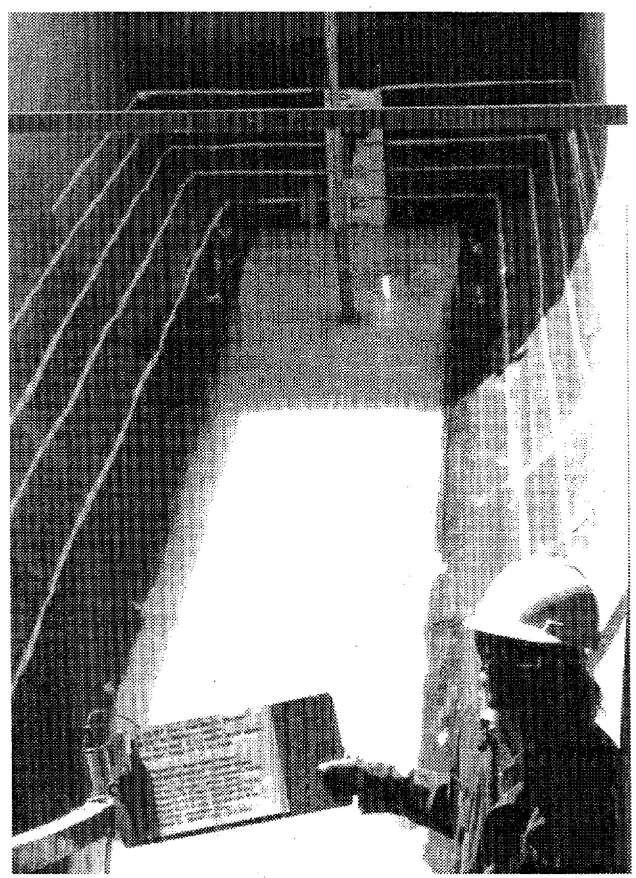

Figure 7.117 Run 8 - After Phase 3, 8.0 min of 1177 psi Slurry-Jet Spray, 6-in. Liquid Layer

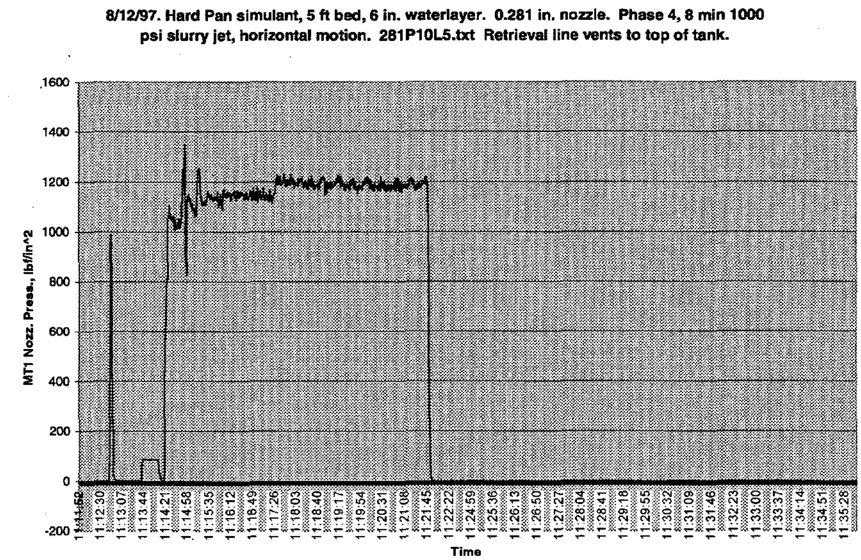

Figure 7.118 Run 8 - Waterjet Pressure During Phase 4

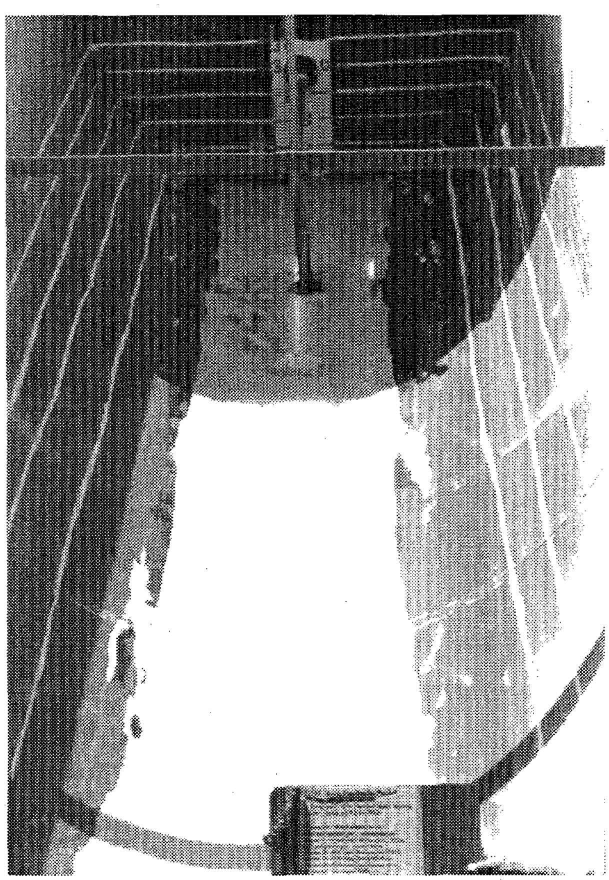

Figure 7.119 Run 8 - After Phase 4, 7.6 min of 1143 psi Slurry-Jet Spray, 2-in. Liquid Layer

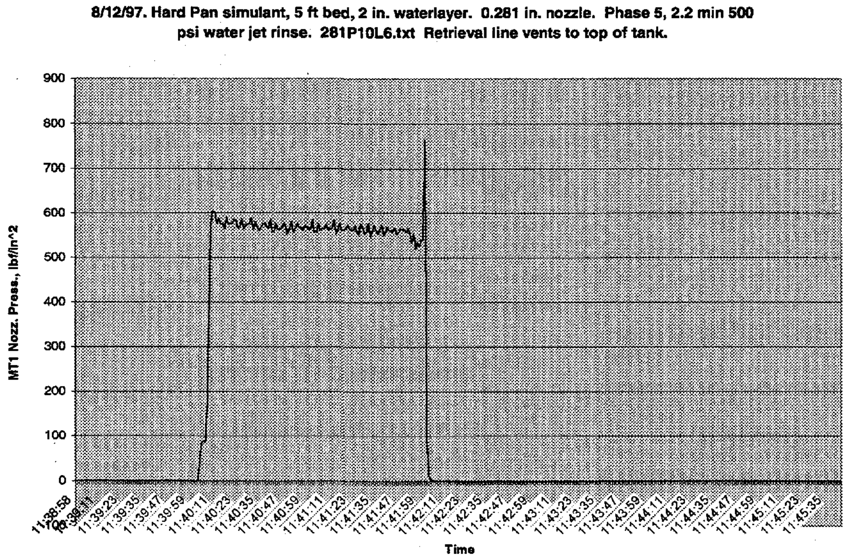

Figure 7.120 Run 8 - Waterjet Pressure During Phase 5

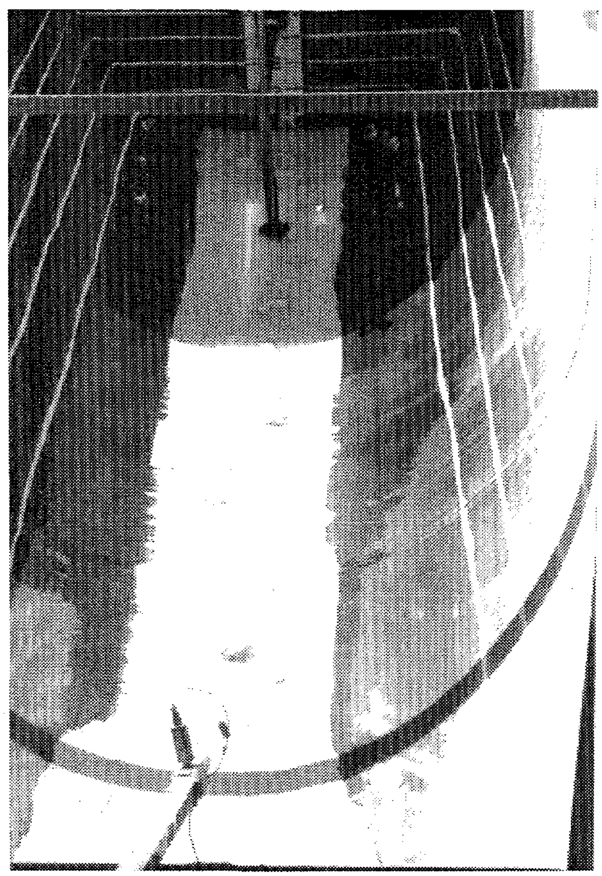

Figure 7.121 Run 8 - After Phase 5, 2.0 min of 535 psi Waterjet Rinse

Figure 7.122 Run 8 - Solids Collected from Tank Floor After Tank Drained

Run 8 - Mass Balance. A summary of test conditions and a mass balance for Run 8 are shown in Table 7.24. The total inventory of solids and liquids added to the horizontal tank is shown under Horizontal Tank Input. After Phase 2, the wt% solids based on initial water addition was 8.3 wt%; near the target 10 wt% solids. This mass was compared to the supernate tank weight and the amount of recycled slurry to estimate the amount of retrieved slurry. The columns used in this estimate are marked with an *. Based on the mass collected in the supernate tank >100% of the slurry was removed. This does not agree with observation. The estimate of 95% for the amount of fluid remaining in the horizontal tank based on a calculation using the height of the fluid remaining in the horizontal tank and the solids collected post test seems plausible.

Table 7.24 Run 8 - Mass Balance Between Horizontal Tank and Supernate Tank

Phase	Horizontal Tank Input lbm			Average wt% Solids	Jet Slurry lbm	Super-nate Tank Weight lbm	Retrieved Slurry lbm	Total Retrieved Based on *-ed Columns lbm	Percent Retrieved
	Solids	Water	Total						
0	605	3166	3771						
1		3560	7331	8.3		3414*	3473	3414	47
2			7331	8.3	5897	4730*	8362	4730	65
3			7331	8.3	5566	6540*	8891	6540	89
4			7331	8.3	4950	7663*	8777	7663	>100
5		870	8201	7.4		9203*	2567	9203	>100
Post Test	35	385 lbm	385 lbm remaining in horizontal tank, estimated from 2 in. water layer(350 lbm) + 35 lbm solids						95

7.7 Performance Summary and Recommendations for OHF Deployment

Retrieval data, grouped by simulant type, are summarized in Table 7.25. The sludge type simulants ranged from prototypic to those with shear strengths 60 times that of the baseline. For all of the cases, retrieval rates were extremely high, averaging 97%. Retrieval performance was evaluated two ways, based on mass balance and by fraction remaining in the tank after sluicing.

- **Nozzle Diameter:** Two nozzle diameters (0.281- and 0.310-in. diameter) were evaluated. These were the two smallest nozzles provided for the extendible nozzle. Slightly higher percent retrieved were obtained with the larger diameter nozzle. This nozzle had a flow rate 18% greater than the smaller diameter nozzle. Good dislodging and retrieval performance were obtained with both nozzles.

- **Jet Pressure:** All tests were conducted at ~1000 psi jet pressure. This pressure was adequate to dislodge all of the simulants selected; therefore, no tests at 1500 psi pressure were conducted. The rinse phases were conducted at 500 psi. This was adequate to rinse the tank and also reduce water usage.

- **Supernate Level:** Two supernate levels were modeled: submerged bed with a 6 or 12-in. layer of water covering the bed or dry bed with no supernate covering the bed. There was no discernable difference in overall retrieval for either of these cases. Retrieval rates were very high ranging from 95 to 100% for all supernate levels.

Table 7.25 Performance Comparison Between OHF Runs

Run	Nozzle Diameter in.	Simulant Bed Length ft	Retrieval Inlet ft from Tank End	Supernate Level in.	Water Spray		Slurry Spray		Percent Retrieved Based On	
					min	psi	min	psi	Mass Balance	Fraction Remaining
OHF Representative Simulant - Kaolin Clay and Plaster; Vane Shear Strength 2.5 ± 0.5 kPa										
1	0.310	5	5	2	7.7	987	8.2	184	97	95
3	0.310	10	5	2	16.7	971	14.4	528	99	98
5	0.310	10	5	12	10.6	983	24.3	986	97	97
6	0.281	10	5	18	5.3	1019	29.6	1067	98	97
OHF Strong Simulant - Pottery Clay; Vane Shear Strength 12 ± 1 kPa										
2	0.310	5	5	2	16.5	992	16.2	887	98	97
4	0.310	5	5	12	4.9	1092	24.3	999	>100	98
9	0.281	5	22	12	5.0	1140	24.0	1157	93	96
Simulant with Larger Sand Particles - Kaolin/Plaster/Sand; Vane Shear Strength 5.5 ± 0.8 kPa										
7	0.281	5	5	12	7.7	1075	23.8	956	99	96
Hard Pan Simulant - Kaolin Clay and Plaster; Vane Shear Strength 150 ± 30 kPa										
8	0.281	5	5	12	5.2	1106	24.0	1148	>100	95

- **Retrieval Strategy:** Two retrieval strategies were evaluated: 1) concurrent balanced operation with the nozzle flow rate matched to the retrieval pump flow rate, obtained with the 0.281-in.-diameter nozzle and 2) unbalanced retrieval with the nozzle flow rate greater than the retrieval flow rate, obtained with the 0.310-in.-diameter nozzle. Percent retrieved were similar for both cases. From observations during the runs, solids tended to settle when the jet was turned off. So for cases with unbalanced retrieval solids were observed to settle along the sides of the tank as the water was pumped out.

- **Sludge Shear Strength and Composition:** The extendible-nozzle system is very robust. It was able to readily dislodge shear strength ranging up to 150 kPa during these tests at stand-off distances of 15 to 20 ft. Stationary-jet tests described in Sections 5 and 6 showed that the system could dislodge stronger simulants at stand-off distances of up to 40 and 50 ft.

- **Extendible-Nozzle Motion:** Two types of extendible-nozzle motion were evaluated: 1) moving the nozzle from side to side by rotating the mast at a constant nozzle-extension length and 2) changing the point of jet impact by increasing or decreasing the nozzle angle with the floor. These methods both worked well. The strategy selected should be based on what is easier for the operator to control or easier to keep the nozzle clean.

- **Retrieval Pump Position:** Two retrieval pump locations were evaluated: 1) multiple riser installation with the retrieval pump inlet some distance away from the base of the nozzle and 2) single riser installation with the retrieval pump inlet beneath the nozzle. During all but one of the tests, the retrieval pump suction inlet was located in the multiple riser configuration, with the inlet 15 ft from the nozzle base and 5 ft from the end of the tank. Solids were dislodged and swept to the retrieval pump inlet by the jet and fluid motion. During one test, the retrieval pump suction inlet was located 22 ft from the end of the tank, almost directly beneath the extendible nozzle, modeling the single riser installation. In this case, the sides of the tank and the jet fluid motion were used to propel the slurry to the retrieval pump inlet. This was accomplished; however, the overall retrieval for this operating strategy was slightly less than that obtained with the multiple riser configuration with the retrieval pump inlet in line with the jet.

Based on these tests, the parameter that had the largest effect on system performance was the location of the retrieval pump. It is preferable to install the extendible-nozzle system in one riser and the retrieval pump in a separate riser so that the extendible nozzle can be used to sweep the solids to be retrieved to the pump inlet without relying on motion induced by the shape of the vessel.

8.0 Horizontal Underground Storage Tank Extendible-Nozzle System Configuration

The initial radioactive deployment of the extendiblenozzle will occur at the Oak Ridge National Laboratory's Old Hydrofracture Facility. This deployment is being conducted as a partnership between the Oak Ridge National Laboratory's US DOE EM-40 Old Hydrofracture Facility remedation project team and the US DOE EM-50 Tanks Focus Area Retrieval Process Development and Enhancements project. The extendible-nozzle system was designed, constructed, acceptance tested and delivered to Oak Ridge in August 1997. This section describes the OHF site and how it impacted the design of the extendible-nozzle, the extendible-nozzle system, the visualization system, and other horizontal tank applications.

8.1 Oak Ridge National Laboratory Old Hydrofracture Facility Site

The OHF site plan is shown in Figure 8.1. The site contains four horizontal underground storage tanks. Tank dimensions and contents are discussed in Section 3. The extendiblenozzle will be sequentially inserted in the central riser of each of the tanks and operated to dislodge and retrieve the sludge and slurry from the tanks.

8.2 Extendible Nozzle

The extendible nozzle was designed, constructed, and acceptance tested by Waterjet Technology, Inc. under contract with Pacific Northwest National Laboratory. The extendible-nozzle components are shown in Figure 8.2. The extendible nozzle was designed and constructed to meet the specifications listed in Table 8.1.

8.2.1 Extendible-Nozzle Overview

The extendible nozzle is a sluicing system designed to dislodge and slurry hard waste from underground storage tanks. The nozzle assembly consists of a support platform and mast that extends below grade into the tank. Inside the mast is a segmented, flexible arm through which passes the high-pressure hose. The exit nozzle is located on the distal end of the arm. The arm is made rigid by four tensioned steel cables passing through the segments. While tensioned, the arm can be deployed radially to a distance of 10 ft from the mast centerline, and also from a horizontal position to vertically downward. In addition, the mast and nozzle assembly can be rotated ±180 degree to give complete coverage of the tank.

Movement and tensioning of the arm is accomplished hydraulically, and the arm's position and extension are determined by potentiometer type encoders.

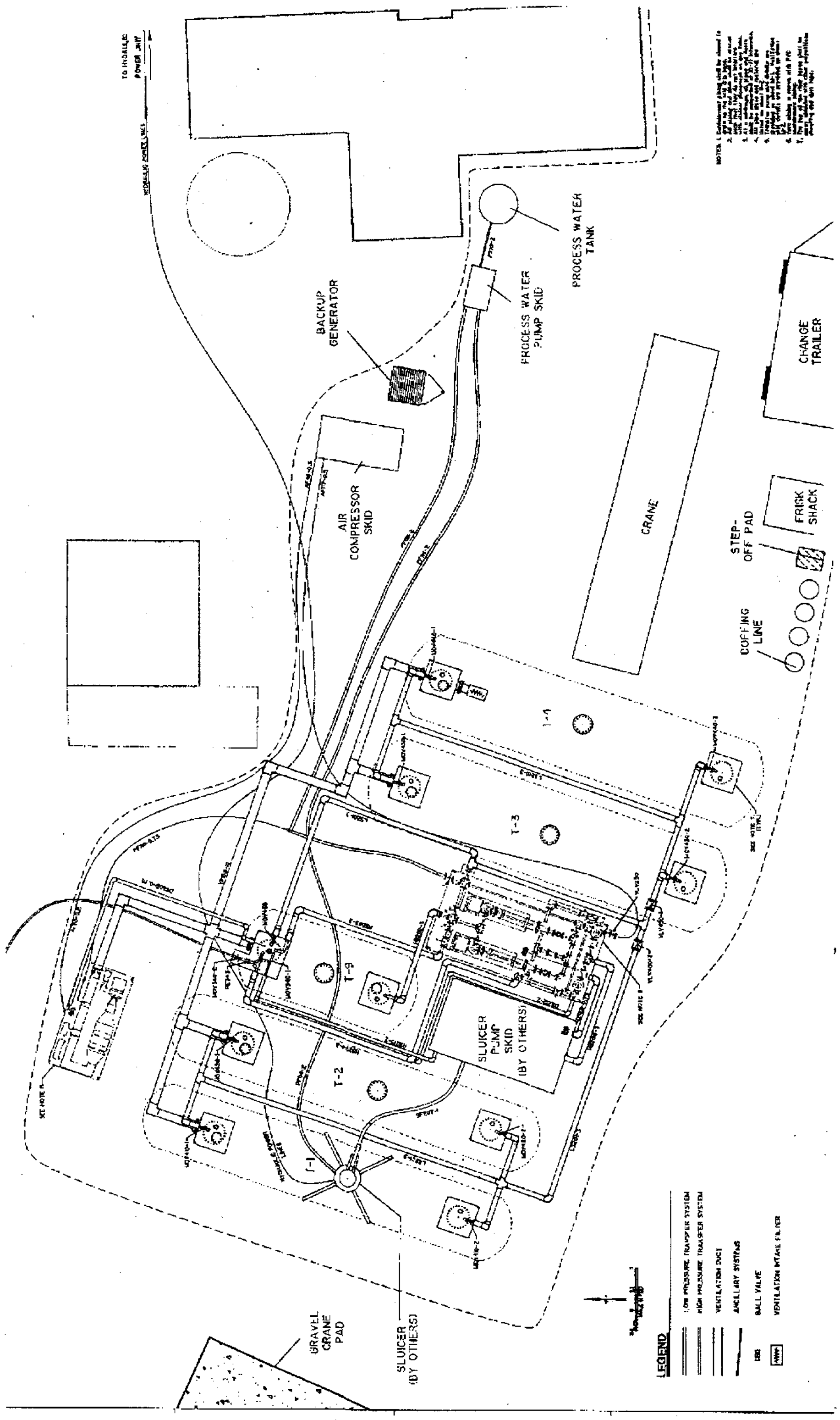

Figure 8.1 OHF Site Showing Tanks and Melton Valley Pipeline

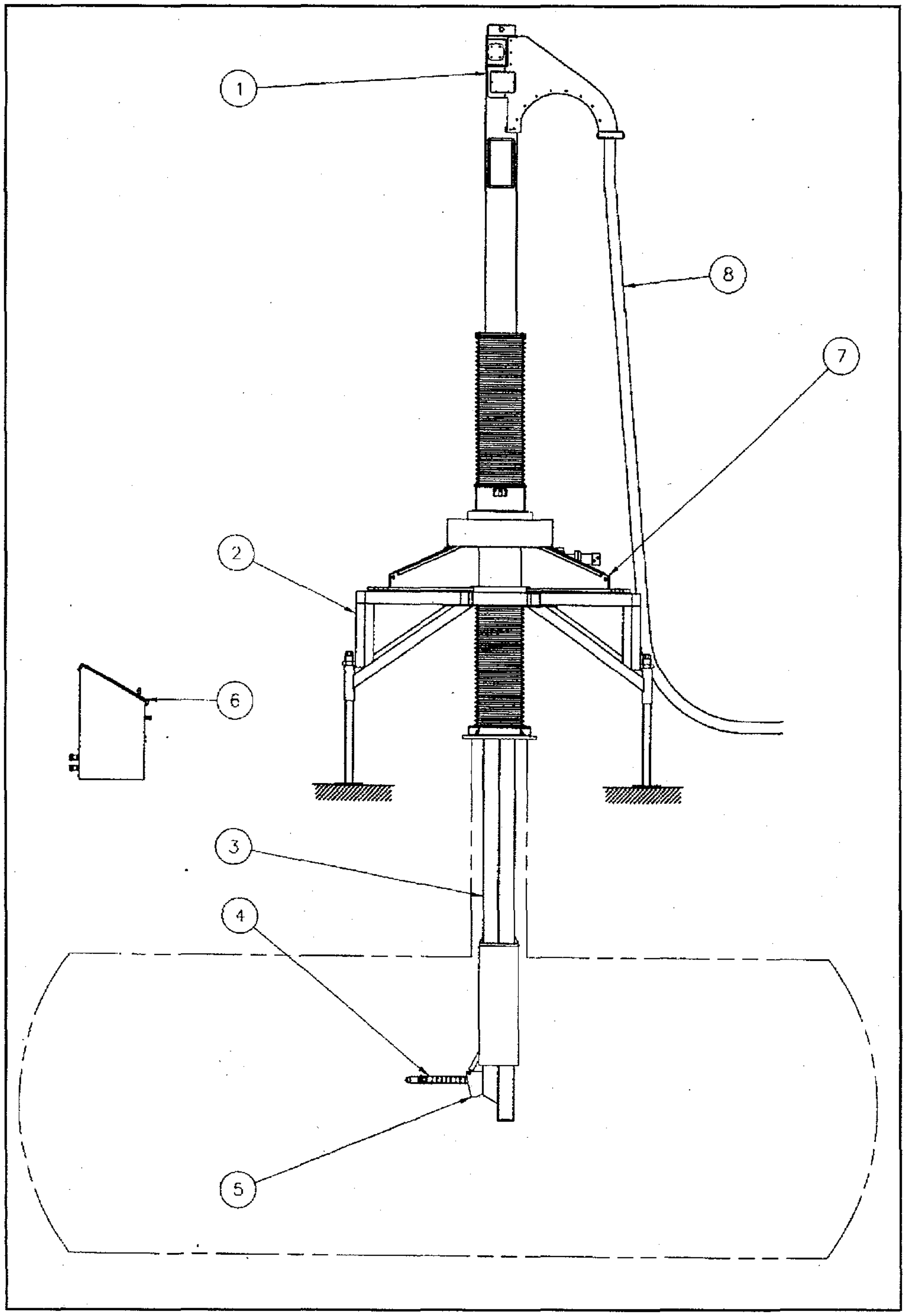

Figure 8.2 Extendible-Nozzle Components

Legend: 1) top mast assembly, 2) platform assembly, 3) lower mast assembly, 4) arm assembly, 5) launch assembly, 6) control console, 7) bridge mount, and 8) containment hose assembly

Table 8.1 Extendible-Nozzle Specifications

Description	Specification
Maximum slurry line working pressure	3000 psi
Design flow rate	150 gpm
Maximum arm extension	10 ft from mast centerline
Arm range of motion rotation azimuthal	 ± 180 degree 90 degree (horizontal to vertically downward)
Platform vertical range	30 in.
Weight	6250 lbm
Maximum arm extension rate	10 in./s
Minimum launch angle rate	9 degree/s
Mast rotation speed	0.012 to 1.2 rpm
Maximum arm rinse working pressure	150 psi
Maximum spray ring working pressure	250 psi
Exposed materials. Materials exposed to waste are stainless steel (300 series, 5 to 15 ph), hard chromium plate, nickel plate, polyurethane enamel-coated carbon steel, polyurethane, neoprène, polyethylene, nylon.	

8.2.2 Arm

The arm consists of small metallic links that are held together with tensioning cables. The arm links mesh together by cylindrically shaped bearings and bearing sockets (pivot points). The 3000-psi water hose runs through the center of the arm links. The arm is anchored to the tensioning assembly, which incorporates a linear actuator that puts a tensile load on the arm cables, thus drawing the arm links together and providing a controlled arm stiffness.

The arm is extended and retracted into the mast by means of a hydraulic motor-driven chain and tie rod system. This chain moves the tie rod and arm tensioning assembly up and down within the mast tube. The arm, anchored to the tensioning assembly goes up and down.

The arm launch mechanism controls the arm angle by means of linear hydraulic actuators. The arm has an azimuthal range of motion from vertically downward to horizontal. The arm is kept from kinking at the elbow by a series of roller and chain guide surfaces within the launch mechanism.

8.2.3 Extendible-Nozzle Weight

The bridge mount and stand are estimated to weigh 3600 lbm. The combined weight of the mast and bridge mount is estimated to be ~6350 lbm, distributed over an area 8 ft x 8 ft on the surface. The maximum force load that is transferred to the supporting surface (ground) due to the jet thrust moment is ~1060 lbm (at maximum jet thrust with the moment load taken on one leg of the stand). The mast weight is estimated to be ~2750 lbm.

Lifting shackles to carry the weight of the bridge mount during installation and removal are incorporated in the bridge mount structure.

8.2.4 Mast Mount

The mast support mount consists of a bridge mount assembly that is bolted to a portable platform over the riser and supports the mast assembly at the desired elevation over the tank floor. The tanks are different diameters and their depths below grade differ. The extendible-nozzle system configuration for deployment in each of the tanks is shown in Figure 8.3. The extendible-nozzle deployment sequence is shown in Figure 8.4. The extendible nozzle is designed to be launched along the center line of the tank; however, the platform legs can be adjusted to position the extendible nozzle either above or below the tank centerline.

The bridge mount provides a rotary motion to the mast about its axis, providing the required 360 degree (±180 degree) sweeping motion to the nozzle. The rotary motion is created by a hydraulic motor powering a turntable. There are provisions for electronic position monitoring of the mast clocking angle. The vertical elevation of the mast relative to the tank and ground level is set manually with the adjustable platform legs. The adjustment is made by changing the extension of Acme screw leg sections.

8.2.5 Bellows Containment

The mast mount assembly includes a bellows type expanding containment cover that encloses the portion of the mast that will be exposed to tank waste. A breather tube is vented into the riser to allow air flow in and out of the cover as it is extended and retracted. The cover is made of polyurethane and nylon. A clamp-on cover plate is used to close the end of the containment cover during storage.

A second bellows cover is located between the bridge mount and riser flange. An interface flange is located at the bottom of the cover to attach to the riser. This interface has an internal 150-psi spray ring to rinse the mast as it is removed from the tank.

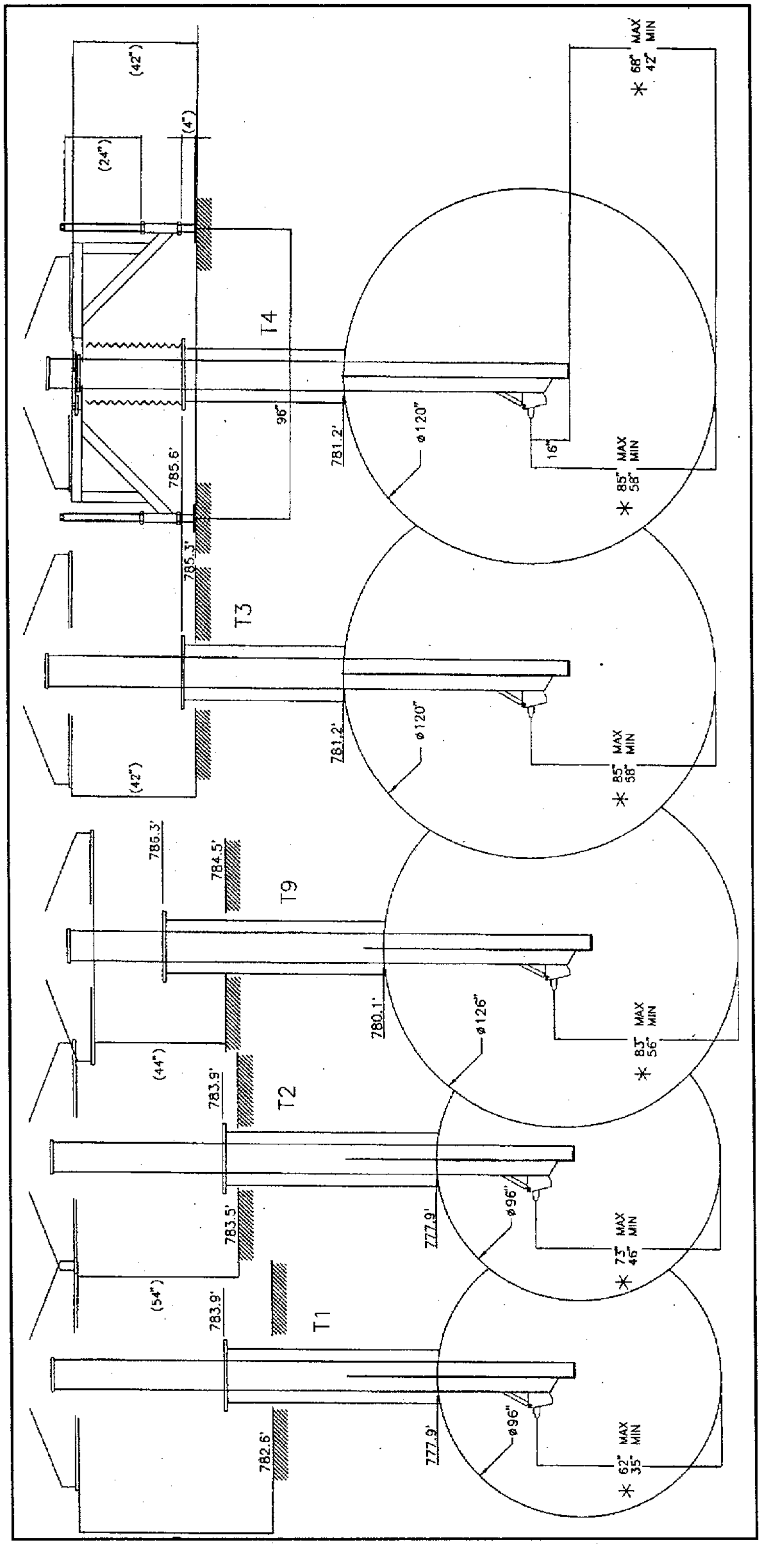

Figure 8.3 Extendible-Nozzle Deployment Configuration

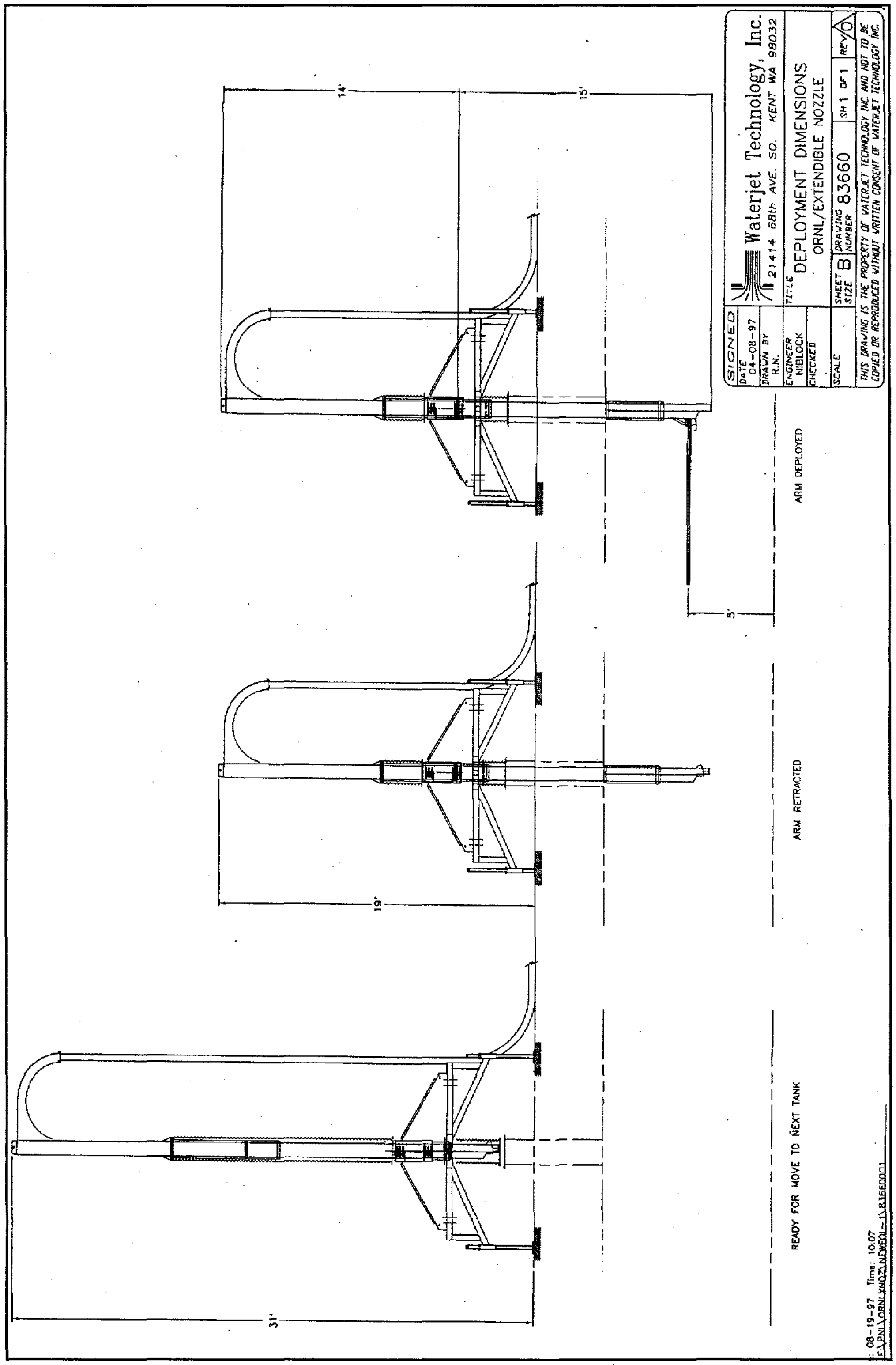

Figure 8.4 Extendible-Nozzle Deployment Sequence

8.2.6 Mast Design

The mast is approximately 29 ft in length and is made up of two sections with a bolted flange joint. The top and bottom mast sections are constructed with 5-in. x 10-in. rectangular tubing and are 14.5-ft long. The bottom mast section contains the arm, arm tensioning assembly, and launch mechanism. Hydraulic hoses are used as conduits between the top and bottom section of the mast. This eliminates the need for hydraulic joints inside the tank, with the exception of the hose termination points at the actuators and waterjet nozzle. The top mast section is designed to prevent rainwater from entering the mast shell. A lifting shackle to carry the weight of the mast and mast mount assemblies are located at the top end of the mast. A fulcrum is located as the bottom of the mast so that the mast can be pinned to a support structure and put in a lay down position.

A safety stop is welded to the mast to eliminate the possibility of the mast contacting internal tank components in the event that the mast is dropped during installation or slips at the bridge mount clamp.

The arm and tensioning mechanism are moved up and down in the bottom mast section by a length of rigid pipe. The hydraulic oil and high-pressure water hoses required to move with the arm tensioning assembly (as the arm is drawn in and out of the mast) run from the bottom mast section to the top mast section within this pipe. This pipe extends from the arm tensioner, through the mast, to the extension actuator, which is located inside the top mast section above the bridge. The arm extension actuator is a hydraulic motor.

8.2.7 Containment Hose

A double-conduit coaxial hose is used to feed the high-pressure water to the inside of the upper mast. The outer shell is a 900-psi working pressure, 3600-psi burst pressure hose. In the event of a hose burst, the maximum pressure in the shell is estimated to be less than 100 psi.

8.3 Extendible-Nozzle Control System

The control system for the extendible-nozzle system consists of a hydraulic power unit, a control console, and a network of hydraulic and electrical circuits. A diagram of the control system in shown in Figure 8.5.

8.3.1 Control Console

The control console performs the following functions:

- performs hydraulic distribution between the hydraulic power unit and the mast
- provides four independent stations for controlling and monitoring the four independent motions permitted by the extendible-nozzle assembly
- provides user-defined automatic shutoff points for mast rotation control

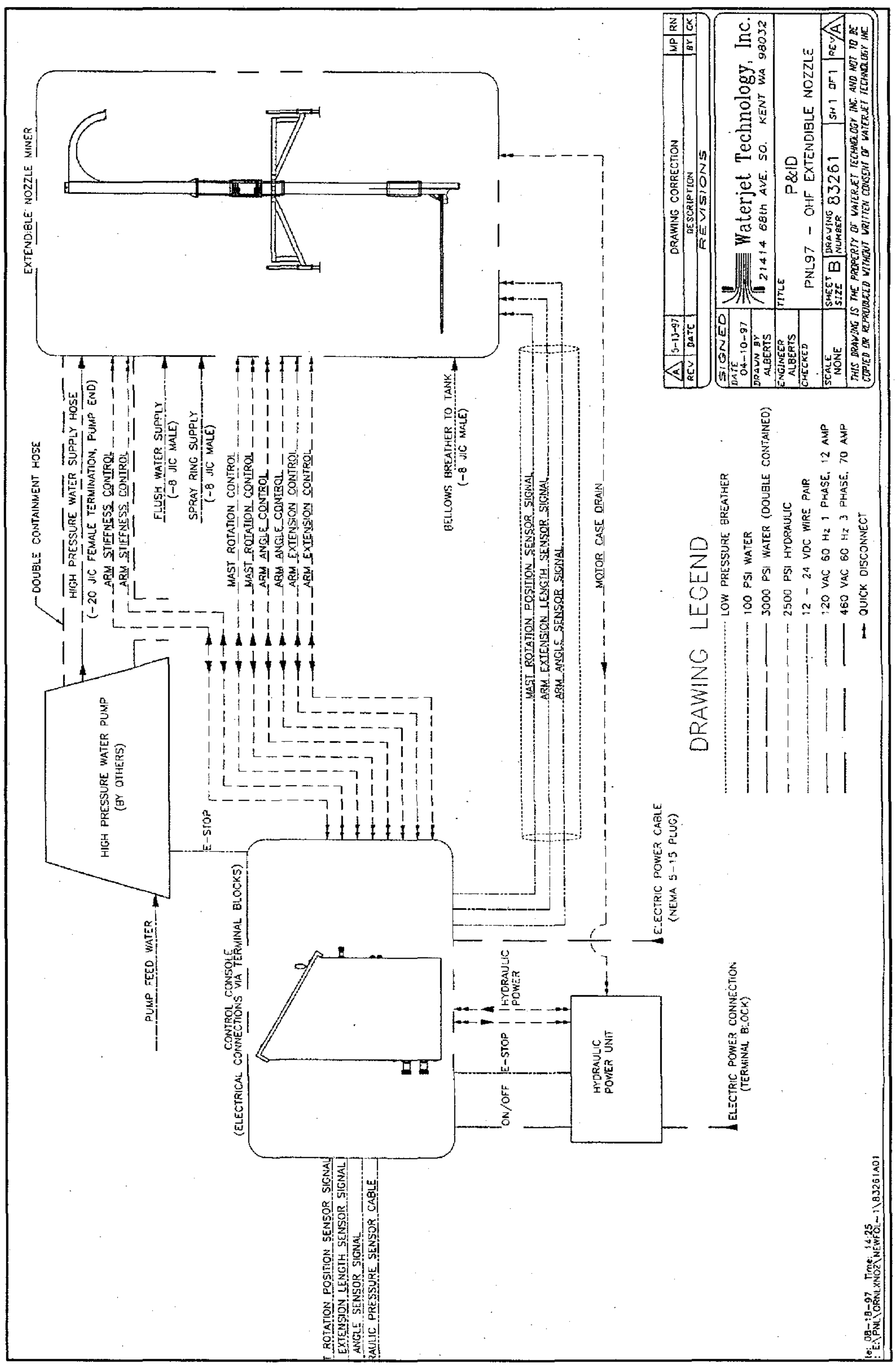

Figure 8.5 Piping and Control Diagram

- provides a circuit that allows the user to disable all motions at the mast while maintaining pressure in the arm stiffening circuit
- provides isolated outputs for external monitoring of mast rotation, arm angle, and arm extension length
- provides a transducer output for external monitoring of system input hydraulic pressure
- provides a pressure switch connected to the tension pressure port of the tensioning cylinder.

8.3.2 Hydraulic Power System

The hydraulic power unit consists of a positive displacement, pressure-compensated pump, driven by a 20 hp electric motor. The motor control box is contained on the skid with the hydraulic power unit. The 3 phase 440 Vac power to drive the motor, and the 110 Vac to drive the control relays contained within the motor control box must be supplied by cords extending from the motor control box. An emergency shut off (E-Stop) exists on the motor control box. An interconnecting electrical umbilical between the control console and the motor control box allows a remote start and stop function from the control console.

8.4 High-Pressure Pump Skid

The extendible nozzle will be powered by a high-pressure pump. Pump operating specifications include providing a flow rate of 150 gpm at a pressure of 1500 psi. The pump must be located on a skid to contain any leakage from the system. The skid configuration is shown in Figure 8.6. Figure 8.7 shows how the pump, piping, and instrumentation are integrated with the balance-of-plant equipment at the Old Hydrofracture Facility installation.

8.5 Extendible-Nozzle Tank Visualization System

The extendible-nozzle visualization system is an operator aid for the extendible-nozzle system. During in-tank operation, the mist from the extendible nozzle may make it difficult to see the position and orientation of the nozzle using remote video cameras. The extendible-nozzle visualization system provides a computer-generated image of the tank with the extendible nozzle to give the operator a view of in-tank operations.

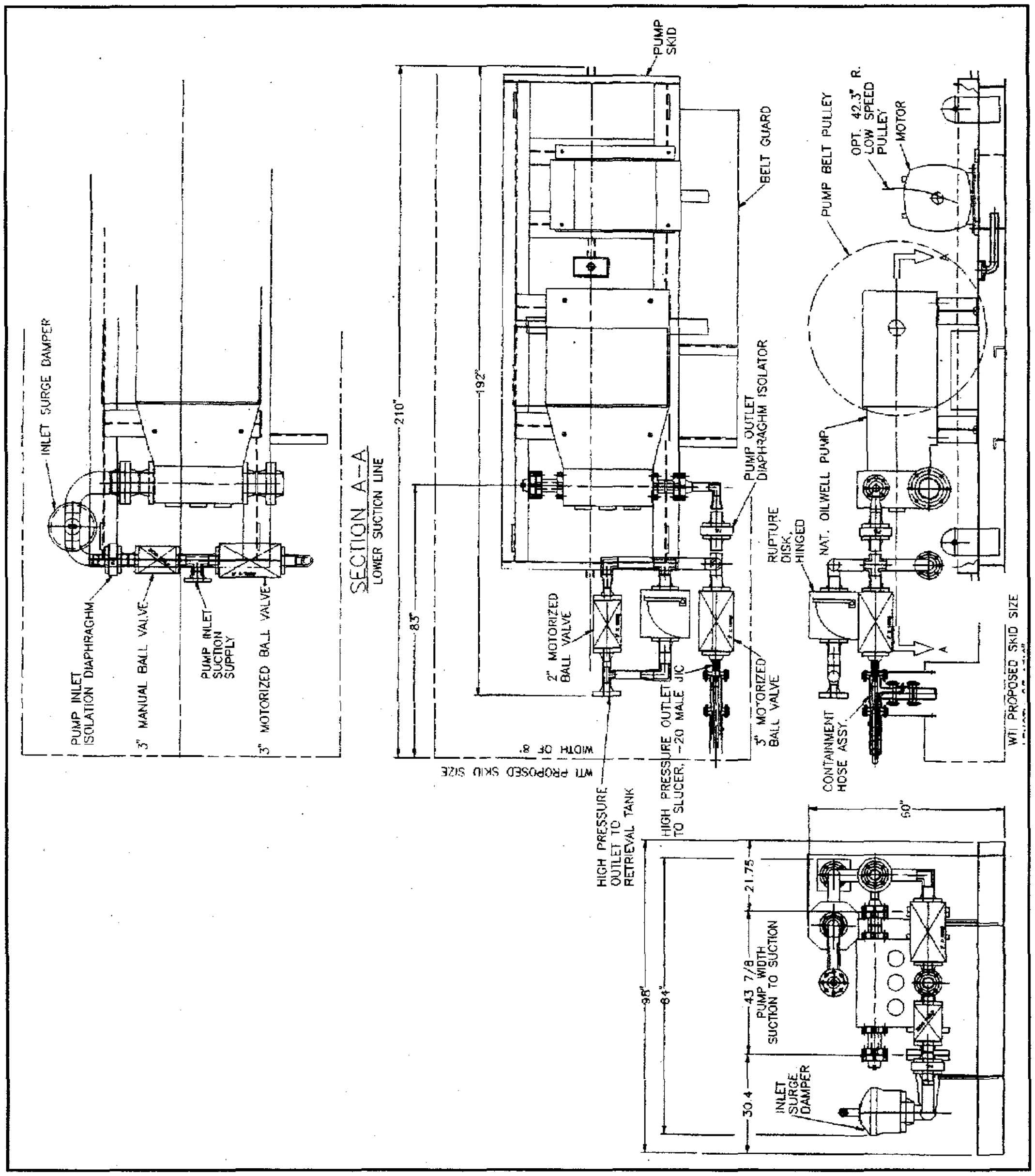

Figure 8.6 High-Pressure Pump Skid

The extendible-nozzle visualization system consists of a Silicon Graphics O2 low-end work station, and I/O (input/output) module that connects to the extendible-nozzle control console and software (called Squirt) that provides a 3-dimensional animated model of the extendible nozzle and the tank in which it is working. Position and orientation information from the extendible nozzle is fed to Squirt via the I/O module so that the 3-dimensional model accurately shows where the extendible nozzle and its spray stream are in relation to the tank. In addition, Squirt can warn of any impending collisions between the nozzle and the tank infrastructure or any modeled items in it. A schematic for the visualization system is shown in Figure 8.8.

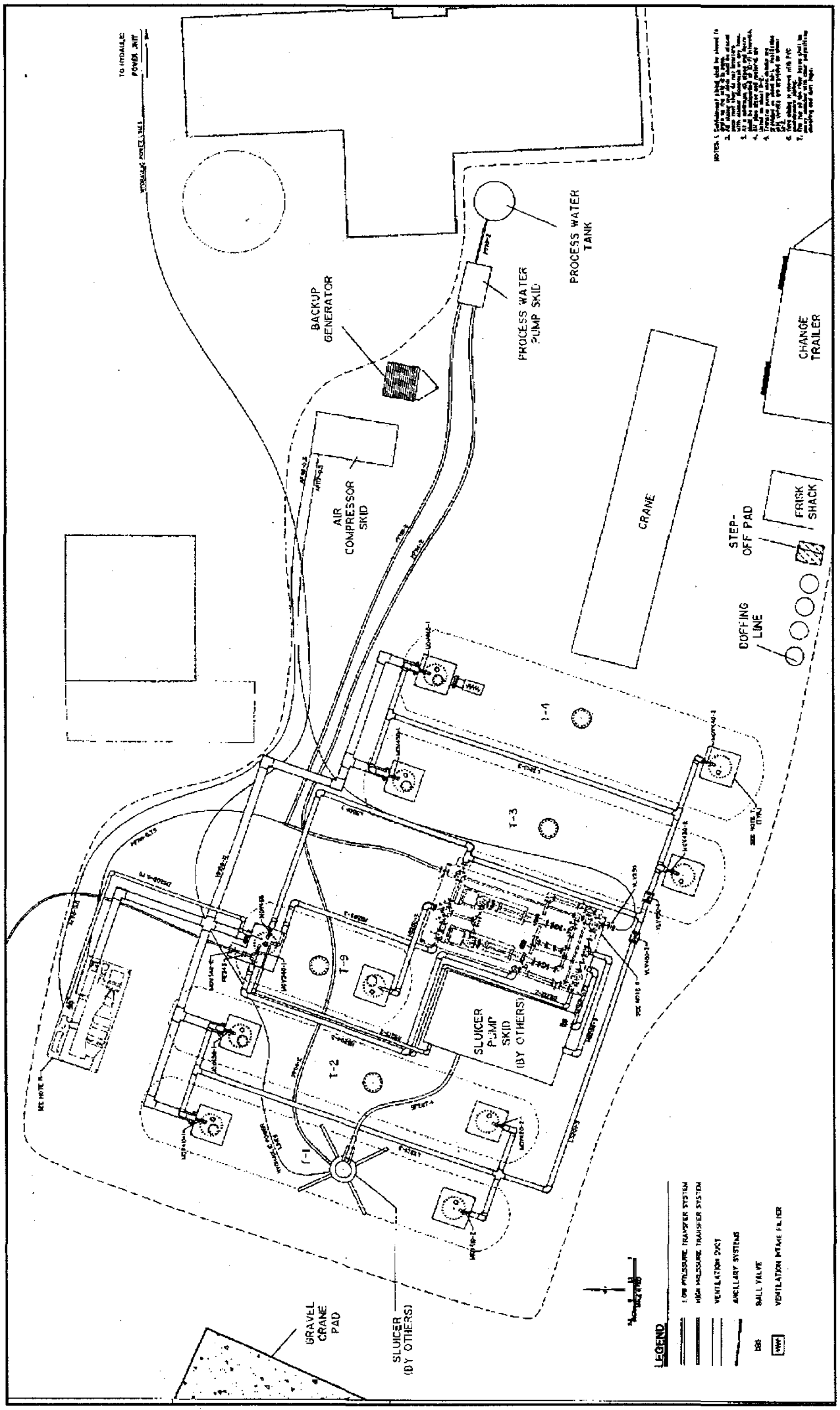

Figure 8.7 OHF Site Layout and Piping Plan

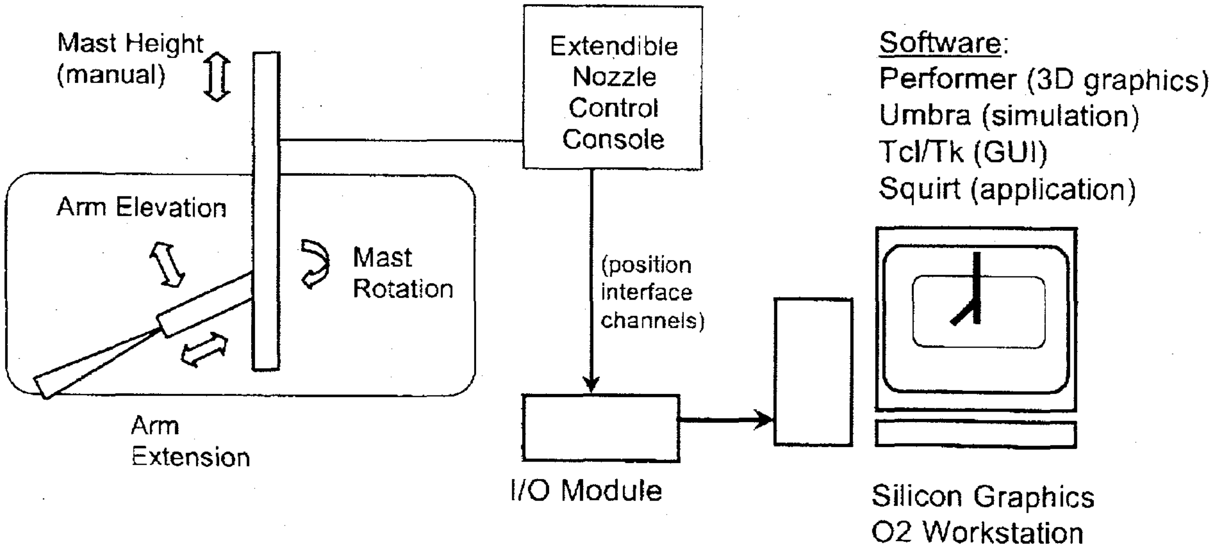

Figure 8.8 Visualization System Components

8.6 Deployment at Other Horizontal Tanks

The extendible-nozzle system design is suitable for deployment in a range of horizontal storage tanks. The Oak Ridge Old Hydrofracture Facility design shows how an extendible-nozzle system can be versatile enough to be deployed in tanks ranging in diameter from 8 to 10.5 ft and lengths from 24 to 44 ft. Other horizontal storage tanks of similar size exist at the Oak Ridge National Laboratory's Bethel Valley Site and at the Idaho National Engineering and Environmental Laboratory's V-Tanks. A successful deployment at Old Hydrofracture Facility should provide a performance base for extendible-nozzle deployment at other DOE sites.

9.0 Vertical Tank Extendible-Nozzle System Configuration

In fiscal year 1996, the initial deployment site selected for the extendible nozzle was Tank 19, an 85-ft-diameter vertical underground storage tank at the Savannah River Site. The extendible-nozzle system design for this tank was completed through the 90% design phase. This design is applicable for all large-diameter vertical underground storage tanks with on the order of 40-ft below grade to reach the tank floor. Savannah River Site, Hanford Site, and West Valley all possess vertical underground storage tanks that have these dimensions.

9.1 Savannah River Site - Tank 19 Configuration

Savannah River Site Tank 19 is shown in Figure 9.1. This figure shows the riser and bridge structure for extendible-nozzle deployment. The extendible nozzle was designed to be deployed in three risers, (the west, southwest, and east) as shown in Figure 9.2. Figure 9.2 also shows the location of the high-pressure pump skid and the control console.

The configuration for the extendible nozzle is shown in Figure 9.3. The mast consists of four segments each 17 to 20 ft in length. Other components are similar to those seen in the Old Hydrofracture Facility extendible-nozzle design.

9.2 Hanford Site Tank Applications

Hanford tanks are 75-ft in diameter and 30-ft high with an overburden layer and riser system similar to that at the Savannah River Site. With 42-in.-diameter risers and significantly more ~18-in.-diameter risers available, the extendible-nozzle system could be deployed in almost every tank. This would be a cost-effective deployment because the system design has been completed to the 90% design phase and after FY98, operating experience in the field from the Oak Ridge OHF tank remediation will be gained.

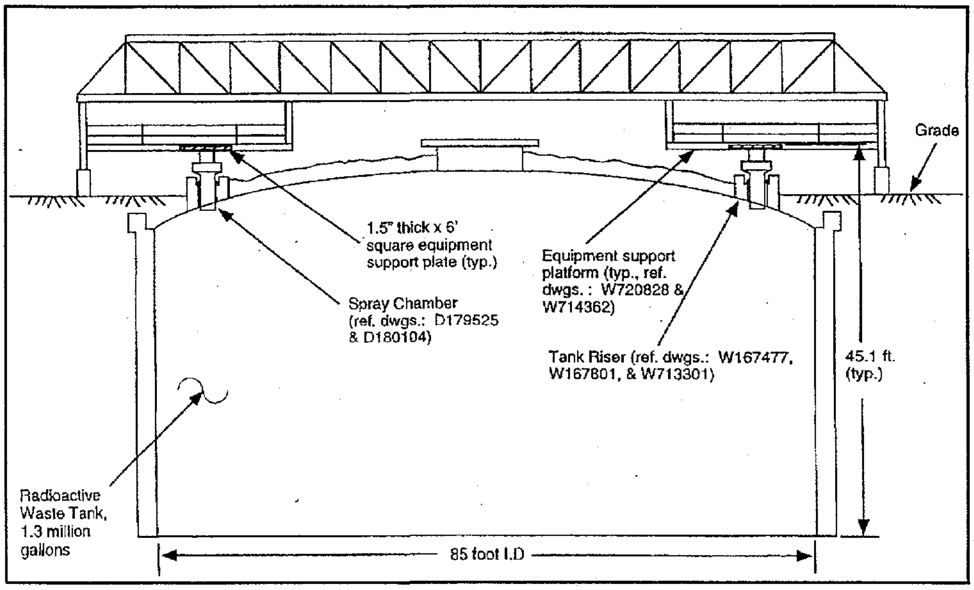

Figure 9.1 Savannah River Site Tank 19 Riser and Bridge Configuration

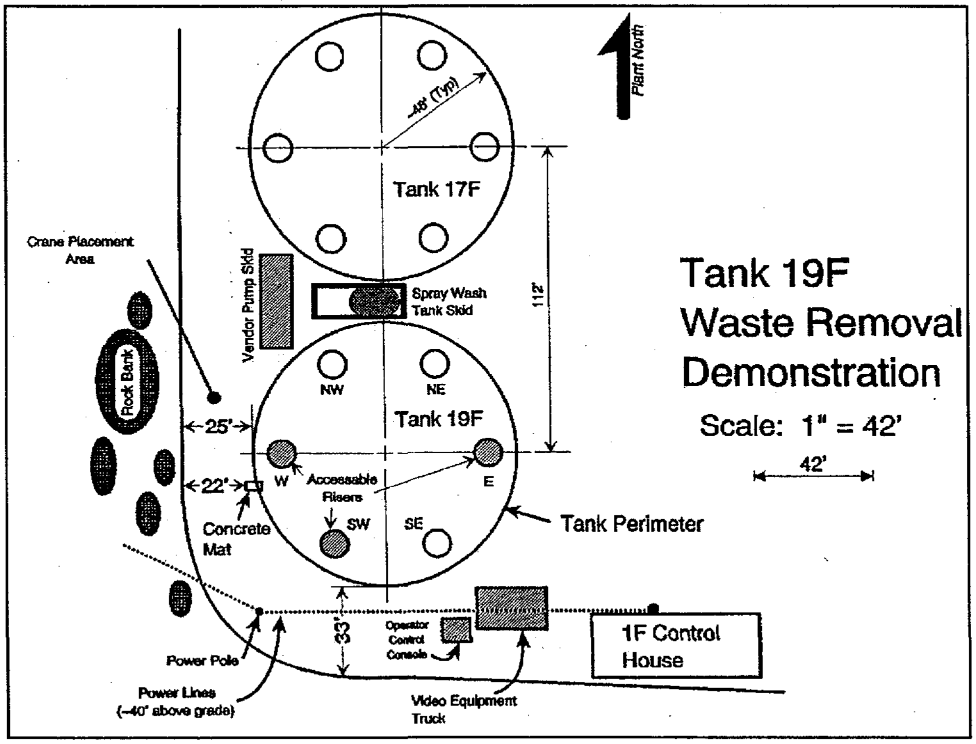

Figure 9.2 Savannah River Site Tank 19 Riser Locations

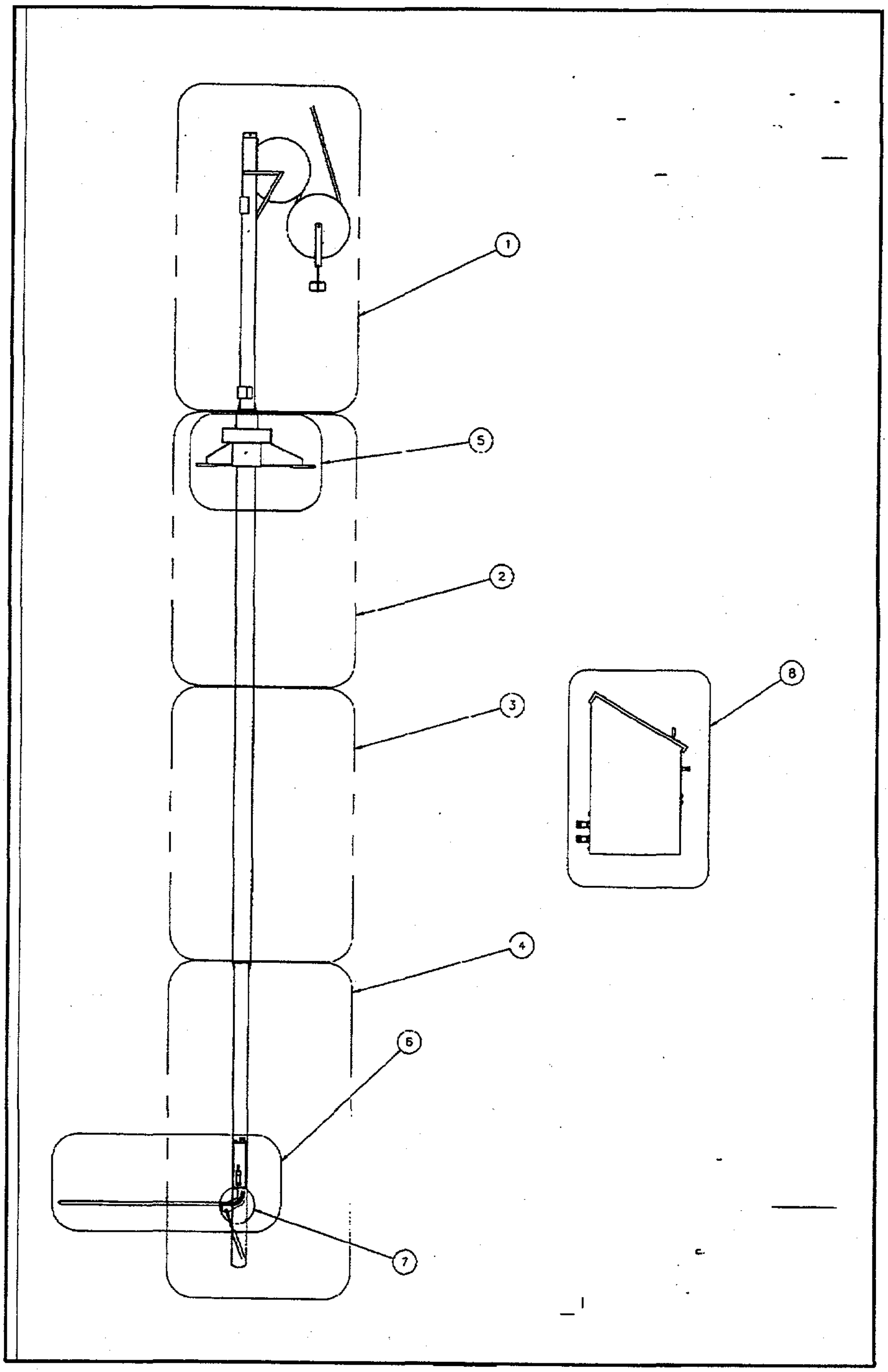

Figure 9.3 Extendible-Nozzle Configuration for Savannah River Site Tank 19

Legend: 1) upper mast assembly, 2) standard mast assembly, 3) standard mast assembly, 4) lower mast assembly, 5) bridge mount assembly, 6) arm assembly, 7) launch assembly, 8) control console assembly.

10.0 Extendible-Nozzle Deployment at ORNL OHF

In fiscal year 1998, the borehole-miner extendible-nozzle system was deployed at ORNL Old Hydrofracture Facility to remediate five tanks. Prior to the hot deployment, the extendible-nozzle system was integrated into the balance-of-plant equipment and the equipment operation and performance verified during cold tests, also conducted at ORNL. Bechtel Jacobs, who manages ORNL for the US Department of Energy, contracted with CDM Federal Programs Corporation to perform the OHF tank contents removal. Reports describing the cold and hot operations are being prepared by the system operators and Tanks Focus Area team members at ORNL. Additional data analysis and a summary report of extendible-nozzle performance during operation will be completed in fiscal year 1999 by this report author.

The major subsystems that comprise the tank contents removal system are:

- sluicing system - borehole-miner extendible-nozzle
- pumping system - that powers the borehole miner
- ventilation system
- instrumentaion and control systemretrieval pump system.

Major components of the sluicing system (the borehole-miner extendible-nozzle system and high-pressure pump skid) were provided by the Tanks Focus Area.

Information presented in this report provides a snapshot of system deployment at the cold test facility and a chronology of hot operations during the OHF tank remediation.

10.1 Extendible-Nozzle System Cold Tests

In fiscal year 1998, the borehole-miner extendible-nozzle was integrated with the balance-of-plant at the ORNL robotics and process systems site, where the cold tests were conducted. In fiscal year 1999, operating data from the cold tests will be analyzed to quantify system operation and performance. Data files describing this information have not yet been released to PNNL for analysis.

Photographs of system components at the cold test facility provide a snapshot of system installation. Figure 10.1 shows the borehole-miner extendible-nozzle system installed at the cold test facility. The double containment hose entering the top of the borehole miner is designed for operating pressures up to 3000 psi. The cold tests were conducted in two horizontal underground storage tanks, shown in Figure 10.2, which modeled the diameter and riser configuration of the OHF tanks. The extendible-nozzle system being extended prior to installation in the tank riser is shown in Figure 10.3. The second tank was used for storing the sluicing fluid.

Figure 10.1 Extendible-Nozzle Installed in the Cold Test Tank Riser

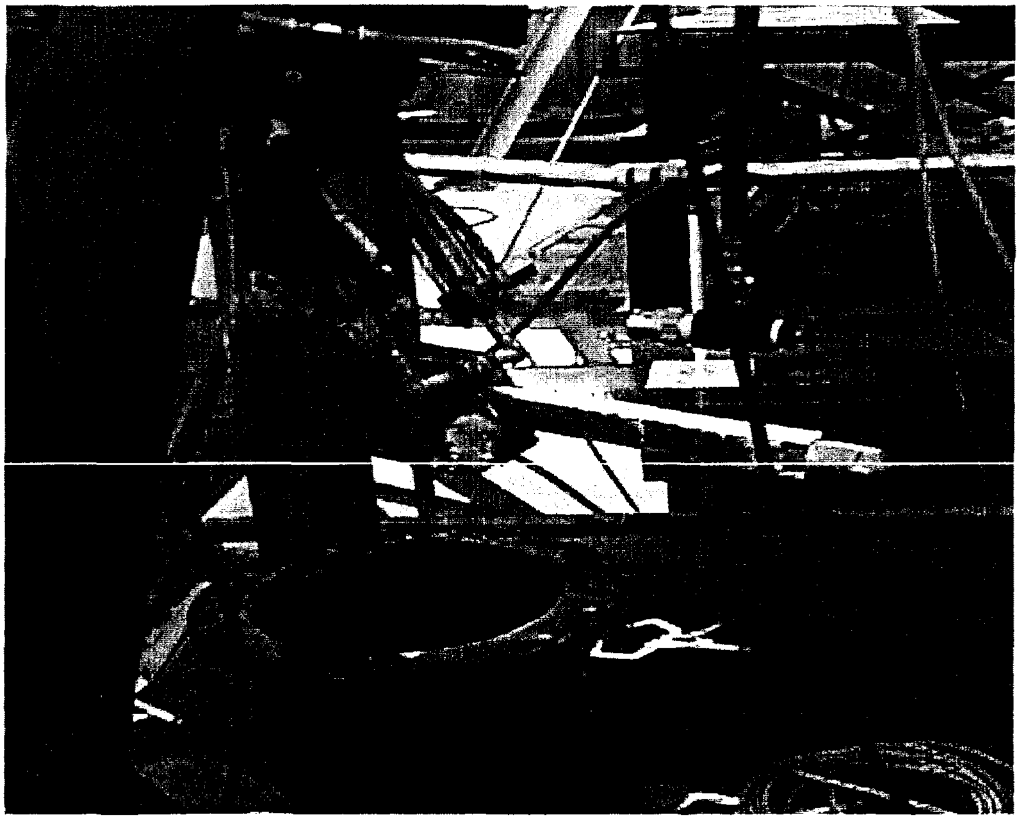

Figure 10.2 Extending the Extendible-Nozzle Prior to Installation in the Cold Test Tank Riser

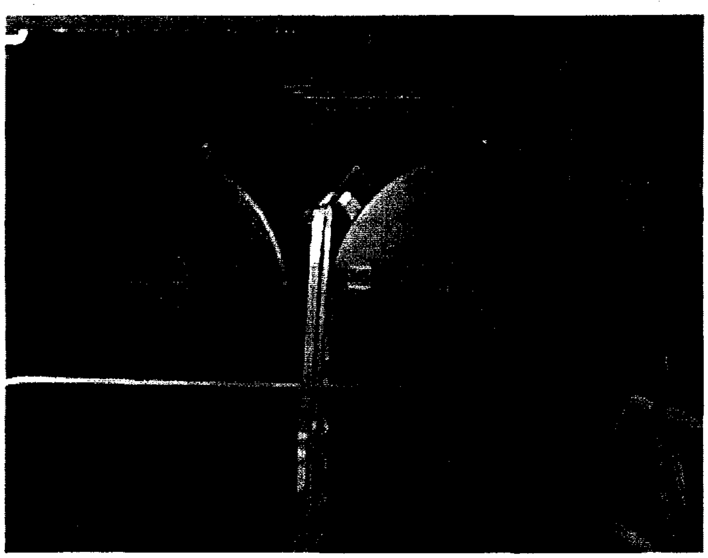

Figure 10.3 Horizontal Test Tanks at Cold Test Facility

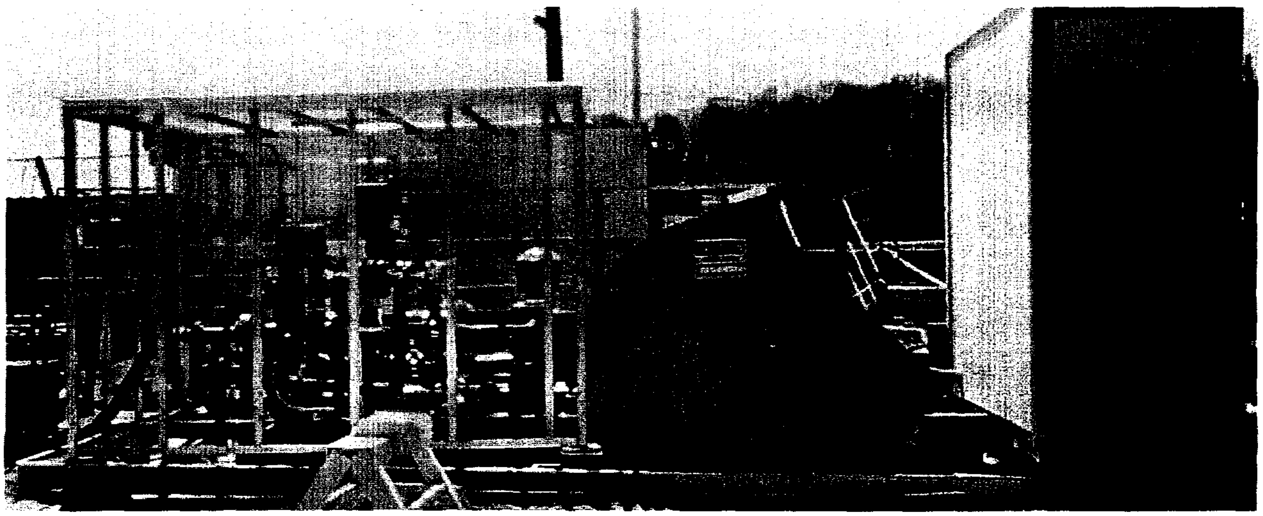

Figure 10.4 High-Pressure Pump Skid

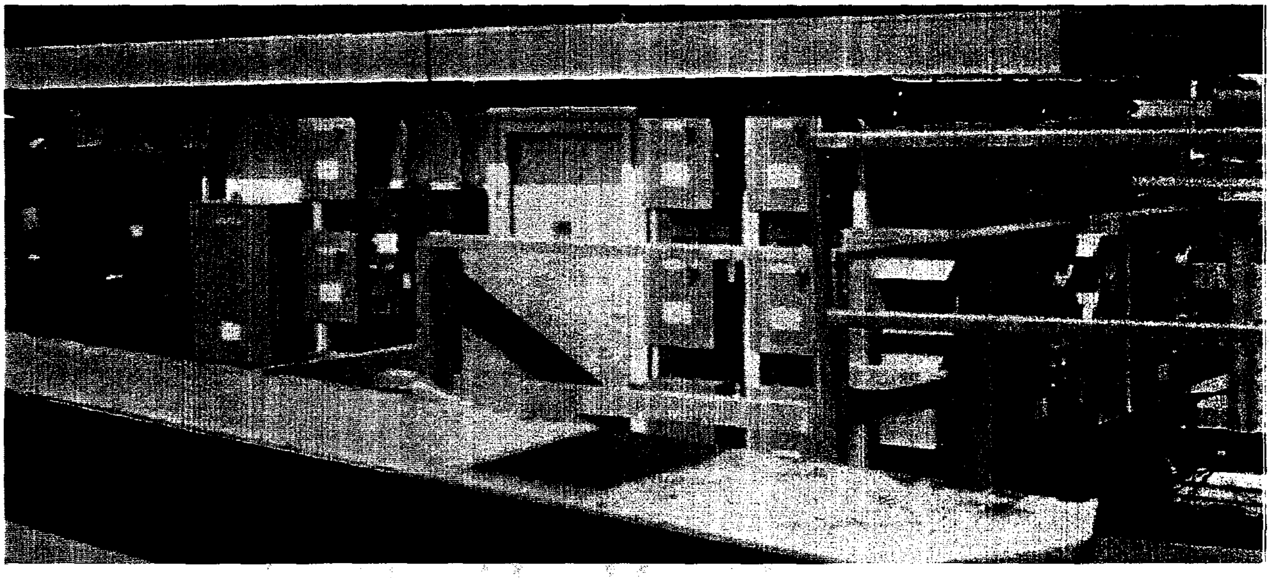

Figure 10.5 Transfer Pump Skid

The high-pressure pump skid is shown in Figure 10.4. This pump boosted the slurry received from the transfer pump to pressures in the range >200 to 1500 psi. The transfer pump skid is shown in Figure 10.5. The two pumps on this skid pressurized the slurry to 200 psi after it was pumped from the supernate tank. Figure 10.6 shows the transfer piping used to route the slurry. Valves to control the transfers are encased in white boxes to contain any leaks.

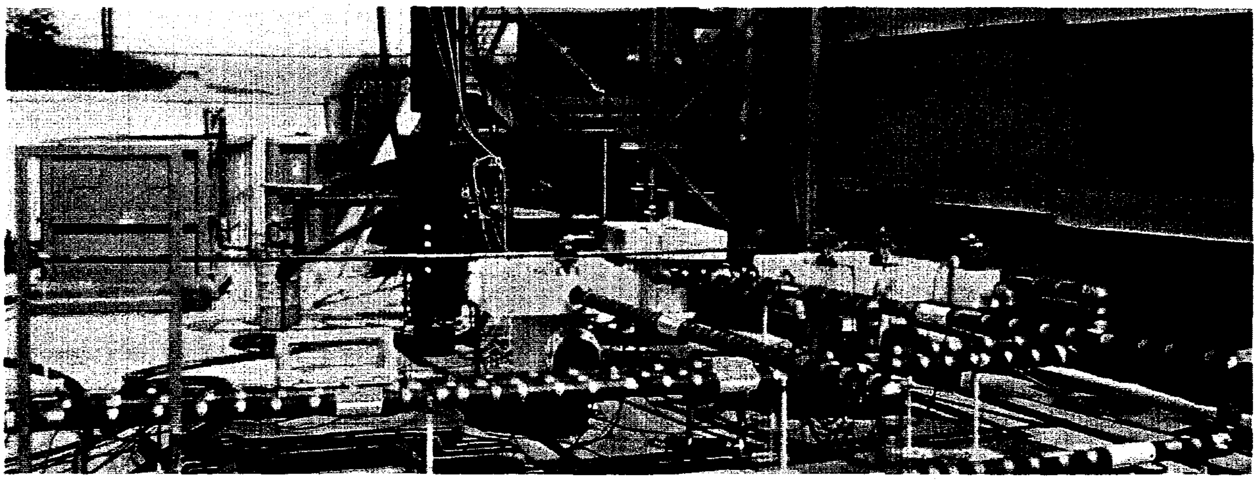

Figure 10.6 Extendible-Nozzle Process Piping and Valve Boxes

The borehole-miner system performed well during the cold tests and was qualified for use at the OHF site for the tank contents removal in May 1998.

10.2 Extendible-Nozzle System Hot Deployment

The borehole-miner extendible-nozzle system was installed at the OHF site in June 1998. Between June 28 and July 20, 1998, the five tanks were remediated. The borehole-miner extendible-nozzle system was removed from the last tank in August 1998 . Upon removal, the extendible-nozzle was bagged and taped, wrapped with Herculite and covered with tarps. The openings in the borehole-miner stand were also bagged and taped. The pump skid and piping was flushed with rinse water and was disconnected from the system.

The State of Tennessee Department of Environment and Conservation concurs that the ORNL OHF tanks were cleaned to the maximum extent practicable using pumping technology.

10.2.1 Remediation Chronology

The brief chronology provides a synopsis of the OHF tank remediation operations and schedule.

Tank T3/T9 Operations

6/28/98 22:48	Began work instruction for auto sluicing
23:03	Sluicing sequence started
6/29/98 00:22	Began transfer to MVST
04:49	Completed partial transfer and line flushing
04:51	Began sluicing of T3 residual
06:55	Sluicing sequence aborted because of submersible sluicer pump failure
08:38	Manual transfer to MVST started

11:12 Manual transfer ended

Tank T4 Operations

7/10/98 22:38 Started submersible pump in T4 (started sluicing)
00:04 Began MVST transfer. Transfer failed due to problem with transfer line to MVST

Tank T4 Restart

7/13/98 18:28 Started submersible pump in T4 (started sluicing)
19:17 Began MVST transfer
23:26 Ended transfer, shut down system, flushed lines
23:44 Began sluicing again with supernate from T3
23:56 Ended sluicing with T3 supernate
23:58 Rinsed lines

7/14/98 00:10 Began transfer to MVST
00:27 Ended transfer to MVST

Tank T2 Operations

7/15/98 20:47 Started submersible pump in T2 (begin sluicing)
21:05 Noticed arm on borehole miner bent near end; retracted arm fully to continue sluicing
21:39 Stopped sluicing because of broken rupture disk. Rupture disk was broken during previous sluice, but no effect noticed until tonight

Flushed lines and switched to high pressure pump #2

Tank T2 Restart

7/15/98 23:00 Started submersible pump in T2 (begin sluicing)
23:38 Began MVST transfer

7/16/98 02:40 Ended MVST Transfer
03:40 Began sluicing with T3 supernate
04:12 Ended sluicing with T3 supernate and started sluicing with T2 submersible pump again
04:30 Began transfer to MVST
05:10 Ended transfer to MVST

Tank T1 Operations

7/18/87 22:11 Began sluicing in tank T1
23:25 Began MVST transfer

7/19/98 02:59 Stopped transfer to MVST, began sluicing with T3 supernate
04:00 Began transfer to MVST
04:37 Stopped sluicing/transfer from T1, continued transfer from T3
04:54 Hydraulic power unit shut down; may be caused by low hydraulic fluid level (that

occurred because of a hydraulic fitting leak)
05:24 Completed transfer from T3, started line flushing.

10.2.2 Operating Data Analysis

Significant operating data that can be analyzed to provide insight into the borehole-miner performance is stored in the project operating logs, data acquisition system computer, and video files. This data is being archived and transferred to staff at Pacific Northwest National Laboratory for performance analysis in fiscal year 1999. This analysis will include 1) evaluation of the borehole miner system performance during the cold tests and during hot deployment, 2) assessment of problems that were documented and 3) lessons learned to enable the system to be successfully deployed to dislodge and retrieve waste from other radioactive waste storage tanks.

11.0 References

Lockheed Martin Environmental Restoration Program. 1996. LMERP. *Preliminary Engineering Report Waste Area Grouping 5 Old Hydrofracture Facility Tanks Content Removal Project, Oak Ridge National Laboratory, Oak Ridge, Tennessee,* ORNL/ER-372. Lockheed Martin Energy Systems, Inc., Oak Ridge, Tennessee.

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