BJC/OR-82

# Deployment of a Fluidic Pulse Jet Mixing System for Horizontal Waste Storage Tanks at Oak Ridge National Laboratory, Oak Ridge, Tennessee

**ENVIRONMENTAL MANAGEMENT & ENRICHMENT FACILITIES**







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**Lockheed Martin Energy Research Corporation**
**and AEA Technology**

contributed to the preparation of this document and should not be considered eligible contractors for its review.

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# Deployment of a Fluidic Pulse Jet Mixing System for Horizontal Waste Storage Tanks at Oak Ridge National Laboratory, Oak Ridge, Tennessee

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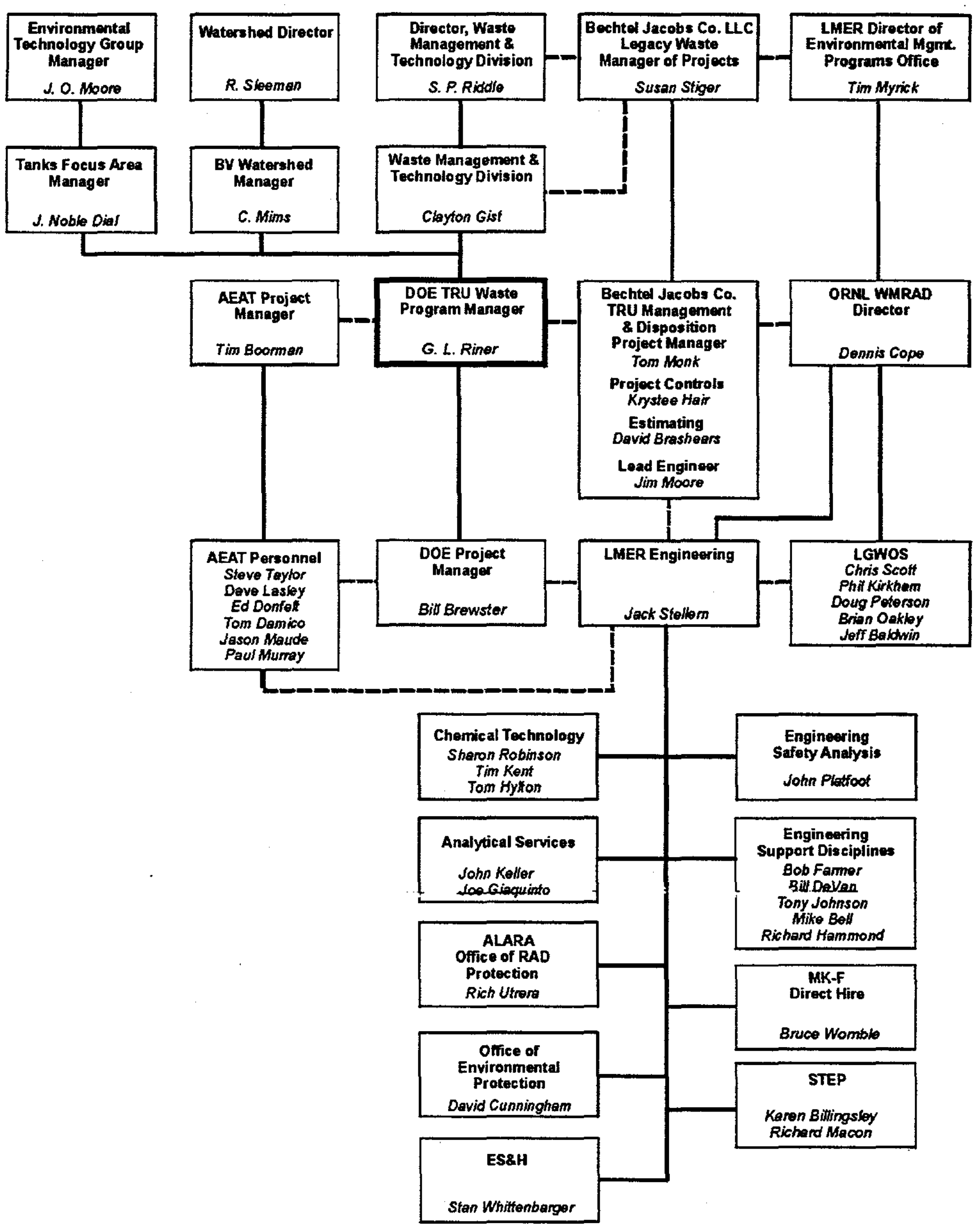
Appreciation is expressed to the DOE Oak Ridge Transuranic Waste Program and DOE Tanks Focus Area for sponsoring the development of this special publication.

ORNL DWG 98C-333

**BVESTs W-21 Mobilization and W-22 and W-23 Tank Transfers Project Organization Chart**



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# ABBREVIATIONS

| | |
|---|---|
| AEAT | AEA Technology |
| BVEST | Bethel Valley Evaporator Service Tanks |
| DOE | U.S. Department of Energy |
| DOE-HQ | U.S. Department of Energy–Headquarters |
| DOE-ORO | U.S. Department of Energy–Oak Ridge Operations |
| LLLW | liquid low-level (radioactive) waste |
| MVST | Melton Valley Storage Tanks |
| ORNL | Oak Ridge National Laboratory |
| PVV | pump and valve vault |
| PWTP | Process Waste Treatment Plant |
| RH-TRU | remote-handled transuranic |
| STEP | Solutions to Environmental Problems, Inc. |

# EXECUTIVE SUMMARY

A fluidic pulse jet mixing system, designed and fabricated by AEA Technology, was successfully demonstrated for mobilization of remote-handled transuranic (RH-TRU) sludge for retrieval from three 50,000-gal horizontal waste storage tanks (W-21, W-22, and W-23) at Oak Ridge National Laboratory (ORNL). The pulse jet system is unique because it does not contain any moving parts except for some solenoid valves which can be easily replaced if necessary. The pulse jet system consisted of seven modular equipment skids and was installed and commissioned in about 7 weeks. The system used specially designed fluidic jet pumps and charge vessels, along with existing submerged nozzles for mixing the settled sludges with existing supernate in the tank. The operation also used existing piping and progressive cavity pumps for retrieval and transfer of the waste mixtures.

In tank W-21, a total of 64,000 gal of liquid were required to mix and transfer 7100 gal of sludge to the Melton Valley Storage Tanks (MVST), which are designated for consolidation of all ORNL RH-TRU sludges. Of the liquid used for the sludge retrieval, 88% was existing or recycled tank supernate. Approximately 7770 gal of process water were added to the system. Minimizing the addition of process water to the liquid low-level waste (LLLW) system is extremely important at ORNL, where tank system storage capacity is limited. A simple manual sluicer was used periodically to wash down and aid the removal of localized sludge heels. After completion of the pulse jet mixing campaigns for tank W-21, the manual sluicer was modified to provide a higher flow rate for removal of additional quantities of the remaining sludge heel. Manual sluicing required the addition of 6000 gal of process water to remove an additional 550 gal of sludge. After the manual sluicing operation, dilute nitric acid was added to the tank in an effort to dissolve the majority of the remaining 350 gal of sludge. After a contact time of several weeks under static conditions, the pulse jet system mixed the acid and sludge for 24 hours. The mixture was transferred from the tank. Ninety-eight percent of the sludge was removed from the tank, or about 7100 gal. It was estimated that about 100 gal of sludge remained in tank W-21 after this operation.

For the sludge retrieval from tank W-22, a total of 52,000 gal of liquid were required to transfer 7000 gal of sludge to MVST. Of the liquid used for the retrieval, 95% was existing or recycled tank supernate. Approximately 2840 gal of additional process water or acid were added to the system. The manual sluicer was not used in tank W-22.

The sludge retrieval effort for tank W-23 used a total of 45,000 gal of liquid to transfer approximately 19,000 gal of sludge to MVST. Approximately 96% of the liquid that was used during retrieval operations was existing or recycled tank supernate. Only 1780 gal of water and acid were added to the system. The manual sluicer was not required in this tank.

The pulse jet system operated well and experienced no major equipment malfunctions. The modular design, use of quick-connect couplings, and low-maintenance aspects of the system minimized radiation exposure during installation and operation of the system. The extent of sludge removal from the tanks was limited by the constraints of using the existing tank nozzles and the physical characteristics of the sludge. Removing greater than 98% of this sludge would require aggressive use of the manual sluicer (and associated water additions), a shielded sluicer system that utilizes supernate from existing inventory, or a more costly and elaborate robotic retrieval system. The results of this operation indicate that the pulse jet system should be considered for mixing and bulk retrieval of sludges in other horizontal waste tanks at ORNL and U.S. Department of Energy sites.

This work was supported by the Oak Ridge Transuranic Waste Program of the U. S. Department of Energy's Office of Environmental Management and by the Tanks Focus Area of the Office of Science and Technology within the U.S. Department of Energy's Office of Environmental Management.

# 1. INTRODUCTION

The U.S. Department of Energy (DOE) is planning the remediation of underground storage tanks containing hazardous radioactive wastes at Oak Ridge National Laboratory (ORNL) and other DOE sites across the country. These tanks contain waste generated from past and present development activities involving national defense initiatives, nuclear energy research, and radioisotope production. The wastes have separated into liquid and sludge layers after many years of storage. The remediation of these tanks involves removing and processing the waste to stabilize the radioactive and hazardous components for disposal. The heavy layer of sludge in these tanks must be mobilized to remove it from the tanks. A preferred method involves mixing the sludge with existing tank liquids, rather than adding more liquids and therefore increasing the waste volume. Optimally, the sludges and liquids would be mixed to produce a uniform slurry of known composition that can be safely transferred by pipeline to another facility for additional processing.

AEA Technology (AEAT) has developed a fluidic pulse jet mixing system for tank waste that utilizes fluidic jet pumps with no moving parts and requires very little maintenance. For the ORNL horizontal tanks, a single pulse jet system can be used for several tanks, and the system required very little modification of the tank system. The pulse jet system has been used in nuclear applications in the United Kingdom for many years. These advantages led to the decision to deploy AEAT's fluidic pulse jet system for mixing and mobilizing the sludges stored in the Bethel Valley Evaporator Service Tanks (BVEST) at ORNL.

# 2. MIXING ALTERNATIVES

Other mixing systems were considered for sludge mobilization and retrieval from large horizontal storage tanks. These alternatives were limited by cost, maintenance requirements, extensive system modifications, and additional water usage.

Mixing sludge with existing liquid in large storage tanks can be challenging. At the Savannah River Site in South Carolina and the West Valley Nuclear site in New York, multiple high-horsepower mixing pumps were installed at several locations in large vertical waste tanks. The vertical geometry and availability of access ports for the mixers improved the feasibility and effectiveness of this approach. However, these pumps are very expensive and have experienced mechanical problems. The horizontal tanks at Oak Ridge, Idaho, and other facilities typically have limited access and a more difficult mixing geometry. The mixing pumps used for vertical tanks would be very costly to install and operate in horizontal tanks.

Single-point sluicing was used at ORNL to mobilize and transfer sludges out of the vertical Gunite tanks in the early 1980s (Weeren 1984). This method used a single jet nozzle installed inside the tank near the tank roof to spray high-pressure liquid to break up the sludge and cause localized mixing with the liquid. This method was reasonably effective for the vertical tanks but would not be as useful or cost-effective for the horizontal waste tanks. The single-point sluicing equipment would require significant design changes to effectively mix sludges in the lengthy horizontal tanks that have more internal obstructions than the vertical tanks. This method also provides little control over the solids content of the slurry being transferred. This increases the risk of plugging the transfer pipeline. Overall, this method would require significant design modifications, be costly to install, and use large amounts of liquid to mobilize the sludges in horizontal tanks.

The Borehole Miner extendable nozzle manufactured by Waterjet Technologies, which is being developed for waste retrieval by the DOE Tank Focus Area, is similar to single-point sluicing from the standpoint that a single high-pressure jet is used to impinge on the sludge and impart mixing. The advantage of the Borehole Miner is the ability to extend the nozzle into the tank, position it to avoid internal obstructions, and have a greater impact on the remote areas of the tank. Like the single-point sluicing method, the Borehole Miner is more complex, requires greater access to the tank, requires additional equipment, and is more maintenance intensive.

Mixing tank waste with air has been considered for horizontal tanks; however, installing multiple air spargers in the tanks would require either additional access ports or a complex and expensive deployment system. In addition, air mixing causes generation of liquid aerosols that are very difficult to separate from off-gases. Additional design work and system modifications would be required to control the aerosols.

## 3. DESCRIPTION OF PULSE JET MIXING

Pulse jet mixing typically involves the use of large-diameter pulse tubes vertically mounted in the tank and immersed in the tank waste. A vacuum is applied to the pulse tube using a jet pump, with air as the motive fluid. Sludge and liquid fill the pulse tube, and when the tube is full, the jet pump is turned off, and the tube is vented. Gravity causes the fluid in the tube to fall back into the tank and impart the mobilization and mixing action.

The AEAT pulse jet system was slightly modified for the BVEST application to make use of existing jet nozzles (six per tank). The nozzles are 3-in.-diam pipes installed from the top of the tank to about 8 in. above the tank bottom (Fig. 1). The nozzles have a 90° elbow at the bottom and were installed in opposing pairs along the length of the tank. These nozzles were originally installed for mixing purposes but were never used and were left in a blanked-off condition within the pump and valve vault (PVV) of the tank system. The pulse jet system was designed to use the existing tank nozzles by connecting each nozzle to a charge vessel in place of the normally used pulse tube. A jet pump is attached to the charge vessel to apply the necessary vacuum to pull the liquid/sludge mixture into the charge vessel via the existing nozzles. When the mixture reaches a predetermined level in the charge vessel, the jet pump is switched from vacuum to pressure mode. Air pressure is applied to the charge vessel to force the fluid back into the tank to create a mixing action. Figure 2 illustrates this operation. The pressure, frequency, and sequence of pulsing for the six jets are adjusted to achieve optimum mixing.

## 4. DESCRIPTION OF THE BVEST SYSTEM

The BVEST are located in the center of the main ORNL complex. These tanks provide surge and storage capacity for processing liquid low-level waste (LLLW) collected throughout the laboratory via an underground collection and transfer system. LLLW is processed by evaporation at the Evaporator Facility (Bldg. 2531) to reduce the volume for long-term storage. BVEST contains five tanks, numbered W-21, W-22, W-23, C-1, and C-2. Historically, tank W-22 has served as the feed tank for the evaporator, while the other tanks stored the LLLW concentrate. Tanks W-21 and W-23 may also serve as alternate feed tanks for the evaporator if tank W-22 is filled to capacity or out of service. Each tank has an operational capacity to hold 47,500 gal of liquid.

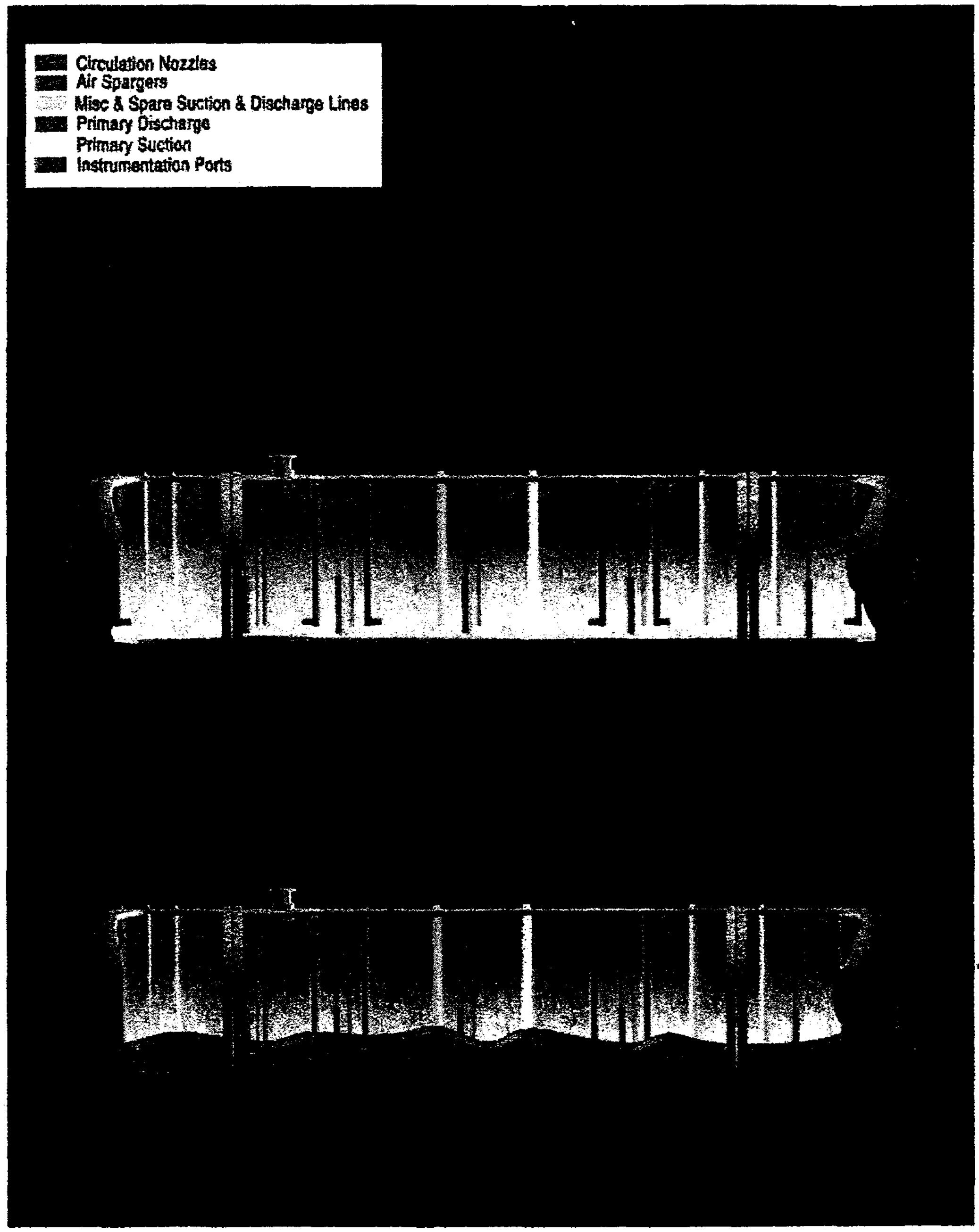


**Fig. 1. Bethel Valley Evaporator Service Tanks are 50,000-gal, horizontal storage tanks with equipment placed along the length of the tanks' center lines.**

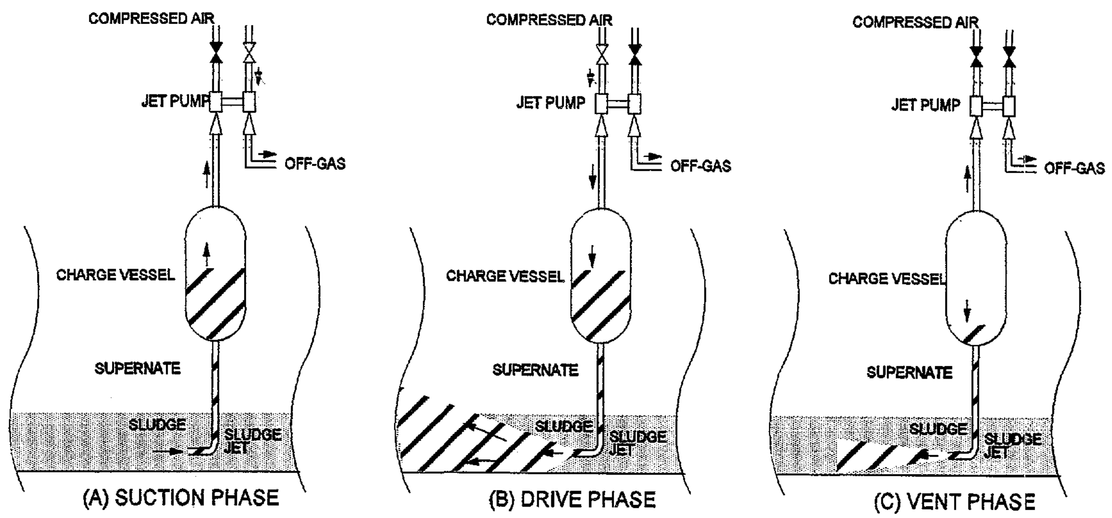


**Fig. 2. Pulse Jet system operating principles.**

A layout drawing of the BVEST system prior to installation of the pulse jet system is shown in Fig. 3. Tanks W-21 and W-22 are horizontally mounted and are located in a single-reinforced concrete underground vault on the ORNL site. The vault is approximately 31 ft wide, 69 ft long, and 16 ft high, and the floor elevation is 780 ft above sea level. Tank W-23 is located in a separate vault, west of W-21 and W-22 at a floor elevation of 788.5 ft.

The tanks and vaults are designed for storage of radioactive liquids and provide double containment. The reinforced concrete walls of the vault vary in thickness from 2 to 3 ft. The concrete roof slabs are 3.5 ft thick over the W-21/22 vault, 3 ft thick over the W-23 vault, and 2 ft thick over PVV. The vault floors and the walls are lined with 16-gauge stainless steel to a height of 7 ft, 2 in. A drainage sump and sump pump are provided in the vault for containment and transfer of liquids from tank leaks or other sources.

The W-21, W-22, and W-23 tanks are essentially identical in construction. Each is an all-welded vessel, fabricated of 0.5-in.-thick stainless steel and approximately 12 ft in diam by 61 ft, 5 in. long. The tanks operate at atmospheric pressure or slightly lower, but they are designed for 15 psig and 150°F. The tanks have limited access by means of a single 19-in. manhole located 17 ft from the north end. The tanks contain a large number of internal obstructions located along their center lines. The six existing tank nozzles in all three tanks are connected by 3-in.-diam stainless steel pipelines back to a common mount point in the adjoining PVV. Prior to installing the AEAT pulse jet system, the pipelines ended in a series of blind four-bolt hole flanges.

The BVEST are connected by double-contained pipelines to the Melton Valley Storage Tanks (MVST) located approximately 1 mile away. Liquid may be transferred from BVEST to MVST by using either of two progressive-cavity (Moyno) pumps located in PVV, which is situated between the tank vaults. The pumps are mounted longitudinally in PVV approximately 2 ft, 4 in. apart, and they are connected to tanks W-21, W-22, and W-23 by piping located in PVV and tank vaults. The pumps are designed to pump fluids to MVST through a nominal 2-in., double-contained pipeline.

The working pressure for the pipeline is 300 psi, and the pumps routinely operate at approximately 240 psig at a flow of 60 gal/min.

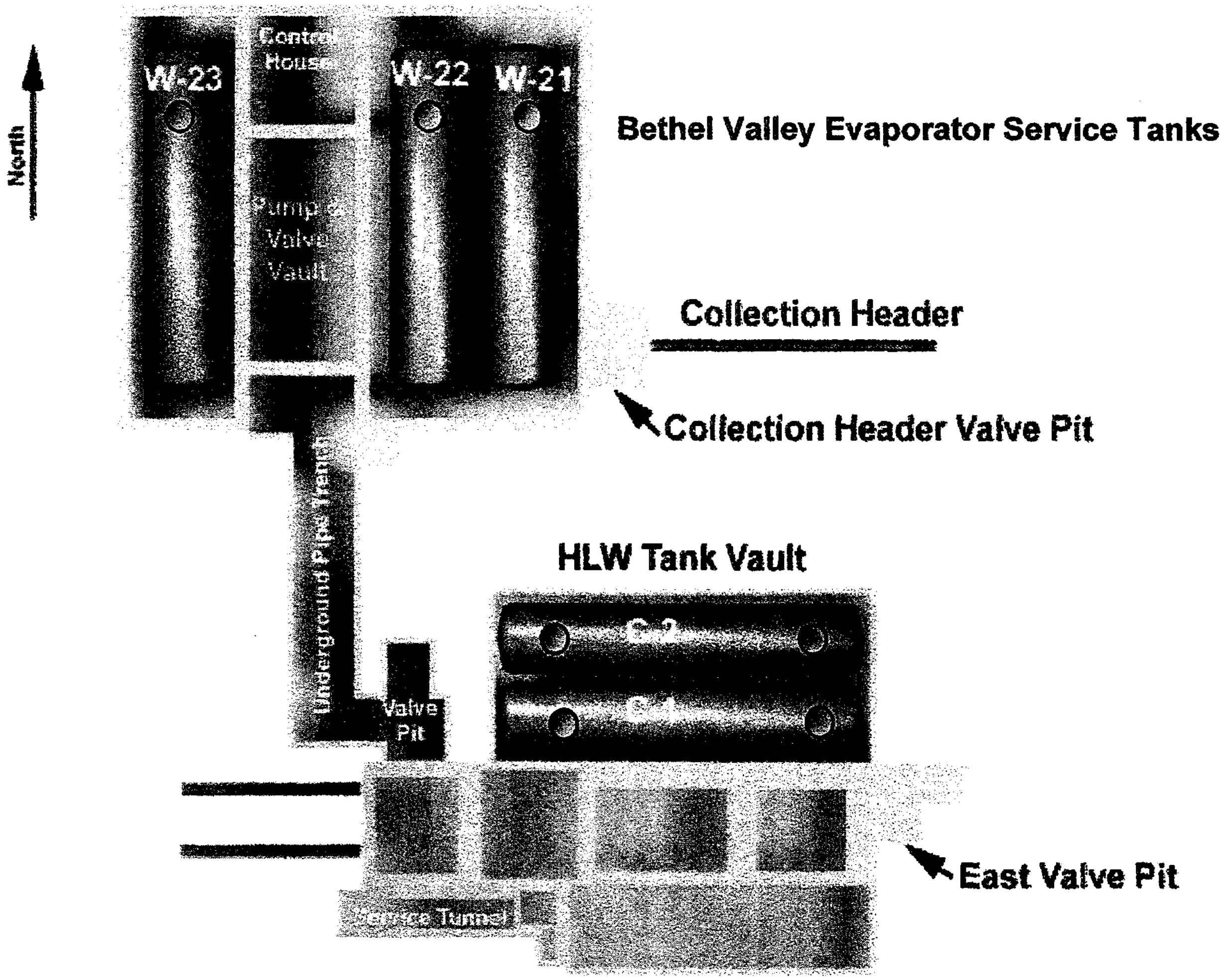


**Fig. 3. Layout of the Bethel Valley Evaporator Service Tanks at ORNL.**

The equivalent length of the pipeline (actual length plus equivalent lengths to account for bends, valves, and other fittings) is about 7100 ft. PVV is an underground vault with internal dimensions of 25 ft long by 15 ft wide by 6 ft high. The vault walls and floor are 2- to 3-ft-thick, reinforced concrete. The ceiling is made of four interlocking 2-ft-thick concrete slabs. Access to PVV is provided by stepped concrete plugs. The vault is designed to provide secondary containment of radioactive liquid. A 16-gauge stainless-steel base covers the floor and extends part way up the walls. A sump and sump pump are provided in the vault to permit the retrieval of any material that may have leaked. PVV is ventilated through an existing centralized off-gas system.

Until the summer of 1997, access into the "W" tanks with camera and sluicing equipment was not possible. The only direct access into the tanks was through a 3-in. pipe nozzle that extended from the tank through the vault roof. This nozzle was used for tank level instrumentation. When the tanks were constructed, a 20-in.-outside-diameter nozzle was installed approximately 17 ft from one end (north, as installed). This nozzle was closed with a bolted blind flange. This blind flange was located approximately 6 ft below the vault roof. Over each "manhole" in the roof of the vault, a removable concrete shield plug was installed. These plugs and the vault roof were up to 42 in. thick.

To provide a more useful access into the tanks, a design, fabrication, and installation task was proposed and approved. After evaluating several options, it was decided that the best approach would be to remotely weld an extension to the existing "manhole flange," and remotely cut a hole through the flange. Stainless-steel "manhole extensions" were designed and procured (see Fig. 4), as were new replacement roof shield plugs. A construction specification was written for the remote installation of the manhole extensions and issued for bids. Two companies returned proposals. Wachs Technical Services, Inc., of Charlotte, North Carolina, was awarded the contract. Their proposal was to remotely weld the manhole extensions to the manhole flange using the tungsten inert gas process, and cut the hole using a plasma arc torch. A requirement of the specification was that a "cold"demonstration be performed to prove the process. Wachs Technical Services designed the remote fixture and controls and successfully demonstrated the process at their shop in Charlotte.

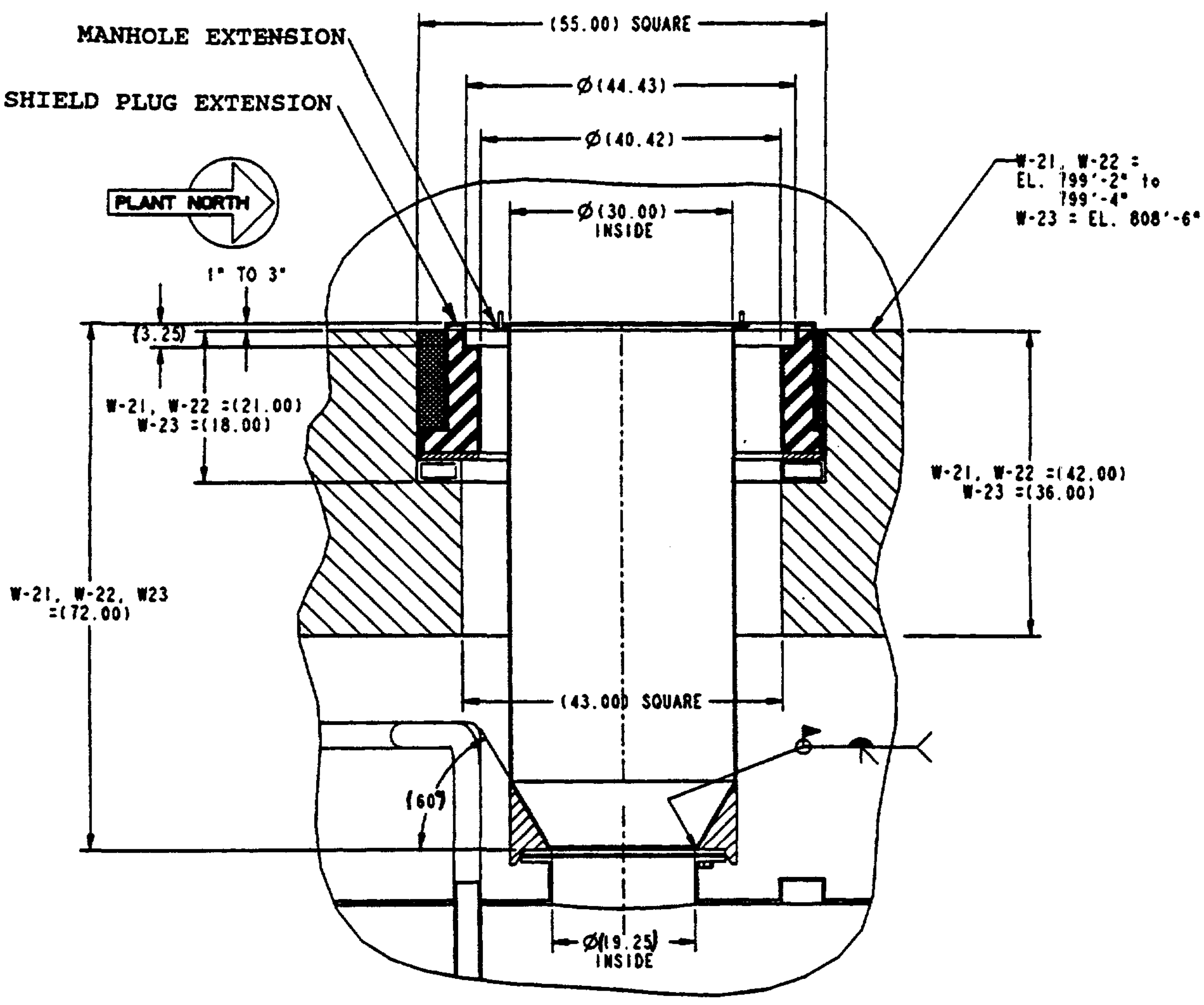


**Fig. 4. Design schematic of "W" tanks' manhole extension.**

During the summer of 1997, Wachs Technical Services successfully installed the three manhole extensions and cut the access holes into the tanks. The entire process was monitored and recorded using a video camera. A photograph of the manhole extension installation is shown in Fig. 5. The installation process went very well, with only very minor problems. Some "dress-out" was required to set up the welding and cutting fixtures, but very little radiation exposure was received. This was the first installation of its type at ORNL. It proved to be very beneficial for monitoring and assisting the sludge mixing and removal activities. In addition, the manhole extension and new shield plug equipment were designed to include a 3-in. port that can be used to sample the tanks. Before this, tank sampling required a significant effort. Several man hours were required to remove the level instrumentation from the existing 3-in. pipe nozzle to allow access for sampling and then reinstall and calibrate the level instrumentation. To access the new port a small shield plug is removed (a one-person task), and a 3-in. pipe plug is removed. Samples can now be taken and the confinement reestablished with a smaller crew in less than an hour, while keeping the tank level instrumentation operational.

# 5. BVEST SLUDGE CHARACTERISTICS

The BVEST are used to collect and store LLLW generated at ORNL. The liquid and solid phases have separated and formed distinct layers in the tanks. The volume of sludge was estimated to be 7200 gal in W-21, 7000 gal in tank W-22, and 19,000 gal in tank W-23.

Tables 1 and 2 provide supernate and sludge characterization data from sampling activities that took place in 1996 (Keller, Giaquinto, and Meeks 1997). The primary components of the sludge are metal nitrates, carbonates, and hydroxides. The pH of the supernate liquid in tank W-21 was acidic due to the addition of spent nitric acid from ion-exchange regeneration operations. Sodium hydroxide is added to the supernate periodically to neutralize the acid, so the pH of the interstitial liquid in the W-21 sludge was 7.7. The major metal constituents include sodium, calcium, magnesium, and potassium. Smaller amounts of heavy metals are also present, such as chromium, cadmium, lead, mercury, and others that are regulated under the Resource Conservation and Recovery Act. The principal radiological components of the sludge are fission products, such as $^{137}Cs$ and $^{90}Sr$; activation products, such as $^{60}Co$; and actinides, such as thorium, uranium, and plutonium. The sludge is classified as transuranic, due to the plutonium and americium content, and it is considered remote handled, due to the high gamma activity.

The rheological properties of the sludges from tanks W-21, W-22, and W-23 were also evaluated by determining the shear strengths and viscosities of the samples. These data were obtained using a HAAKE[1] Rotovisco RV30 Searle type rotational controlled-rate rheometer. Every effort was made to minimize any disturbance to the core samples prior to determining the shear strength; however, removal of samples from the containers and introduction of air into the samples complicated the effort.

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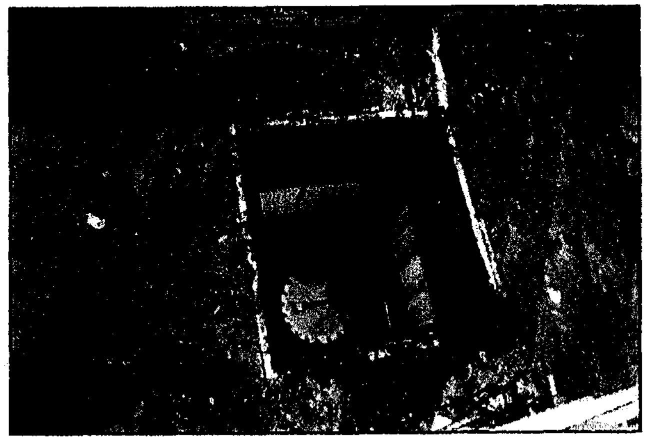
[1]Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply endorsement, recommendation, or favoring by the United States Government or any agency thereof.



BVEST W-22 access port before upgrade. 7/12/97

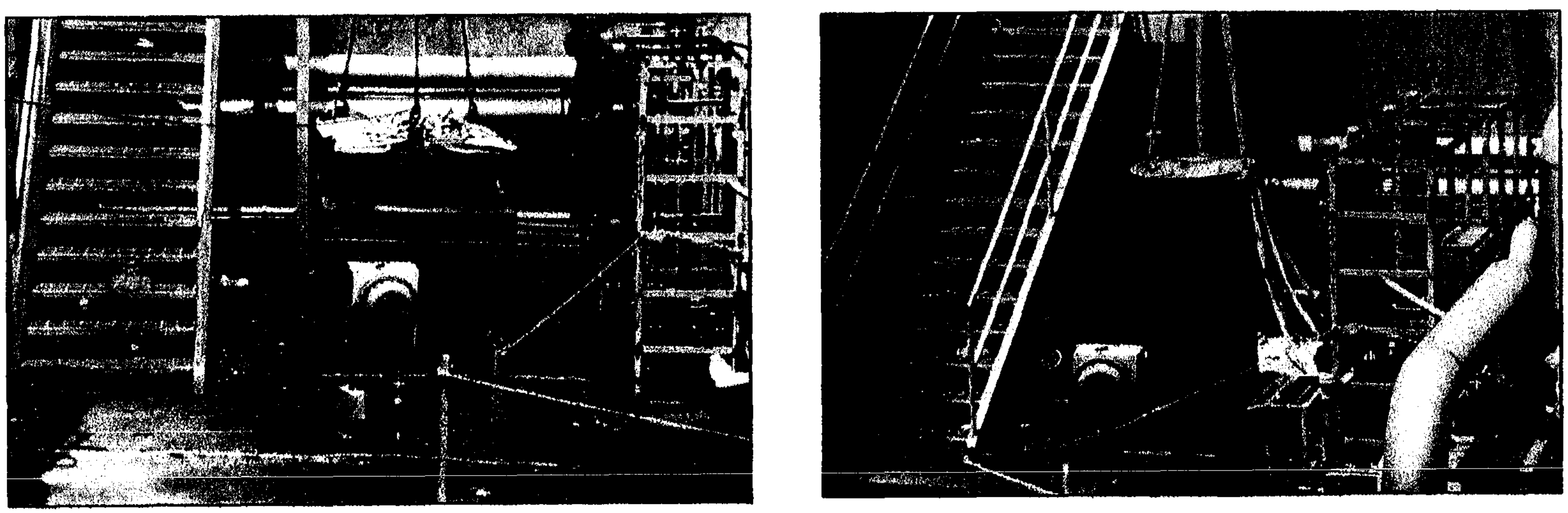


**Fig. 5. Manhole extension installation in tank W-21 on July 12, 1997.**

**Table 1. BVEST supernate waste characteristics from the 1996 sampling campaign[a]**

| Parameter | Units | Tank W-21 | Tank W-22 | Tank W-23 |
|---|---|---|---|---|
| pH | | 0.9 | 8.9 | 12.7 |
| Density | g/mL | 1.27 | 1.01 | 1.34 |
| Total solids (TS) | mg/mL | 410 | 3.5 | 530 |
| Total organic carbon (TOC) | mg/L | 533 | 67 | 2310 |
| Total inorganic carbon (TIC) | mg/L | 11 | 414 | 9390 |
| Total activity (LSC) | Bq/mL | 610000 | 19000 | 1400000 |
| Gross alpha | Bq/mL | 21000 | 52 | 430 |
| $^{244}$Cm | Bq/mL | 18000 | 41 | 360 |
| $^{241}$Am | Bq/mL | 1500 | - | - |
| $^{238}$Pu | Bq/mL | 100 | - | 20 |
| $^{239}$Pu | Bq/mL | 39 | - | 3 |
| $^{240}$Pu | Bq/mL | 40 | - | 3 |
| $^{241}$Pu | Bq/mL | 590 | - | 48 |
| $^{242}$Pu | Bq/mL | <0.1 | - | <0.1 |
| $^{233}$U | Bq/mL | 1800 | 9.8 | 38 |
| $^{234}$U | Bq/mL | 27 | 0.8 | 1.3 |
| $^{238}$U | Bq/mL | 50 | 0.8 | 1.8 |
| $^{60}$Co | Bq/mL | 7900 | 320 | 2200 |
| $^{90}$Sr/$^{90}$Y | Bq/mL | 87000 | 320 | 4100 |
| $^{137}$Cs | Bq/mL | 95000 | 3600 | 1100000 |
| $^{152}$Eu | Bq/mL | 190000 | <57 | <890 |
| $^{154}$Eu | Bq/mL | 77000 | <18 | <530 |
| $^{155}$Eu | Bq/mL | 21000 | <64 | <1900 |
| | | *Anions* | | |
| Bromide | mg/L | 109 | <12 | 1390 |
| Chloride | mg/L | 1170 | 168 | 8830 |
| Fluoride | mg/L | 236 | 57.9 | 1210 |
| Nitrate | mg/L | 204000 | <25 | 225000 |
| Nitrite | mg/L | <31 | <12 | 17300 |
| Phosphate | mg/L | <50 | 169 | 675 |
| Sulfate | mg/L | 1400 | 153 | 10600 |
| | | *Cations* | | |
| Ag | mg/L | <0.2 | <0.2 | <0.2 |
| Al | mg/L | 299 | <0.3 | 5.7 |
| Ba | mg/L | 60 | <0.02 | 0.46 |
| Ca | mg/L | 34500 | 32 | 111 |
| Cd | mg/L | 7.8 | <0.02 | 8.8 |
| Cr | mg/L | 57 | 0.1 | 12.4 |

Table 1 (continued)

| Parameter | Units | Tank W-21 | Tank W-22 | Tank W-23 |
|---|---|---|---|---|
| Cu | mg/L | 12 | 0.14 | 13.7 |
| Fe | mg/L | 532 | <0.04 | <0.04 |
| Hg | mg/L | 1.3 | - | 0.31 |
| K | mg/L | 6810 | 180 | 51300 |
| Mg | mg/L | 3560 | 10 | 0.47 |
| Mn | mg/L | 32 | 1 | 0.07 |
| Na | mg/L | 52200 | 665 | 126000 |
| Ni | mg/L | 22 | 1 | 14 |
| P | mg/L | 239 | 58 | 567 |
| Pb | mg/L | 43 | <0.09 | 11 |
| Sr | mg/L | 235 | 0.22 | 1 |
| Th | mg/L | 507 | 0.59 | <0.5 |
| U | mg/L | 4030 | 67 | 148 |
| Zn | mg/L | 168 | 1 | 79 |

[a]Data excerpted from Keller, Giaquinto, and Meeks 1997

**Table 2. BVEST sludge waste characteristics from the 1996 sampling campaign[a]**

| Parameter | Units | Tank W-21 | Tank W-22 | Tank W-23 |
|---|---|---|---|---|
| pH | | 7.7 | 11.3 | 12.3 |
| Density (bulk) | g/mL | 1.36 | 1.16 | 1.57 |
| Total solids (TS) | mg/g | 491 | 290 | 552 |
| Water | wt % | 50.9 | 71.0 | 44.8 |
| Total Organic Carbon (TOC) | mg/Kg | 17600 | 32500 | 4700 |
| Total activity (LSC) | Bq/g | 31000000 | 3900000 | 11000000 |
| Gross alpha | Bq/g | 150000 | 150000 | 440000 |
| $^{244}Cm$ | Bq/g | 100000 | 100000 | 330000 |
| $^{241}Am$ | Bq/g | 12000 | 12000 | 33000 |
| $^{238}Pu$ | Bq/g | 15000 | 19000 | 49000 |
| $^{239}Pu$ | Bq/g | 6400 | 6200 | 11000 |
| $^{240}Pu$ | Bq/g | 4800 | 5000 | 7700 |
| $^{241}Pu$ | Bq/g | 100000 | 77000 | 160000 |
| $^{242}Pu$ | Bq/g | 5 | 5 | 7 |
| $^{233}U$ | Bq/g | 8500 | 5600 | 7300 |
| $^{234}U$ | Bq/g | 120 | 160 | 130 |
| $^{238}U$ | Bq/g | 330 | 440 | 99 |
| $^{60}Co$ | Bq/g | 51000 | 38000 | 30000 |
| $^{90}Sr/^{90}Y$ | Bq/g | 580000 | 860000 | 4600000 |
| $^{137}Cs$ | Bq/g | 160000 | 270000 | 400000 |

Table 2 (continued)

| Parameter | Units | Tank W-21 | Tank W-22 | Tank W-23 |
|---|---|---|---|---|
| $^{152}Eu$ | Bq/g | 930000 | 900000 | 220000 |
| $^{154}Eu$ | Bq/g | 330000 | 330000 | 99000 |
| $^{155}Eu$ | Bq/g | 90000 | 74000 | 29000 |
| | | *Anions* | | |
| Bromide | mg/Kg | 97 | 25 | 362 |
| Chloride | mg/Kg | 1370 | 249 | 3420 |
| Chromate | mg/Kg | <10 | 13 | 16 |
| Fluoride | mg/Kg | 23 | 21 | 149 |
| Nitrate | mg/Kg | 158000 | 6930 | 109000 |
| Nitrite | mg/Kg | 1180 | 480 | 6290 |
| Phosphate | mg/Kg | <10 | <10 | <10 |
| Sulfate | mg/Kg | 6030 | 191 | 3850 |
| | | *Cations* | | |
| Ag | mg/Kg | 22 | 32 | 20 |
| Al | mg/Kg | 1230 | 2100 | 1740 |
| Ba | mg/Kg | 82 | 80 | 77 |
| Ca | mg/Kg | 68300 | 43500 | 63200 |
| Cd | mg/Kg | 38 | 29 | 33 |
| Cr | mg/Kg | 229 | 132 | 194 |
| Cu | mg/Kg | 83 | 31 | 38 |
| Fe | mg/Kg | 2980 | 3090 | 2020 |
| Hg | mg/Kg | 24 | 72 | 26 |
| K | mg/Kg | 11500 | 3260 | 20500 |
| Mg | mg/Kg | 11500 | 5110 | 14500 |
| Mn | mg/Kg | 173 | 784 | 937 |
| Na | mg/Kg | 44000 | 10000 | 75500 |
| Ni | mg/Kg | 104 | 50 | 142 |
| P | mg/Kg | 3550 | 10400 | 3570 |
| Pb | mg/Kg | 394 | 427 | 1200 |
| Sr | mg/Kg | 266 | 175 | 473 |
| Th | mg/Kg | 8650 | 9580 | 29600 |
| U | mg/Kg | 26300 | 35600 | 7990 |
| Zn | mg/Kg | 801 | 1060 | 588 |

[a]Data excerpted from Keller, Giaquinto, and Meeks 1997

Shear strength is a measure of the shear conditions needed to overcome the substance's resistance to flow. It is measured using a constant shear rate and determined from the peak shear stress on a shear stress versus time curve. The shear rate was selected so that the rotor would make one revolution in 12 min (0.016 $s^{-1}$). It is necessary that the shear rate be slow to determine the maximum resistance of the sludge. A six-vane rotor (FL100) was used for the determination. The same rotor was used with W-22 and W-23 sludges, but the shear rate was erroneously set at 0.16 $s^{-1}$; however, it is believed that this only resulted in the shear strength value being reached in a shorter time period. Shear strength data for the sludges are shown in Table 3.

**Table 3. Shear strength and viscosity data for sludge and slurry samples**

| Tank | Total solids (wt %) | Undissolved solids (wt %) | Viscosity[a] (mPa·s) | Shear strength[b] (Pa) |
|---|---|---|---|---|
| W-21 | 37.6 | 13.5 | 16 | 8.5[c] |
| W-22 | 21.4 | 19.5 | 16 | 16.3[d] |
| W-23 | 42.3 | 17.3 | 19 | 19.7[d] |

[a]Slurry samples created by mixing one part sludge with one part supernate. The concentrations of solids shown in second and third columns refer to the slurry mixture evaluated for viscosity.
[b]Shear strength analysis was performed on undiluted sludge. The concentrations shown in the second and third columns are not applicable to this analysis.
[c]Shear strength analysis performed at shear rate of 0.016 $s^{-1}$ with rotor FL-100.
[d]Shear strength analysis performed at shear rate of 0.16 $s^{-1}$ with rotor FL-100.

Viscosity is a measure of a fluid's resistance to continuous deformation when subjected to a shear stress. Viscosity is formally defined as the ratio of the shear stress to the shear rate. If a fluid exhibits a shear stress that is linearly proportional to the shear rate and the shear stress equals zero at a shear rate of zero, then that fluid is defined as a Newtonian fluid. Any fluid that behaves differently is defined as a non-Newtonian fluid.

The sludges were diluted with supernate from their respective tanks at an approximate ratio of 1:1 to create a slurry from which to measure the viscosity. An aliquot was removed from the slurry for total and undissolved solids analysis. The viscosity of the mixture was measured over a range of increasing (0 to 450 $s^{-1}$) and decreasing (450 to 0 $s^{-1}$) shear rates. A time interval of 3 min was selected for both scales. The results from the viscosity testing showed that the slurries exhibited behavior similar to Newtonian fluids. When analyzed with a Bingham Plastic model, the results indicated that the yield stress was quite small (maximum value of 2.2 Pa). The viscosity results are shown in Table 3. The report by Keller, Giaquinto, and Meeks (1997) provides more information about the viscosity analysis and results.

## 6. COLD PILOT TEST EVALUATION

To evaluate the effectiveness of the conceptualized BVEST pulse jet system, pilot testing was performed by AEAT at the Risley facility in the United Kingdom. The test system consisted of a full-scale, two-charge vessel system connected to a tank (Fig. 6) with the same diameter (12 ft) and one-third the length (20 ft) of BVEST. Photographs of the charge vessels and tank used for the testing are shown in Figs. 7 and 8, respectively. The tank contained two opposing jet nozzles configured the same as those in the BVEST (reference Lockheed Martin Drawings P-20237-YC-036-E and S-20237-YB-016-E). The piping between the charge vessels and the tank was designed to simulate the worst-case 3-in. piping run for BVEST: 22-ft vertical lift, 65-ft horizontal run, and five 90° elbows (reference Lockheed Martin Drawings P-20237-YC-28-E, Rev. 3; P-20237-YC-29-E, Rev. 3; P-20237-YC-30-E; P-20237-YC-31-E, Rev. 2; P-20237-YC-32-E, Rev. 2). The tank also contained obstructions configured and located to simulate those in BVEST (reference Lockheed Martin Drawings P-20237-YC-036-E, Rev. C, and S-20237-YB-016-E, Rev. 3). The type and amount of sludge simulant were chosen based on the worst-case sludge depth and rheology for BVEST. The solids content and specific gravity of settled china clay were about 60 wt % and 1.7, respectively. This is slightly heavier than the W-23 sludge (55% solids; specific gravity, 1.57). The shear strength and viscosity for a 19.5 wt % W-22 sludge sample corresponded similarly to those for a 22 to 30 wt % china clay slurry [maximum of 16-Pa shear strength and maximum of 40-mPa·s viscosity (Keller, Giaquinto, and Meeks 1997)]. The specifications for the china clay are given in Table 4. The china clay was mixed with water to produce slurries of various solids content for the pilot testing. Mixing tests were performed under various operating conditions to determine the optimum mixing conditions for the china clay. Laboratory-scale work provided data on the specific gravity, viscosity, shear rate, and shear stress of the various slurries.

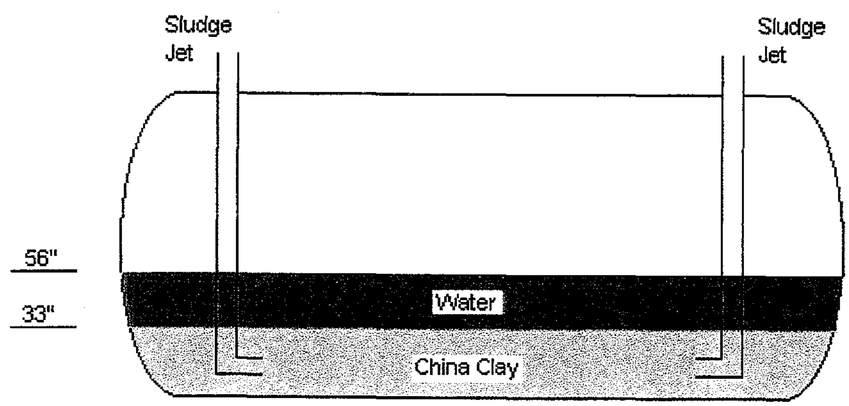



**Fig. 6. Pilot tank for pulse jet system testing.**

## 6.1 COLD TEST DATA

The tank was charged with 10,800 kg of china clay and 18,000 kg of water. This gave a sludge depth of at least 33 in. and a tank level of 56 in., which correspond to a total volume of 22 $m^3$. These components, if homogeneously mixed, would produce a suspension containing 37.5 wt % china clay with a specific gravity of 1.29.

The mixer was set up as outlined in Table 5. The "drive time" (duration during which the charge vessel was pressurized with air) could not initially be set at 15 s because overblow of air into the tank would occur. Overblow was to be avoided in actual operations due to the potential generation of foams and aerosols. The drive time was gradually extended from 10 to 15 s over the first few hours of the test as the volume of liquid in the charge vessels increased.

Figure 9 illustrates how suction time (time required to fill the charge vessel with slurry) varies during the period of the test. The suction time is directly related to the physical conditions of the

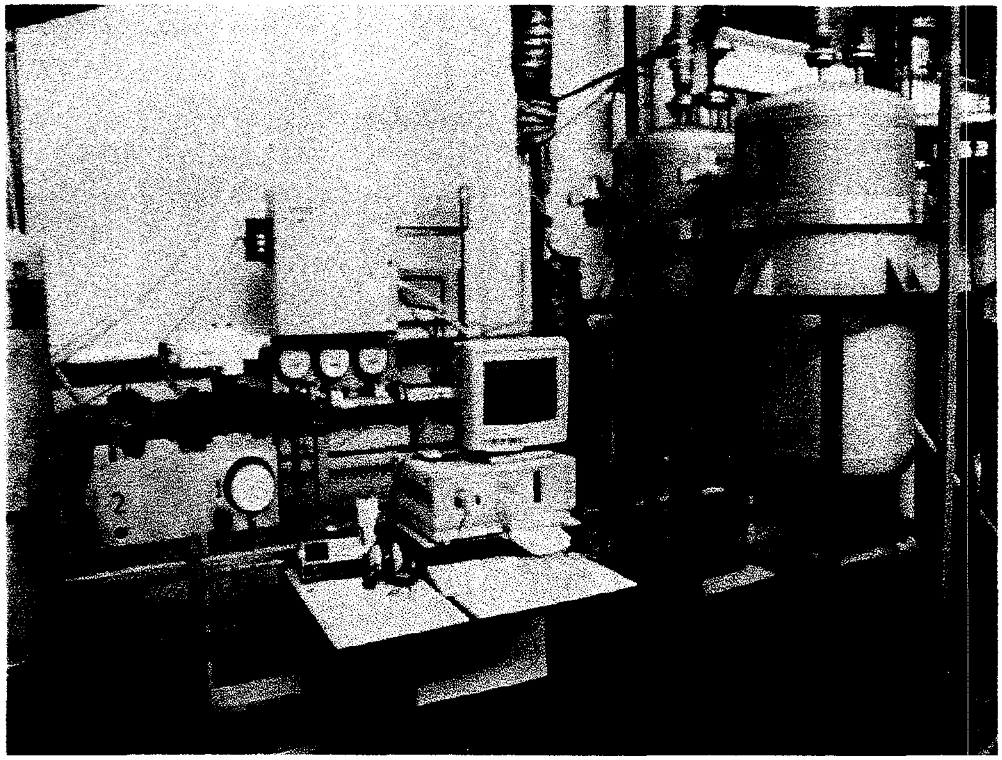


Fig. 7. Pilot test system charge vessels and controls.

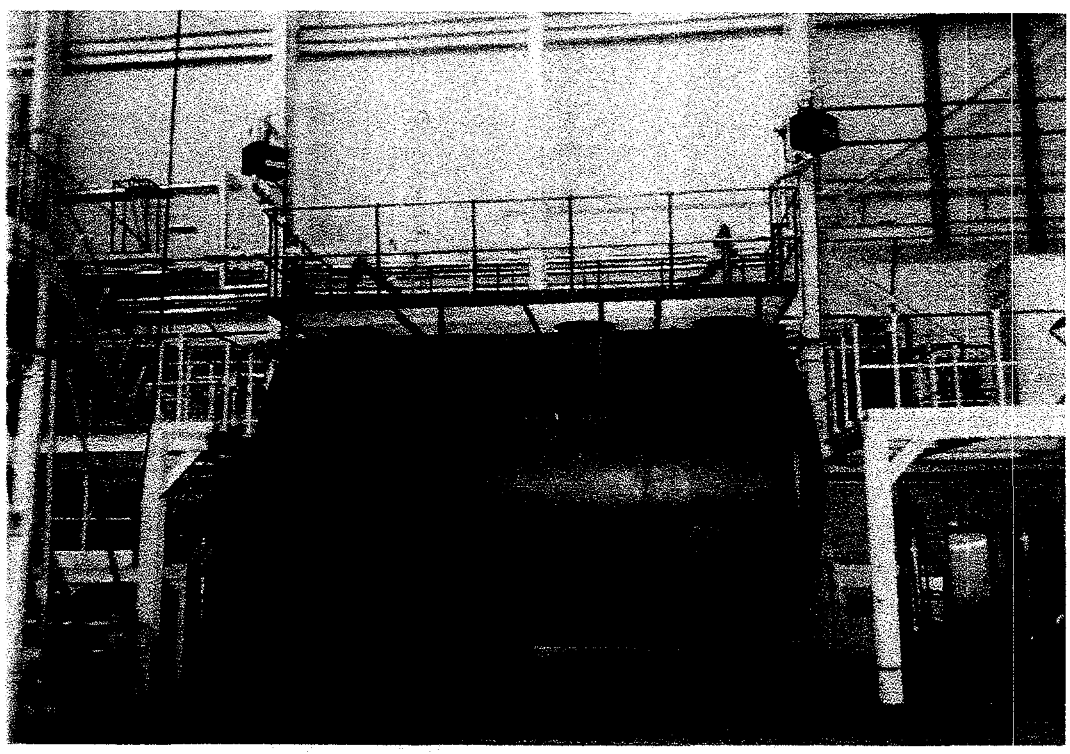


Fig. 8. Pilot test tank, one-third scale BVEST.

sludge and shows a measurable change as the sludge mixes with the liquid in the tank. The initial period shows that the charge vessel was not completely filled until approximately 8 h into the test. The suction time then decreases until approximately 60 h into the test, when it reaches a minimum value of 85 s. Further mixing does not significantly affect the suction time, thus indicating that the mixing has reached steady state.

**Table 4. Specifications and properties for Grade E china clay produced by ECC International**

| Specification or property | Value |
|---|---|
| Brightness, ISO | 77.0 ± 1.0 |
| +300 mesh, % max. | 0.05 |
| +10 $\mu$m, % max. | 35 |
| −2 $\mu$m, % max. | 25 |
| Moisture, % max. | 1.5 |
| pH | 5.0 ± 0.5 |
| Yellowness | 7 |
| Specific gravity | 2.6 |
| Surface area (BET), $m^2/g$ | 8 |
| Oil absorption, g/100 g | 33 |
| Water-soluble salt content, % | 0.15 |
| $SiO_2$, % | 50 |
| $Al_2O_3$, % | 35 |

**Table 5. Operating conditions for pulse jet during Test 1**

| Variable | Value |
|---|---|
| Nominal suction time, s | 150 |
| Air pressure used to drive jet pump, bar-gauge | 4.32 |
| Maximum vacuum, bar | -0.95 |
| Drive time, s | 15 |
| Drive pressure, bar-gauge | 2.00 |
| Vent time, s | 10 |

Figure 10 is a plot of the variation of specific gravity during the test period. The triangular data points show the predicted specific gravity for a completely homogenous mixture. The circular and square data points represent the specific gravity at the liquid surface and at the bottom of the tank, respectively. These data clearly show that steady state was achieved after 68 h of operation. They also indicate that not all the sludge has been mobilized, since the actual specific gravity was less than that predicted for a completely mixed tank. The graph of percentage solids versus specific gravity shows that a specific gravity of 1.248 corresponds to a 34 wt % solids mixture of china clay and water. The remaining sludge is estimated to be a 53 wt % solids mixture. It is therefore possible to approximate the quantity of sludge remaining.

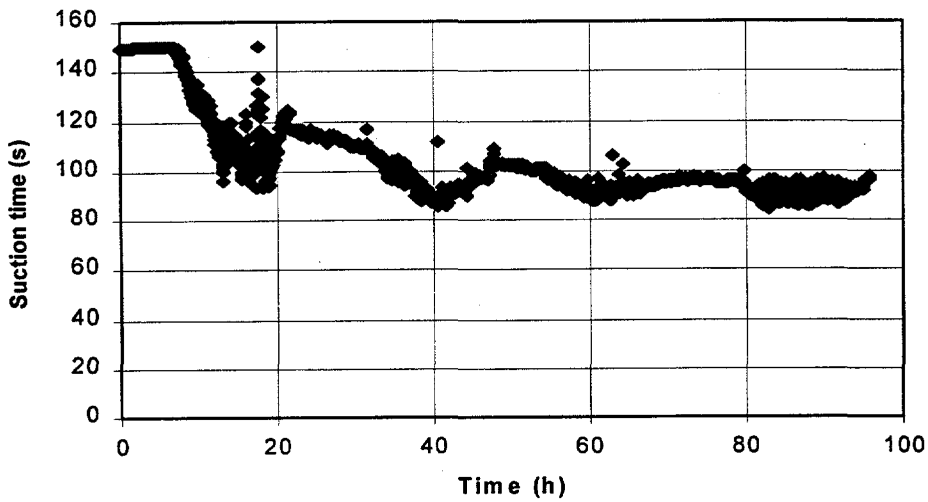



Fig. 9. Suction time versus mixing time for cold test 1.

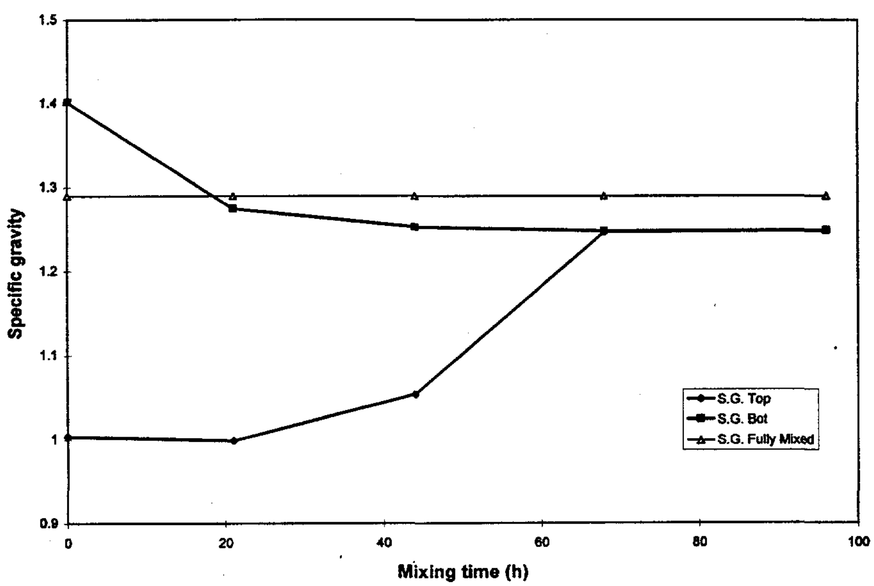



Fig. 10. Specific gravity versus mixing time for cold test 1.

### 6.2 MASS BALANCE ON CLAY

$$Clay_{init} = (Y \times wt\,\%_{remaining}) + (Total_{init} - Y) \times wt\,\%_{mixed}$$

where

| | | |
|---|---|---|
| $wt\,\%_{remaining}$ | = | wt % solids in unmixed sludge, |
| $wt\,\%_{mixed}$ | = | wt % solids in mixed slurry, |
| $Total_{init}$ | = | total mass of water and clay at start of trial, |
| $Clay_{init}$ | = | mass of clay at start of trial, and |
| Y | = | mass of sludge remaining. |

$10{,}800 = (Y \times 0.53) + (28{,}800 - Y) \times 0.34.$
$Y = 5305$ kg of 53 wt % sludge remaining.

This gives 2812 kg of china clay and 2493 kg of water unmixed. Percentages for clay mixed, water mixed, and total mixed are 74, 86, and 82%, respectively.

Sludge-retrieval tests were performed by pumping the clay mixture out of the pilot tank to a holding tank under conditions similar to those expected for the tank transfers. Tests indicated that the pulse jet system could successfully remove the majority of the clay mixture, which was believed to be a worst-case simulant for the BVEST sludges. Additional tests were performed where sludge conditions and system operating parameters were varied to determine favorable operating conditions for the W-21 mixing operation. The data collected from this testing were used to set the initial operating conditions for the BVEST W-21 operation. AEAT is preparing a more detailed summary of the cold pilot testing, which will be published at a later date.

## 7. DESCRIPTION OF PULSE JET SYSTEM FOR BVEST

The pulse jet system was designed to mix and mobilize the sludges stored in tanks W-21, W-22, and W-23. Each of these tanks is equipped with six spaced jet nozzles, oriented to form three sets of opposing nozzles (see Fig. 1).

The pulse jet system was fabricated in seven separate modules, including the charge vessel skids (two), jet pump skid, valve skid, off-gas skid, pipe bridge skid, and control cubicle. The charge vessel skids were installed within the PVV. Other skids were located on or near the BVEST vault roof. Interconnections between the skids used steel-reinforced flexible hose with quick-connect couplings. The valve skid, jet pump skid, and charge vessels skids were constructed of 304 L stainless steel for compatibility with acidic cleaning solutions.

### 7.1 CHARGE VESSEL SKIDS

Skid Dimensions: 74 in. L × 30 in. W × 56 in. H
Weight: 2200 lb ea.

The charge vessels for the pulse jet system were designed to be installed within the existing PVV. The vault provides the necessary shielding for the charge vessels to minimize gamma radiation exposure during the mixing operation. The charge vessel system was carefully designed to fit into the PVV. It was necessary to construct the charge vessel system in two skids with three vessels per skid because of the limited space in the PVV. The charge vessels were initially connected to the six jet nozzles for tank W-21 by 3-in. flexible hoses with quick-connect fittings. A photograph of one of the charge vessel skids during installation in the PVV is provided in Fig. 11.

Each charge vessel is a stamped pressure vessel designed for full vacuum and up to a positive pressure of 116 psi. The vessels are 24 in. in diameter, with a capacity of about 85 gal. Each vessel contains a liquid level switch which deactivates the fluidic pumps when the liquid level reaches the desired height in the vessel.

### 7.2 JET PUMP SKID

Skid Dimensions: 330 in. H × 276 in. diam for tripod support
Weight: 5325 lb

The jet pump skid contains the piping and jet pumps required to pull a vacuum and apply pressure to the charge vessels to mix the sludges. The skid was designed to prevent the charge vessels from being accidentally overfilled. This safety measure prevents the tank contents from reaching the off-gas skid, where it could overcome the air filters and possibly be released to the environment. The overfill protection was achieved by extending the vertical height of all pipes connecting the jet pumps to the charge vessels to a height of 28 ft. With the additional elevation change between the top of the vault and the tank (>6 ft), this made it physically impossible for tank liquids to reach the jet pumps due to limit of absolute vacuum pressure. Figure 12 shows a photo of the jet pump skid being installed at BVEST. The jet pump is a dual jet nozzle/venturi system. One jet is designed for drawing vacuum on the charge vessel. The other jet supplies air pressure for the drive cycle. Figure 13 is a sketch of a typical jet pump and mode of operation. An air compressor capable of 425 cfm at 50 psi was provided to operate three jet pumps at the same time.

### 7.3 VALVE SKID

Skid Dimensions: 197 in. L × 55 in. W × 80 in. H
Weight: 3802 lb

The valve skid includes the piping and valves required to supply compressed air for the jet pumps and process water to rinse the system after use. Dilute nitric acid may also be supplied through the valve skid to decontaminate the system before transport to another location.

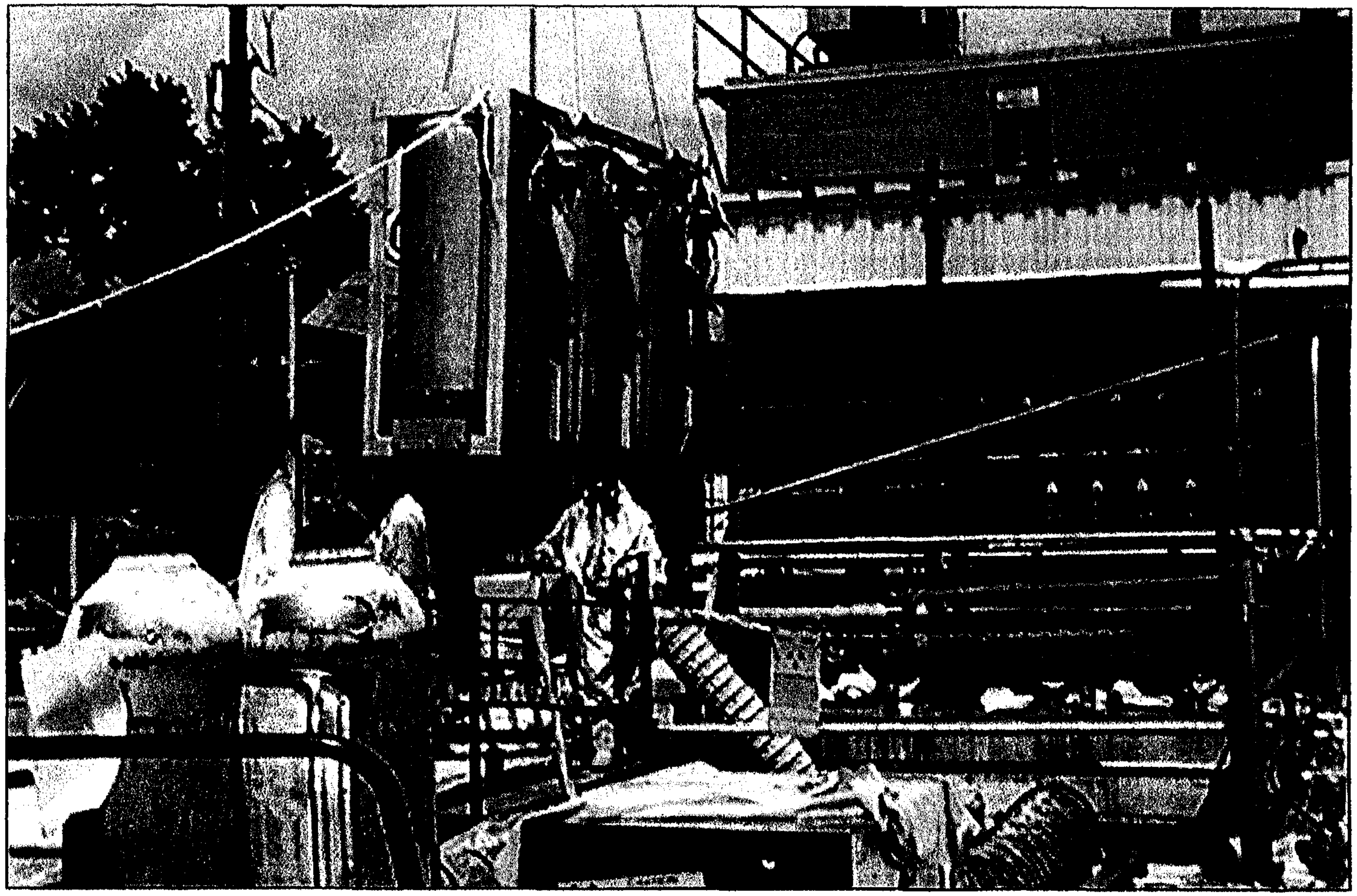


**Fig. 11. Installation of the charge vessels in the PVV.**

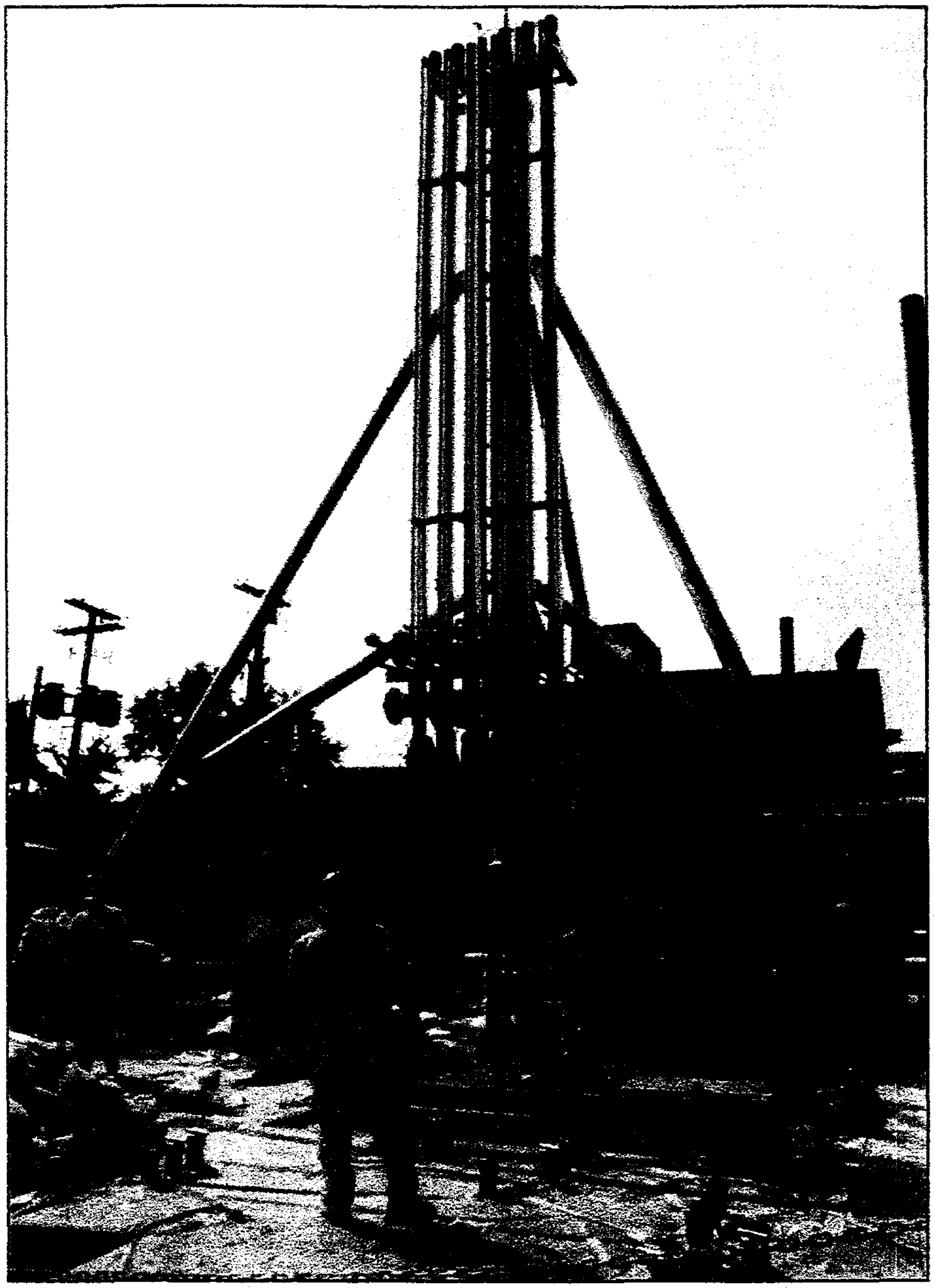


**Fig. 12. Installation of the jet pump skid.**

### 7.4 OFF-GAS SKID

Skid Dimensions: 287 in. L × 87 in. W × 81 in. H (stack height: 189 in.)
Weight: 7870 lb

The off-gas skid allows the air used by the jet pumps for filling and discharging the charge vessels to be vented to the atmosphere. The off-gas system uses the following:

- a demister to remove any liquid mists that may enter the charge vessel head space during filling;
- a heater to increase the temperature of the off-gas to prevent condensation of water vapor, which could plug the air filters;
- a filter bank (including two stages of high-efficiency particulate air filters) to remove particulate matter;
- makeup air inlet and prefilters;
- fans to transport the air and maintain negative pressure on the system; and
- a stack to discharge the treated off-gas.

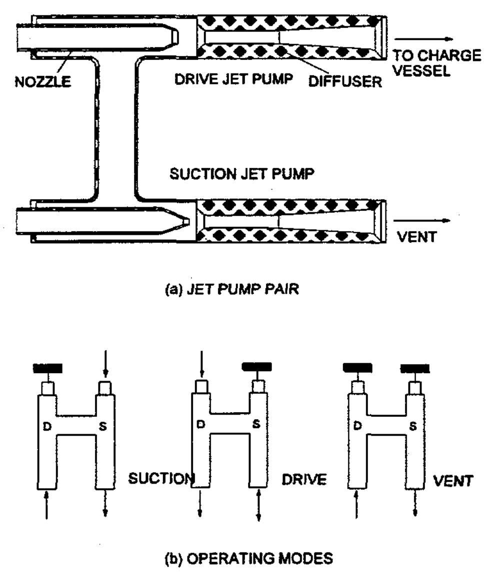



**Fig. 13. Jet pump and mode of operation.**

The makeup air system included two styles of roughing filters, a backflow-prevention high-efficiency particulate air, and a flow-regulating damper. The system was designed to handle a maximum airflow of 1000 cfm. An off-gas monitoring system was installed in the stack by ORNL to monitor radioactive emissions.

### 7.5 PIPE BRIDGE SKID

Skid Dimensions: 358 in. L × 17 in. W × 60 in. H
Weight: 2620 lb

The pipe bridge is a rigid frame structure that supports all the piping and electrical cabling routed from the valve skid to the jet pump skid. The skid includes twelve 1.5-in. stainless-steel pipes for compressed air for the jet pumps; six 1-in. stainless-steel, flexible pipes to connect water feed lines to the jet pump skid; copper steam feed line for heat tracing; and instrument air lines. The skid was designed to ensure that all air, water, and steam lines self-drain back to the valve skid.

### 7.6 CONTROL CUBICLE

A control system was provided for remote operation and monitoring of the system. Separate control systems were provided for the pulse jet and off-gas systems. The Prescon system, provided and patented by AEAT, controlled and monitored all process equipment on the valve, jet pump, and charge vessels skids.

The Prescon system includes a PC-compatible computer and associated input/output cards. Configuration and control of the system are handled by a Windows™-based application that is configured to run when power is applied to the unit. The application closely monitors key parameters and halts the system if these parameters exceed normal operating tolerances. A sophisticated algorithm monitors the operation of the mechanical level switches in the charge vessels and halts the system if a failure is detected.

Safety interlocks were provided for the following conditions:

- Loss of airflow or high pressure in the ventilation skid duct automatically shuts off the process air and water feeds to the valve skid, which shuts down the mixing process.
- A loss of negative pressure in the W-21 tank trips the main process air supply to the mixing system.
- Tilt switches mounted on the jet pump skid close the main air and water supplies automatically during a seismic event.
- Malfunctions of the ventilation system components, such as the demister or heater, will trip the ventilation fan and cause the rest of the system to shut down.

## 8. INSTALLATION OF EQUIPMENT SKIDS

The pulse jet system was designed to minimize the time required for installation. The design of the tank system was carefully reviewed, and a mockup PVV was constructed from plywood to simulate and practice the procedures required to replace the blind flanges with quick disconnect flanges and install the flexible pipes and charge vessel skids (the task involving the greatest potential for worker exposure). General area radiation dose rates in the PVV ranged from 200 to 2700 mR/h.

The installation activities began shortly after receipt of the equipment skids on July 8, 1997. On July 14, four concrete PVV vault plugs and the entry hatch were removed to allow access to install the charge vessel skids. Radiation surveys of the work area were performed, followed by decontamination work to reduce the amount of transferrable contamination. A lead sheet was used in the PVV to reduce the general area dose to a 1200 mR/h maximum. The highest localized hot spot in the PVV measured 8000 mR/h. Workers entered the vault and replaced the blank flanges on the W-21, W-22, and W-23 nozzles with adaptors for quick-connect couplings. The two charge vessel skids were placed and secured, and the six flexible pipes were connected to the W-21 jet nozzles. Photographs of the PVV, jet nozzle connections, and the installed charge vessels are shown in Figs. 14, 15, and 16. The vault covers were replaced on the PVV, except for the middle concrete vault cover, which was replaced with a steel cover that included openings for equipment connections plus a hatch for personnel access. The total exposure received by all workers during this task was 855 mR.

After installing the charge vessel skids, the jet pump skid was lifted into position and connected via flexible hoses to the charge vessel connections routed through an opening in a steel replacement cover over the top of the PVV. This was followed, in order, by installation of the off-gas skid, pipe bridge skid, valve skid, and control cubicle. A remote-controlled video camera was also installed in the tank via an existing manway on the top of the tank extending to the vault roof by a new manway extension. Installation and shakedown activities were completed by August 4, 1997. Drawings and a photograph of the installed system are provided in Figs. 17, 18, and 19.

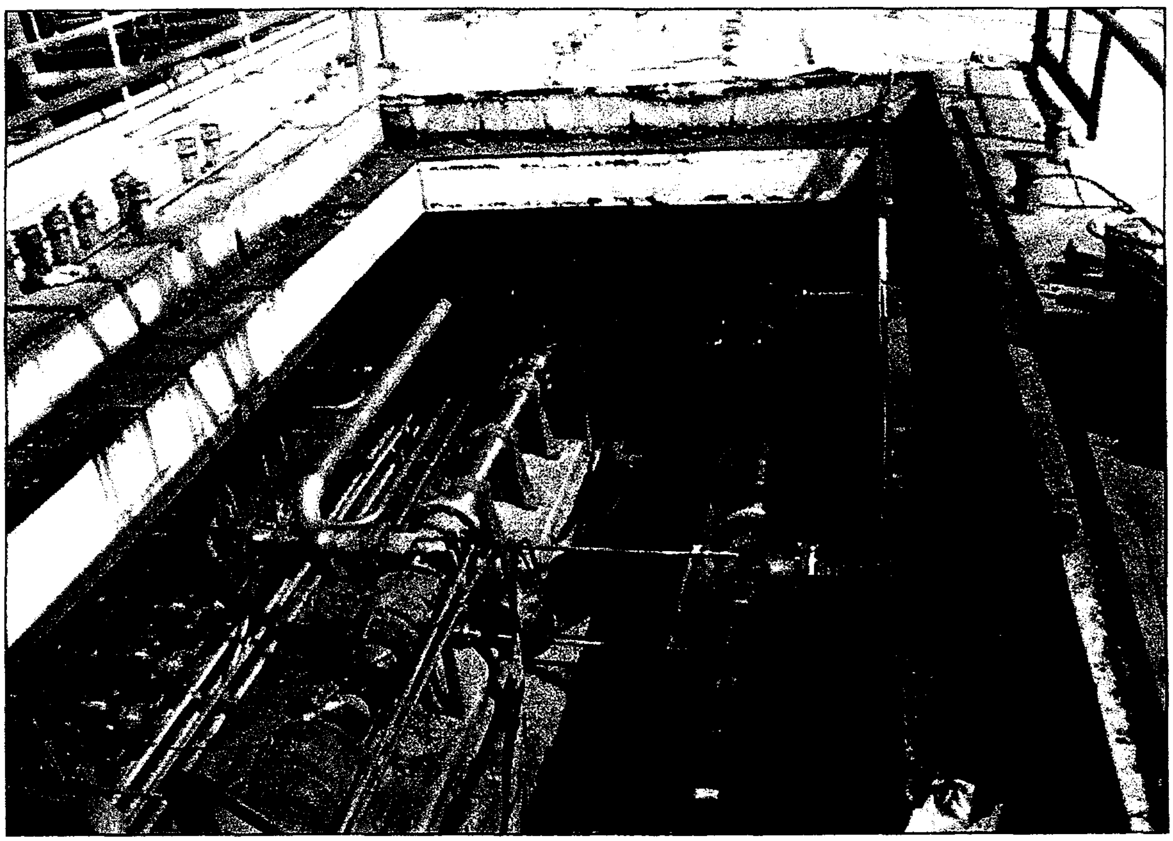


**Fig. 14. BVEST pump and valve vault on July 11, 1997, before installation of the fluidic pulse jet mixing system.**

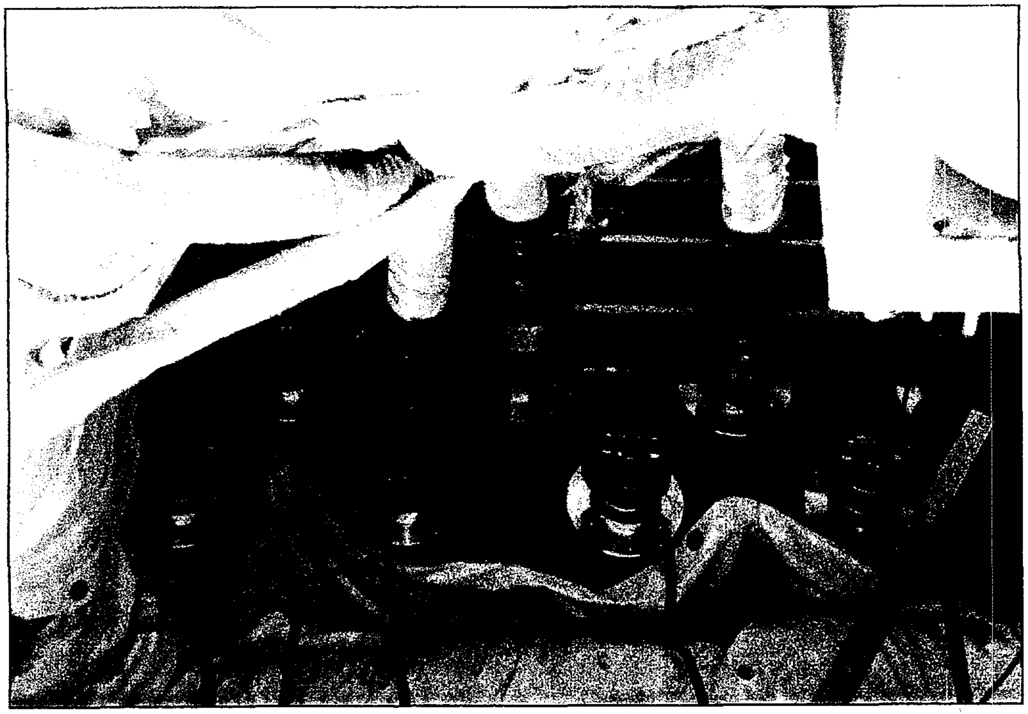


**Fig. 15. Camlock connections for BVEST within the pump and valve vault.**

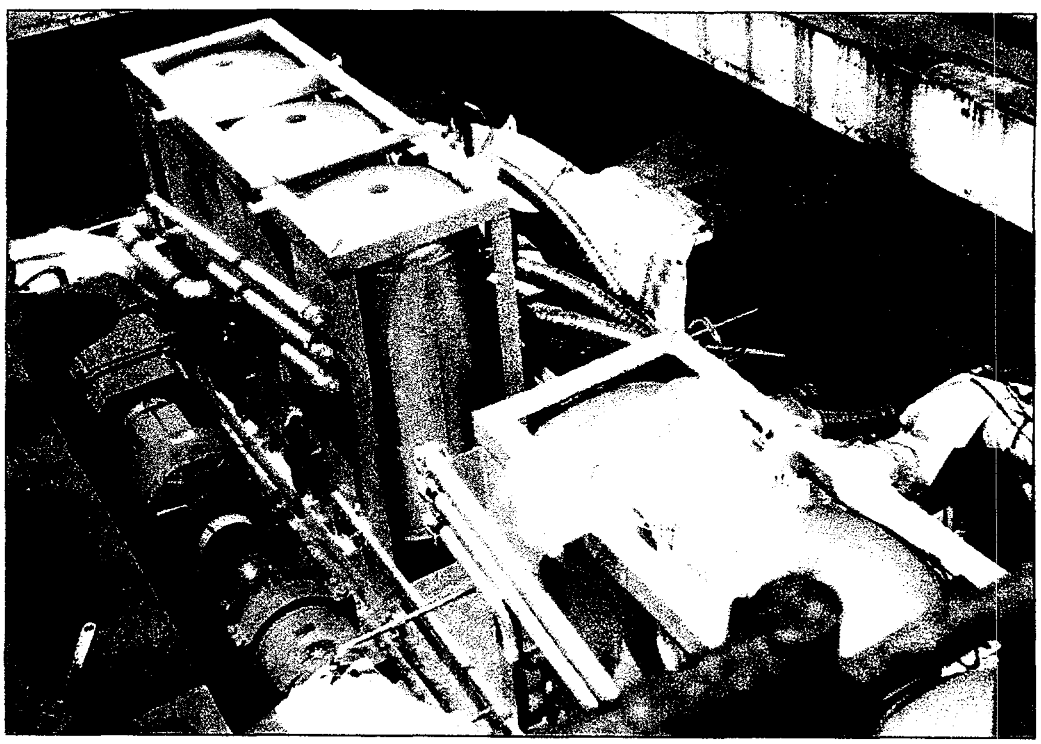


**Fig. 16. Charge vessels installed in the pump and valve vault at the BVEST site.**

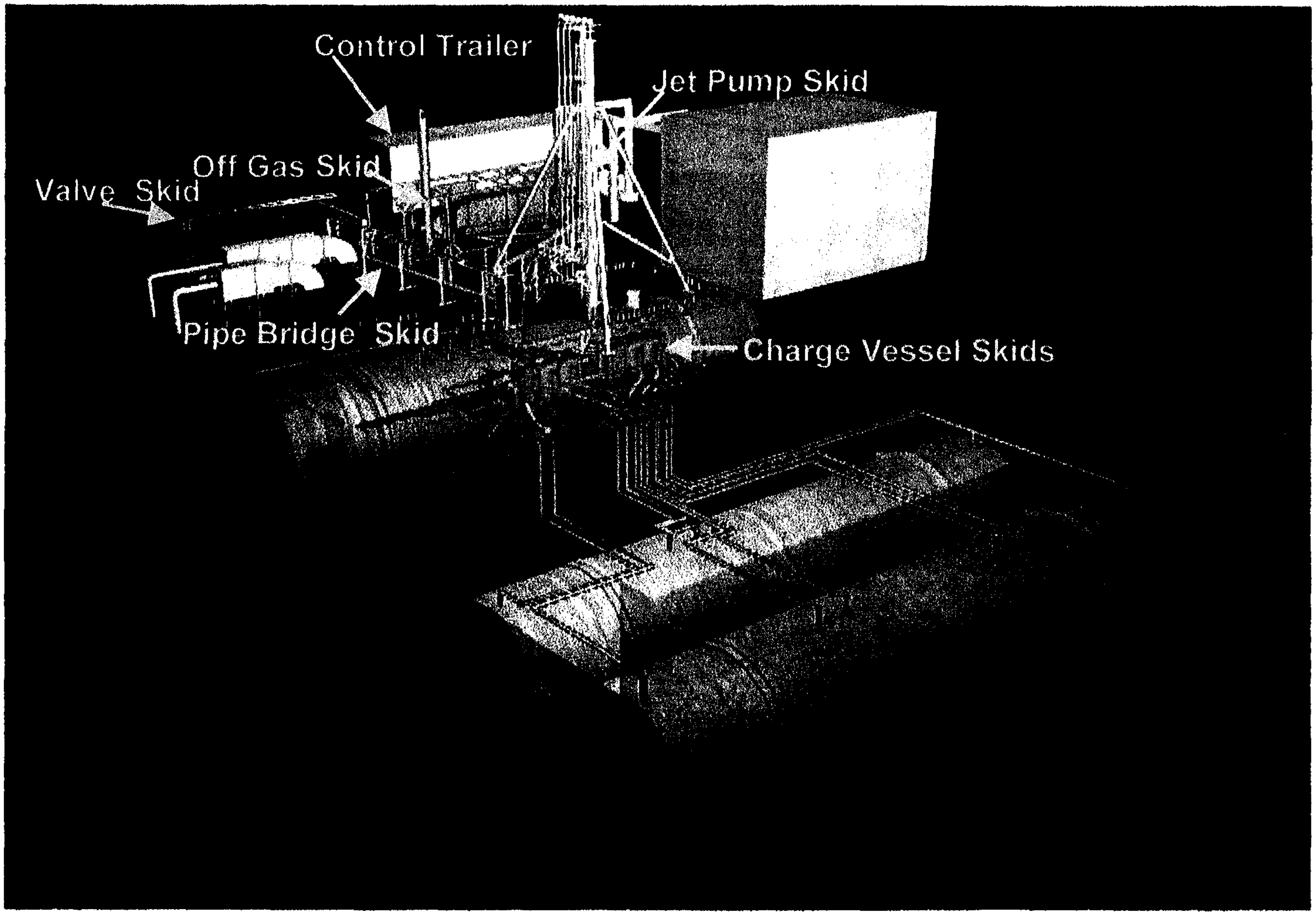



Fig. 17. Three-dimensional model of the fluidic pulse jet mixing system installed at the BVEST site.

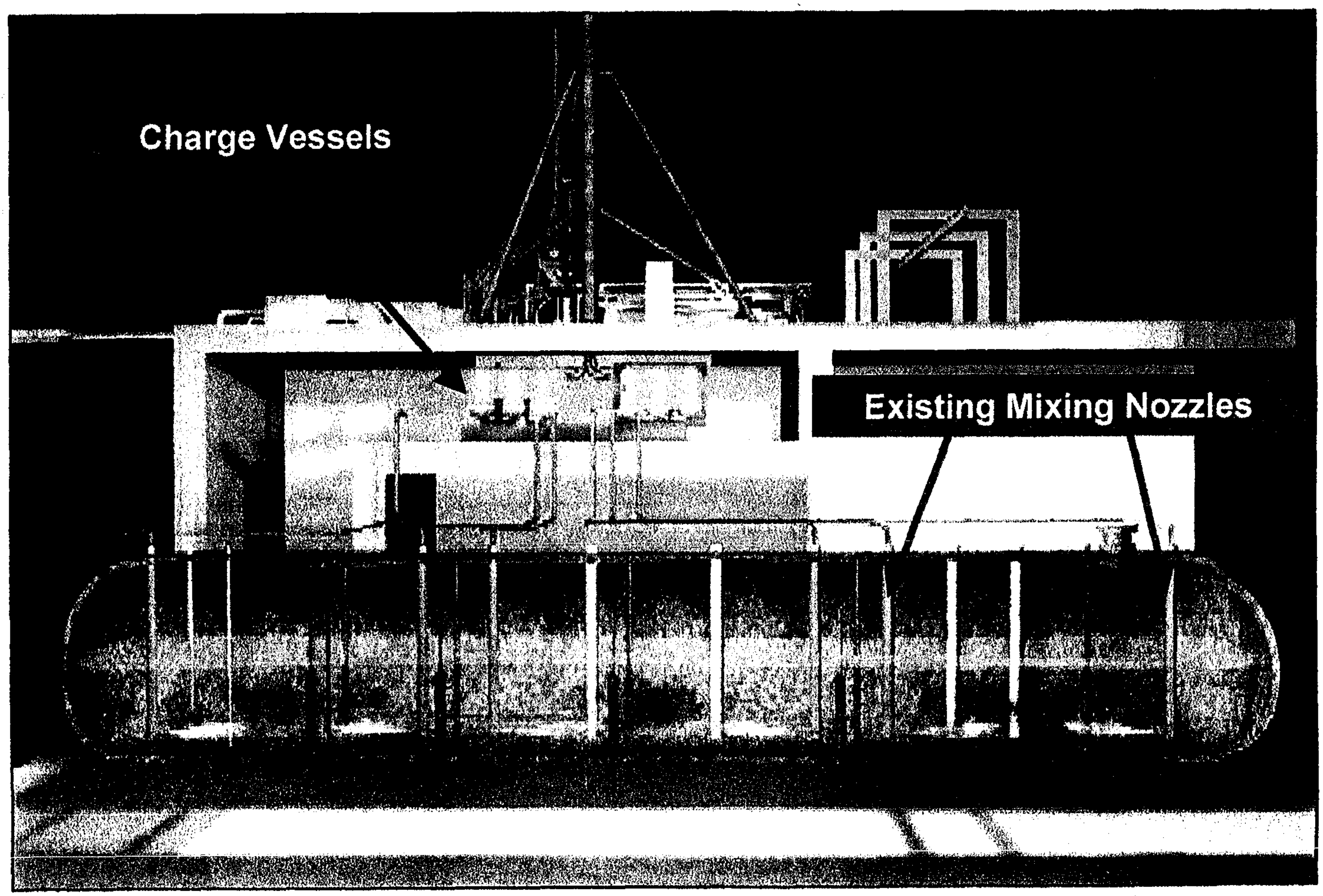



Fig. 18. Graphic cross-section of BVEST W-21 during operation of the AEAT fluidic pulse jet mixing system.

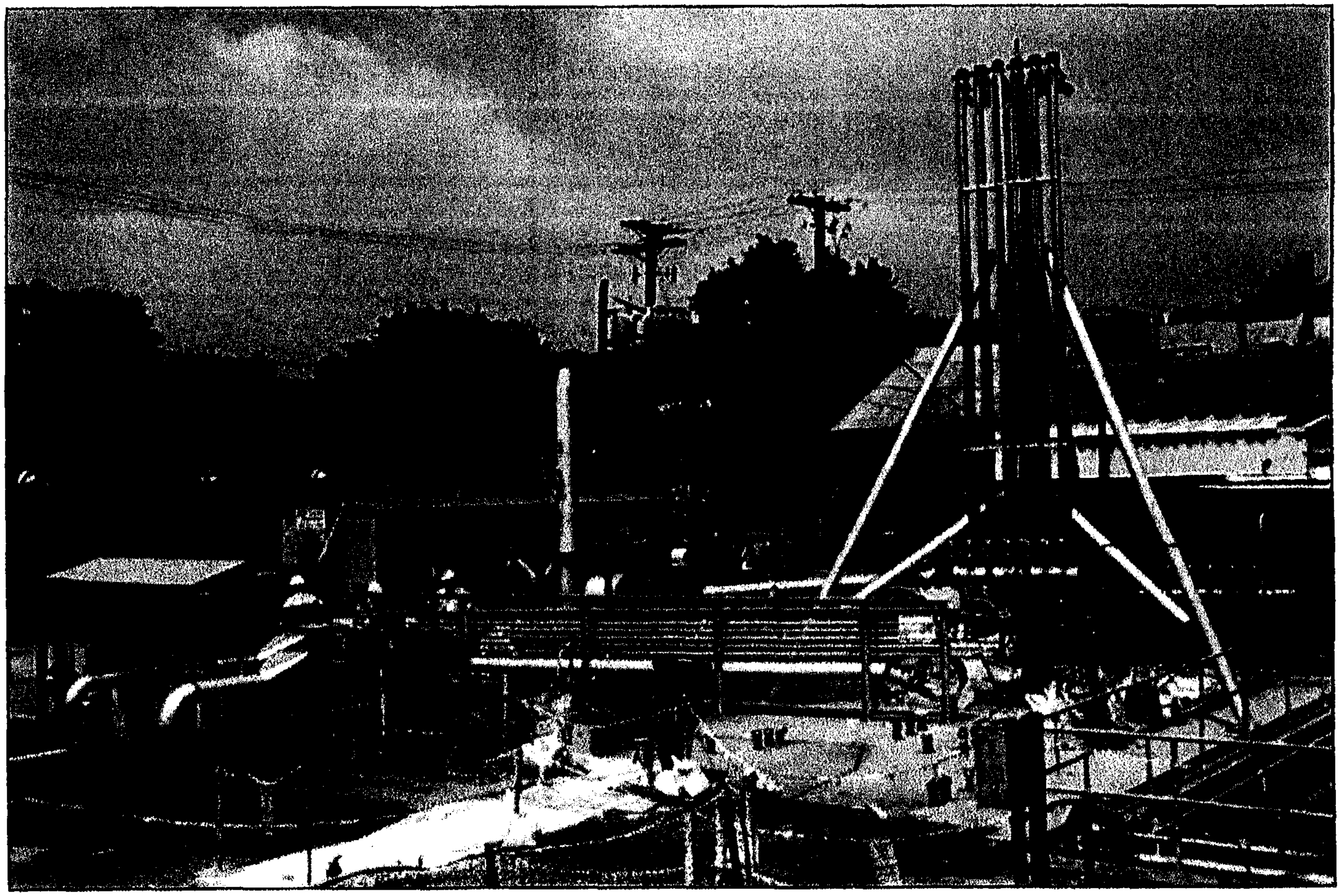


Fig. 19. Completed installation of the AEAT fluidic pulse jet mixing system at the BVEST site.

# 9. PULSE JET OPERATING PLAN

## 9.1 GENERAL OPERATIONS

The preliminary plan for operating the pulse jet system was devised based on pilot test experience. The plan involved initiating sludge mixing by first forcing a small amount of water into the tank through the tank jet nozzles via the charge vessels. This liquid, along with some entrained sludge, would then be drawn back into the charge vessels via the suction induced by the jet pump. Pressure would then be applied to the charge vessels, forcing the mixture back into the tank. This sequence would be repeated, entraining more sludge with each cycle. Water would be added to the charge vessel with each cycle until the sludge/liquid mixture breaks through the sludge layer into the overlaying supernate. Once this occurs, there is no need to add additional water to the charge vessels, and the suction/pulse cycles would be continued. When the desired sludge/supernate mixture composition is achieved, the mixture would be transferred to MVST using the existing progressive cavity (Moyno®) pumps. The targeted composition for transfer of the mixture was initially ≤5 wt % suspended solids. The permissible transfer concentration was later increased to >10 wt % for tank W-23.

## 9.2 EXECUTION PLAN

The execution plan used for the mobilization of sludge in tank W-21 is as follows. Progress with this plan was recorded in the Operations Logbook in the control cubicle. Deviations from this plan were reported, and proposed changes were approved by ORNL Waste Operations before implementation.

### 9.2.1 Execution Plan Steps for Tank W-21

**Stage 1** Mix the center segment of tank W-21 using sludge jets A3 and A4 until a steady state is achieved.

**Stage 2** Mix the northern segment of tank W-21 using sludge jets A5 and A6. To keep the central segments mixed, A3 and A4 nozzles will be pulsed periodically (see *Note*).

**Stage 3** Mix the southern segment of tank W-21 using sludge jets Al and A2. To keep the central and northern segments mixed, A3/A4 and A5/A6 nozzles will be pulsed periodically (see *Note*).

**Stage 4** Notify ORNL Waste Operations that the contents of tank W-21 are ready for transfer. This notification will be made verbally by the operations manager and recorded in the Operations Logbook. ORNL Waste Operations will then transfer the contents out of tank W-21 to the MVST.

**Stage 5** Transfer supernate and/or water into the tank to mobilize the remaining sludge deposits. This will be done by ORNL Waste Operations.

**Stage 6** Repeat stage 1.

**Stage 7** Repeat stage 2.

**Stage 8** Repeat stage 3.

**Stage 9** Agitate the areas of tank W-21 between and behind sludge jets by operating three north-facing sludge jets (Al, A3, and A5) until steady-state conditions are reached or for 24 h, whichever is longer.

**Stage 10** Agitate the areas of tank W-21 between and behind sludge jets by operating three south-facing sludge jets (A2, A4, and A6) until steady-state conditions are reached or for 24 h, whichever is longer.

**Stage 11** Repeat stage 9 conditions for one cycle, followed by stage 10 conditions for one cycle. Repeat until steady-state conditions are reached or for 24 h, whichever is longer.

**Stage 12** Notify Waste Operations that the contents of tank W-21 are ready for transfer. This notification will be made verbally by the AEAT operations manager and recorded in the Operations Logbook.

*Note*: The values for pulse frequency will be determined by the operations manager based on mixing performance.

Though it is not noted above in stages 4 and 12, the tank mixture is sampled prior to transfer to determine solids content of the mixture.

### 9.2.2 Execution Plan Steps for Tanks W-22 and W-23

The execution plans for tanks W-22 and W-23 were identical.

**Stage 1** Set up a mixing sequence comprising the following steps:

(a) Operate the center nozzle pair A3 & A4 for 1 cycle
(b) Operate the north nozzle pair A5 & A6 for 1 cycle
(c) Operate the south nozzle pair A2 & A1 for 1 cycle
(d) Operate the south-facing nozzles A6, A4 & A2 for 1 cycle
(e) Operate the north-facing nozzles A5, A3 & A1 for 1 cycle

*Note*: 1 cycle = 1 suction phase + 1 drive phase + 1 vent phase

Repeat these steps until mobilization has reached steady-state.

**Stage 2** AEAT Operations Manager will notify Lockheed Martin and DOE personnel that the contents are ready for transfer based on cycle time.

**Stage 3** ORNL Waste Management Operations will collect a sample of the slurry and have it analyzed to verify the concentration is ≤5 wt% suspended solids. Based on experience with tank W-21, it was decided not to sample each batch from tank W-22 if the first batch of slurry was ≤5 wt% suspended solids. After the tank W-22 sludge retrieval effort, it was decided to sample each batch of slurry for tank W-23 for inventory purposes.

**Stage 4** When the concentration of suspended solids is confirmed, ORNL Waste Management Operations will transfer the slurry to MVST.

**Stage 5** If sludge remains in the tank, AEAT will advise on the amount of supernate to be added back into the tank. ORNL Waste Management will transfer the supernate into tank W-22 (or W-23).

**Stage 6** Repeat from stage 1.

# 10. SLUDGE MOBILIZATION OPERATIONS

## 10.1 TANK W-21 OPERATIONS

The tank W-21 sludge retrieval required six mixing and transfer campaigns with the AEAT pulse jet system. The pulse jet system was used to mobilize and mix as much of the sludge as possible during each campaign. The resulting slurry was transferred to MVST. Based on the results of the cold testing performed by AEAT, it was planned to determine the extent of sludge mobilization by charge vessel suction time versus mixing time. In most cases this trend was very erratic and did not show evidence of steady state mixing. Visual observation and sampling of the tank contents at several depths during each campaign were necessary to judge the uniformity of the mixture prior to transfer to MVST. After the transfer, the in-tank video camera was used to inspect the tank and estimate the amount of sludge remaining. The estimated sludge quantity was used to determine the amount of liquid to add to the tank for the next mixing campaign. The operation was terminated when it appeared that the amount of additional sludge being mobilized for transfer was relatively small. Table 6 provides a summary of the volumes of liquid and sludge used in the tank W-21 sludge-retrieval operation. Photographs that show the interior of tank W-21 at various stages in the sludge removal effort are shown in Figs. 20, 21, and 22. Based on visual observations and sample results, it is estimated that 7100 gal of sludge (approximately 98%) was retrieved from tank W-21.

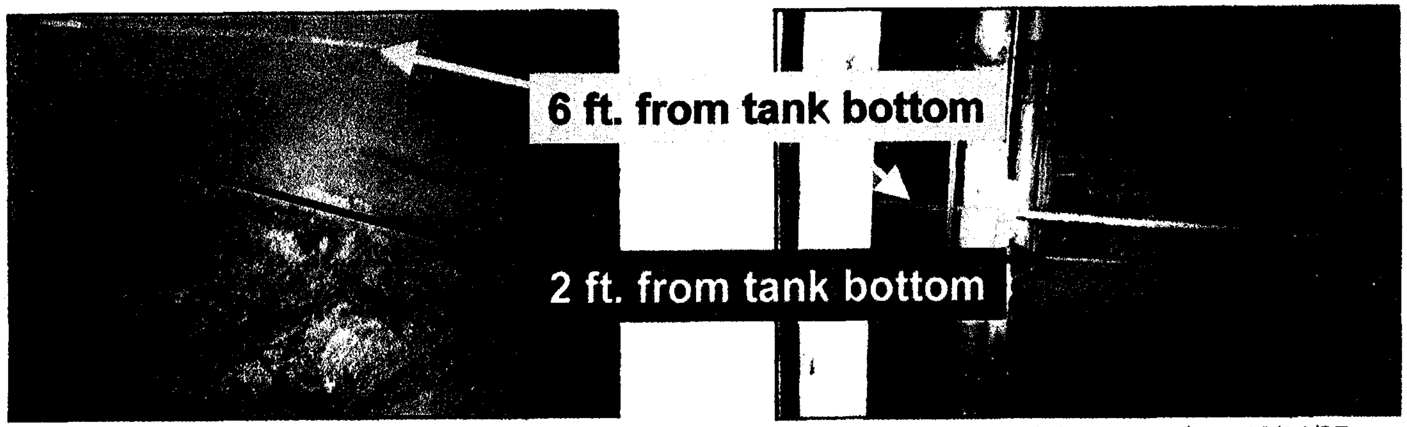
### 10.1.1 Tank W-21, Campaign 1

The first campaign began on September 5, 1997, with an estimate of 6500 gal of sludge (based on sludge depth of core sample) and 33,000 gal of liquid in the tank. The mixing proceeded as outlined in the execution plan, though it was quickly found that the mixing characteristics of the actual tank sludge were different from what was expected. It was found that the sludge from tank W-21 could be drawn into the charge vessel and mixing initiated without the need for addition of water to the charge vessel, as described in the preliminary plan. Suction time data for the pulse jets, for the most part, were erratic and did not follow the trend that was expected based on information from the pilot tests. Suction time varied significantly at times and showed only a small decline as mixing proceeded. These data proved less than adequate to determine the uniformity of the liquid/sludge mixture. Only nozzle A1 at the south end of the tank provided a trend of data that was similar to what was experienced during the pilot testing. Data for nozzle A1 are given in Fig. 23 and show the characteristic pattern, though it appears that uniform mixing in the proximity of this nozzle was achieved after only about 1.2 h.

## Table 6. Summary of mixing and transfer data for W-21 sludge retrieval activities

| Transfer No. | Date completed | Starting volume (gal) | Starting liquid level (in.) | Transferred volume (gal) | Final liquid level (in.) | Final volume[a] (gal) | Suspended solids[b,c] (wt %) | Density (g/mL) | Weight of sludge transferred[d] (lb) | Volume of sludge transferred[e] (gal) | Volume of sludge remaining[f] (gal) | Receiving tank | Supernate from W-21 and other tanks (gal) | Sluice water added by sluicer (gal) | Flush water added to MVST (gal) | MVST transfer flow rate (gal/min) | Transfer pressure (psig) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | 7200 | | | | | | |
| 1 | 9/17/97 | 40000 | 108 | 37700 | 14 | 2300 | 2.16 | 1.221 | 29672 | 2617 | 4853 | W-24, -25 | 32800 | 0 | 900 | 57 | 240 |
| 2 | 9/26/97 | 9500 | 35 | 7400 | 12 | 2100 | 13.11[g] | 1.106 | 31941 | 2817 | 1766 | W-25 | 7200 | 0 | 720 | 50 | 165 |
| 3[h] | 10/06/97 | 6900 | 24 | 4850 | 12 | 2050 | 2.49 | 1.272 | 4578 | 404 | 1362 | W-25 | 4870 | 1000 | 1050 | 57 | DNR[i] |
| 4[h] | 10/10/97 | 6100 | 23 | 5000 | 9.5 | 1100 | 1.50 | 1.272 | 2839 | 250 | 1112 | W-25 | 2960 | 2000 | 1100 | 57 | DNR |
| 5[h] | 10/14/97 | 9000 | 34 | 7700 | 10 | 1300 | 0.75 | 1.272 | 2186 | 193 | 919 | W-25 | 6030 | 1000 | | 51 | DNR |
| 6 | 10/27/97 | 9000 | 34 | 8300 | 8 | 700 | 0.24 | 1.260 | 741 | 65 | 854 | W-25, -28 | 6300 | | | | |
| 7[j] | 10/27/97 | 1100 | 9.5 | 4200 | 10 | 1300 | | | | 250 | 604 | W-23 | | 3335 | | | |
| 8[j] | 10/28/97 | 1350 | 10 | 3400 | 5 | 500 | | | | 250 | 354 | W-23 | | 2650 | | | |
| 9[k] | 1/13/98 | 4000 | 19 | 3500 | 6 | 750 | | | | 250 | 104 | W-22 | | | | | |
| Total | | | | 82050 | | | | | | 7096 | | | | | | | |

[a]As indicated by liquid level instrumentation.
[b]The suspended solids concentrations were not determined for transfers 4 and 5. For this calculation, the % suspended solids values were estimated based on the values determined for transfers 3 ad 6.
[c]The % suspended solids values are factored, based on the bulk density of the slurry.
[d]The "weight of sludge" calculation assumes that the concentration of undissolved solids was 28% in the original sludge (based on the last core sampling of W-21). Value shown is not adjusted for significant digits.
[e]The volume of sludge transferred assumes that the density of the sludge was 1.36 g/mL, based on the last core sampling of W-21. Value shown is not adjusted for significant digits.
[f]The initial starting sludge volume was generated by using volumes and % suspended solids transferred. The original sludge volume estimate was 6700 gal based on sludge depth measurement made in Sept. 1996.
[g]Dilute liquid from W-22 was used to refill W-21; The % suspended solids value shown is calculated from the total solids minus 2.4% (typical dissolved solids concentration in W-22) to account for total
solids in the original liquid. The total suspended solids for this transfer was actually 4.1 to 4.6 wt %.
[h]A "simple" sluicer waqs used to assist on sludge removal at the end of the slurry transfer.
[i]DNR = did not record.
[j]An "improved" sluicer was used to remove sludge for Campaigns 7and 8.
[k]Campaign 9 was an acid dissolution of the sludge. The acid was mixed in the tank with the AEA charge vessels.

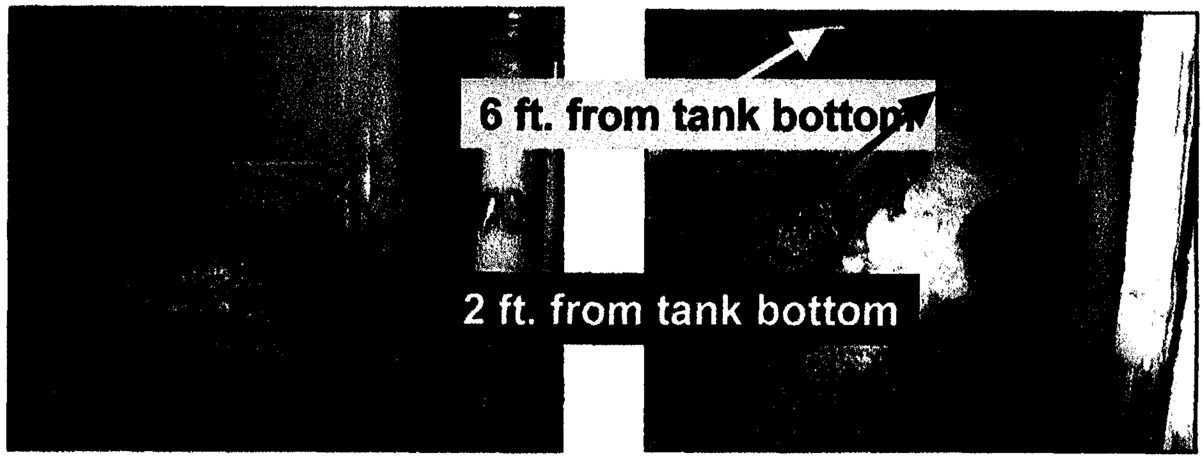



Following 1st Jet Mixing Campaign. 9/19/97

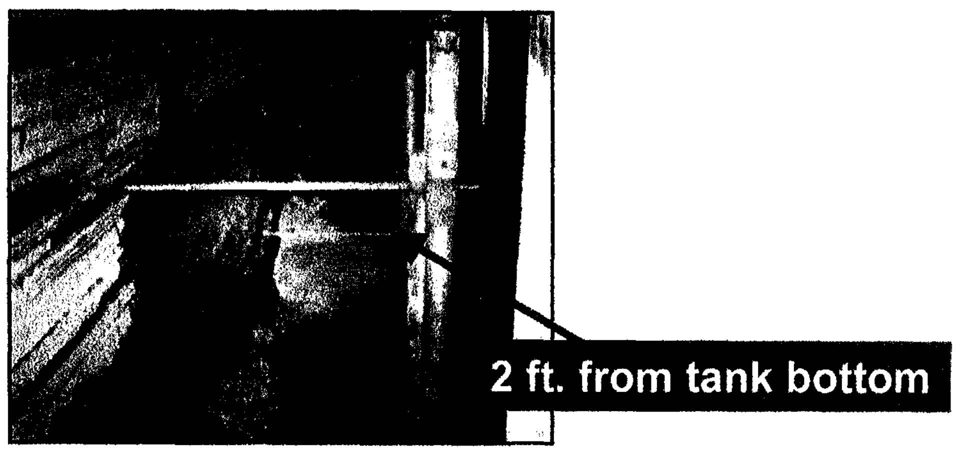
Following 4th Jet Mixing Campaign. 10/14/97


Following final pressure washing and waste transfer. 10/28/97

**Fig. 20. BVEST W-21 inspections: south end of tank at various stages of bulk sludge removal.**

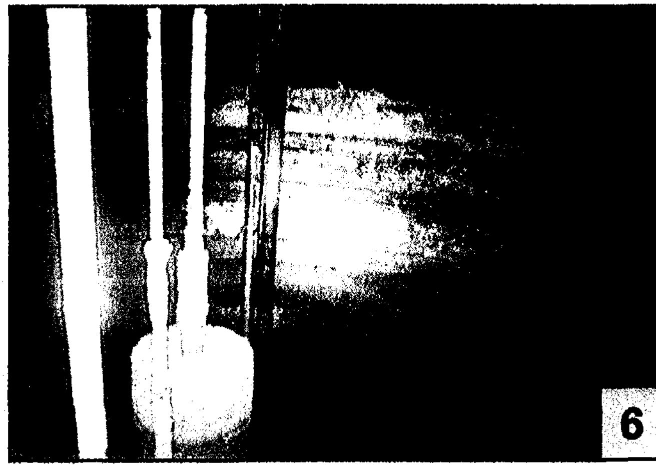



Following 1st Jet Mixing Campaign. 9/19/97 Following 3rd Jet Mixing Campaign. 10/6/97

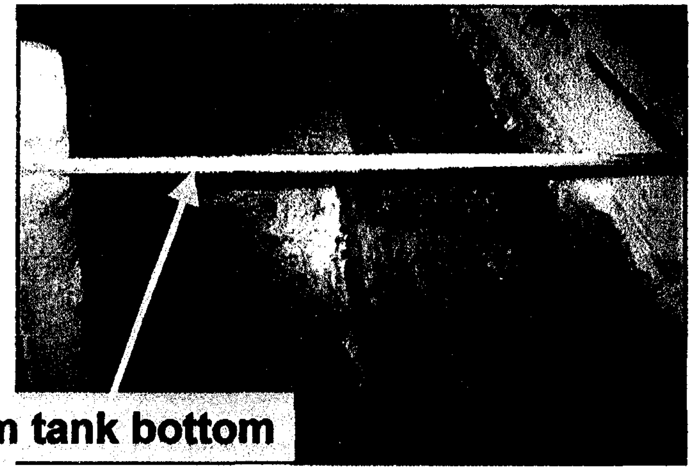



Following 4th Jet Mixing Campaign. 10/14/97

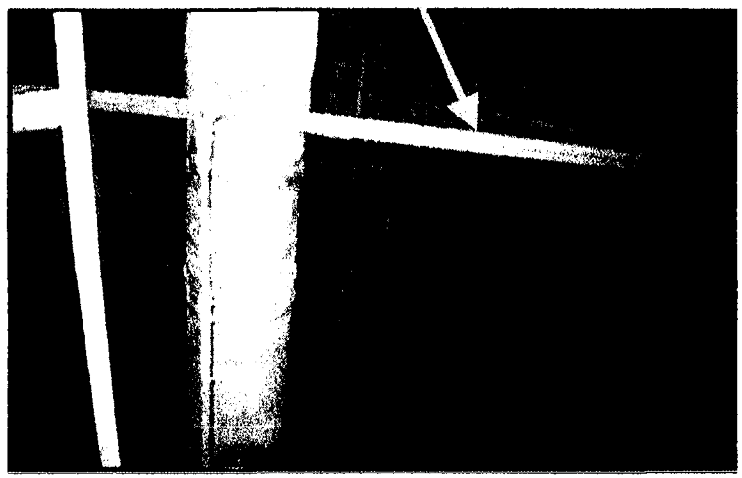
**Fig. 21. BVEST W-21 inspections: east wall of tank at various stages of bulk sludge removal.**



Following 3rd Jet Mixing Campaign. 10/6/97




Following 4th Jet Mixing Campaign. 10/14/97



Following final power washing and waste transfer. 10/28/97

**Fig. 22. BVEST W-21 inspections: north end of tank at various stages of bulk sludge removal.**

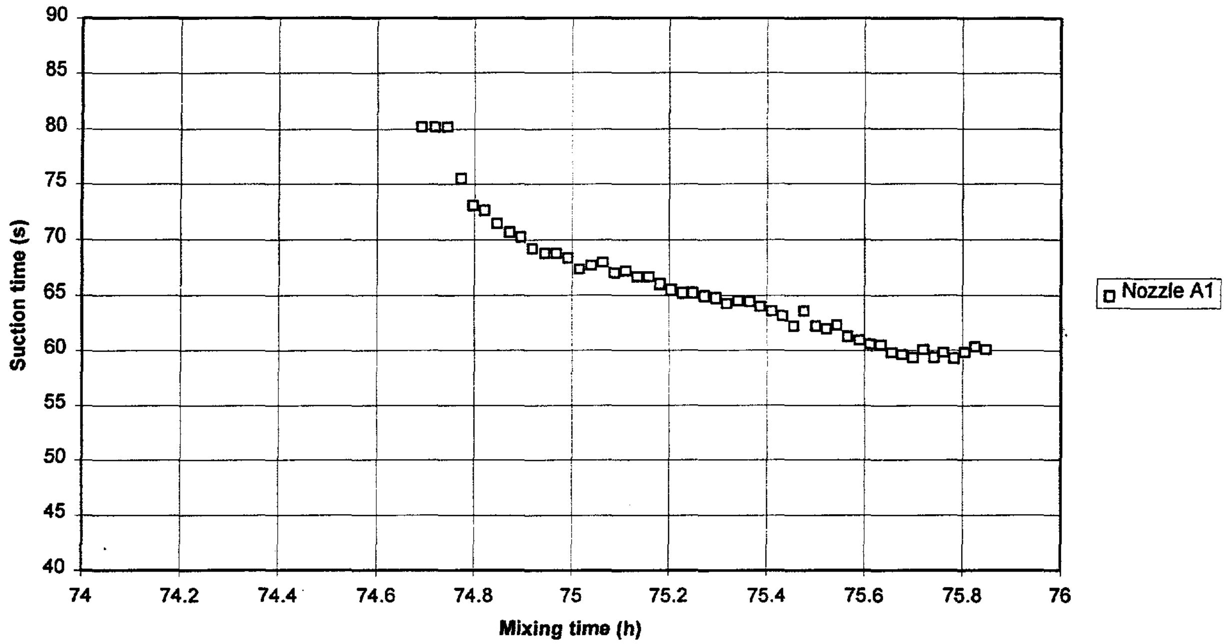



**Fig. 23. Tank W-21 mixing Campaign 1 suction time versus mixing time.**

The frequency and nozzle location of the jet pulsing was adjusted to mobilize as much of the sludge as possible. Pulse jet operations and data collection continued for 12 days. Slurry samples were taken at three depths: 1 ft from the top, 1 ft from the bottom, and at the mid-level of the slurry. The samples indicated an average total suspended solids content of 2.16 wt %. A total of 37,700 gal of this mixture was successfully transferred to MVST. Based on the sample results, a total volume of 2617 gallons of sludge was transferred. The maximum working pressure for the transfer pipeline is 300 psig, and the targeted minimum velocity for slurry transfer was 5 ft/s or 50 gal/min. The actual discharge pressure of the Moyno pumps was 240 psig at a flow of about 57 gal/min, which was within acceptable operating limits. Inspection of the tank following the transfer showed that a significant amount of sludge had been removed but also revealed that there was likely more sludge in the tank than earlier estimated. It was apparent that sludge had sloughed down into the main mixing area as the slurry was pumped out. In addition, some sludge remained on the tank walls to heights several inches above the 24-in.-high horizontal angle braces. Figures 20 and 21 show photographs of the west and east walls of the tank following the slurry transfer, respectively.

### 10.1.2 Tank W-21, Campaign 2

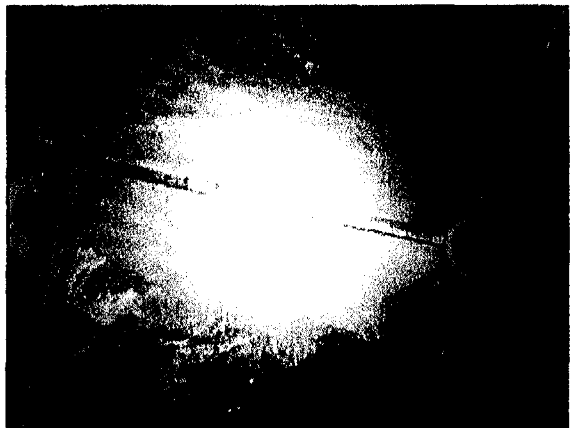
For Campaign 2, 7400 gal of liquid from tank W-22, the evaporator feed tank, was added to W-21 for mixing with the remaining sludge, increasing the total volume in the tank to 9500 gal. This volume was selected to ensure that all sludge was covered by the liquid. A smaller volume of liquid would increase agitation and thereby increase the fraction of solids in the mixture to be transferred to MVST. The pulse jet system was operated for 96 h, and a sample of the mixture was taken to determine solids content. The total solids content of the mixture was 15.5 wt %, with a suspended solids content of 4.1 to 4.6 wt %. This mixture was successfully transferred to MVST, increasing the total quantity of sludge mobilized and transferred to about 5400 gal (based on the final estimated total sludge volume of 7200 gal). The discharge pressure of the Moyno pumps was 165 psig at a flow of about 50 gal/min, which was within acceptable operating limits. The lower discharge pressure during transfer was due to the lower flow rate and the use of the dilute W-22 supernate liquid, which has a much lower density than the concentrated supernate used in the first campaign. After the transfer, it was apparent that additional sludge had sloughed down the walls and into the mixing zone of the tank nozzles. The settling time for this sludge was also shorter than expected, based on the characteristics of the clay used in the pilot tests. Tank inspection showed approximately one-third of the 3-in. A5 pipe nozzle was visible above the sludge level.

### 10.1.3 Tank W-21, Campaign 3

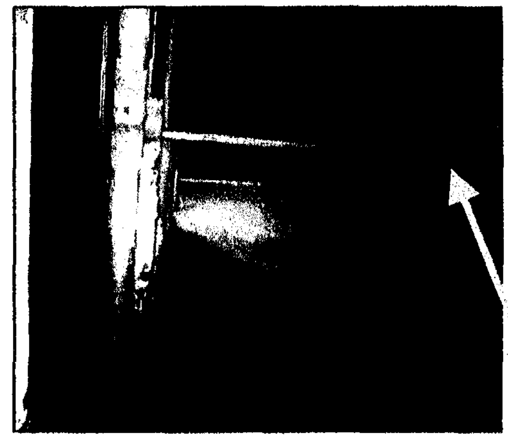
Supernate from tank W-23 was added to W-21 to increase the fluid level to about 6900 gal for Campaign 3. The pulse jet system was operated for about 10 days, creating a mixture containing about 2.5% suspended solids. Samples of the mixture were taken approximately 96 h apart and indicated no change in solids content. This mixture was transferred to MVST, increasing the total quantity of sludge removed to about 5800 gal, or about 87% of the sludge.

The video inspection revealed that a considerable amount of the suspended sludge had been redeposited between the pairs of jet nozzles (A4 and A5, A2 and A3) and at the north and south ends of the tank. The sludge between the nozzles had formed "dams" laterally across the tank. These dams impeded mixing between sections of the tank and movement of the slurry to the transfer pump suction pipe located near the A3 nozzle. There was also a rather large sludge heel at the north and south ends of the tank. Figures 21 and 24 show photos of the east wall of the tank following the slurry transfer. Figure 25 shows a photo of the sludge dam created between nozzles A4 and A5.

**Fig. 24. BVEST W-21 inspections: east wall after third jet mixing campaign.**

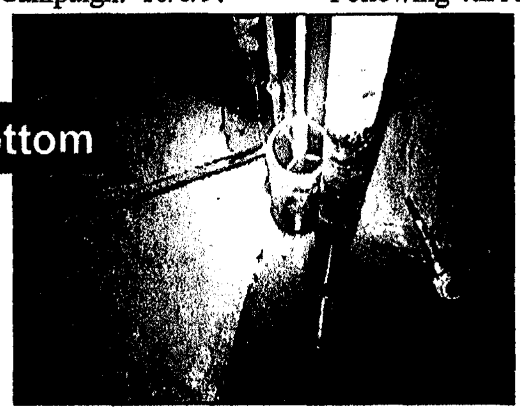


Following 3rd Jet Mixing Campaign. 10/6/97



Following 4th Jet Mixing Campaign. 10/14/97





Following 4th Jet Mixing Campaign. 10/14/97

**Fig. 25. BVEST W-21 inspections: sludge dams built up in the tank in areas of low mixing velocity.**

To restore mixing across the jet nozzle pairs, a simple manual sluicer consisting of a 3/4-in. diam pipe extension with a spray nozzle on the end was fabricated and manually inserted into the tank in an attempt to "hose down" the dams and move the sludge to areas that would be impacted by the pulse jet system. This operation was effective for washing down one of the two sludge dams but could not impact the other sludge dam or the sludge heels at the ends of the tank. A photo of the sluicing operation is shown in Fig. 26. The sluicing operation added about 1000 gal of process water to the tank.

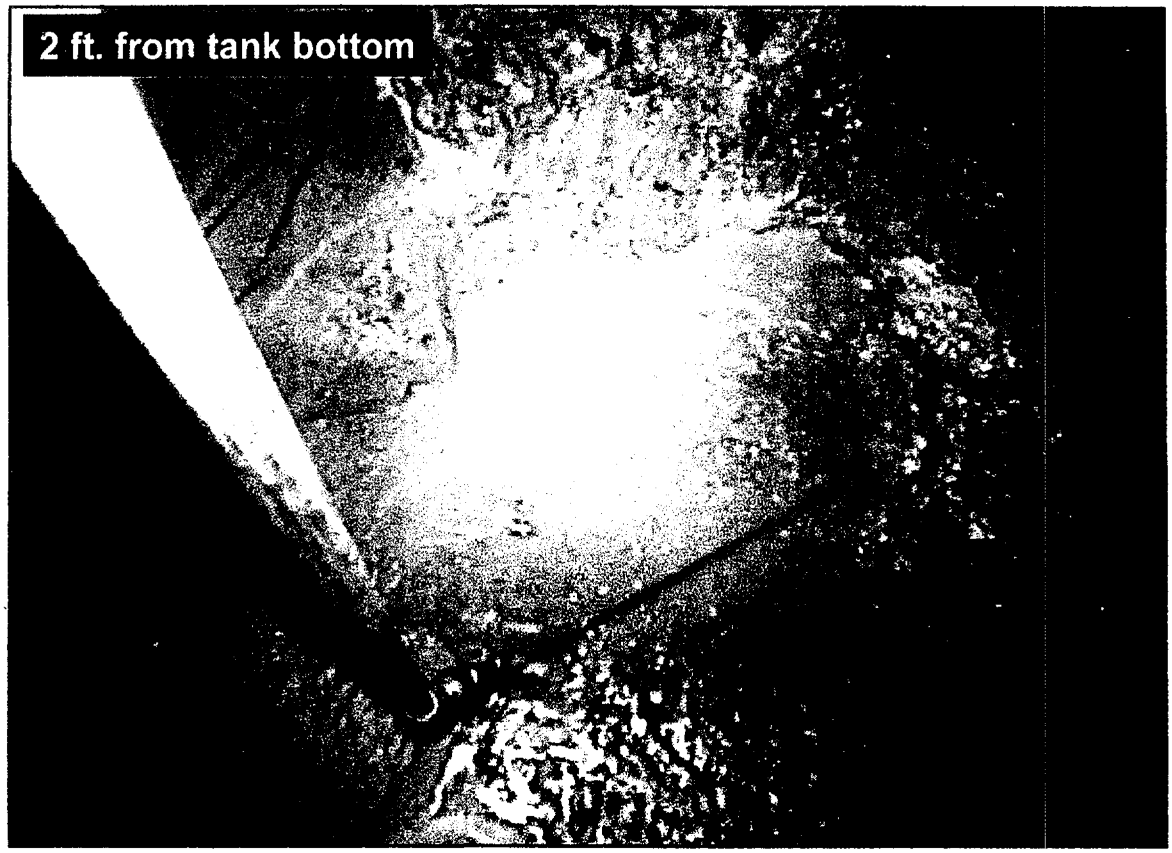



**Fig. 26. Pressure washing the sludge pile built up on the tank support between nozzles 4 and 5 in BVEST W-21, October 6, 1997.**

Figure 27 shows the suction time data recorded for the first 120 h of Campaign 3. The data indicate a significant difference between the suction times for each charge vessel and also a cyclic behavior, with variation in suction time of over 10 s (positive and negative) during a 20-h time period. The difference in suction time between charge vessels is due to the difference in the length of the pipelines between each of the charge vessels and the particular tank nozzle. The reason for the cyclic behavior has not been determined. There appears to be more scatter in the data at the beginning of the mixing campaign, which may indicate incomplete mixing and variation in the density of the slurry mixture in different areas of the tank. The general trend of all the data indicates a slow decline in suction time, and the data appear to converge slightly after 80 h of mixing. However, the data are not stable and do not show the clear plateau, making it difficult to determine when steady-state mixing conditions were achieved. The decision to transfer a particular mixture had to be based on judgement of several parameters: (1) suction time trends and indication of erratic behavior, (2) visual observation of the mixture via the in-tank video camera, (3) results of sample analysis, and (4) the duration of mixing.

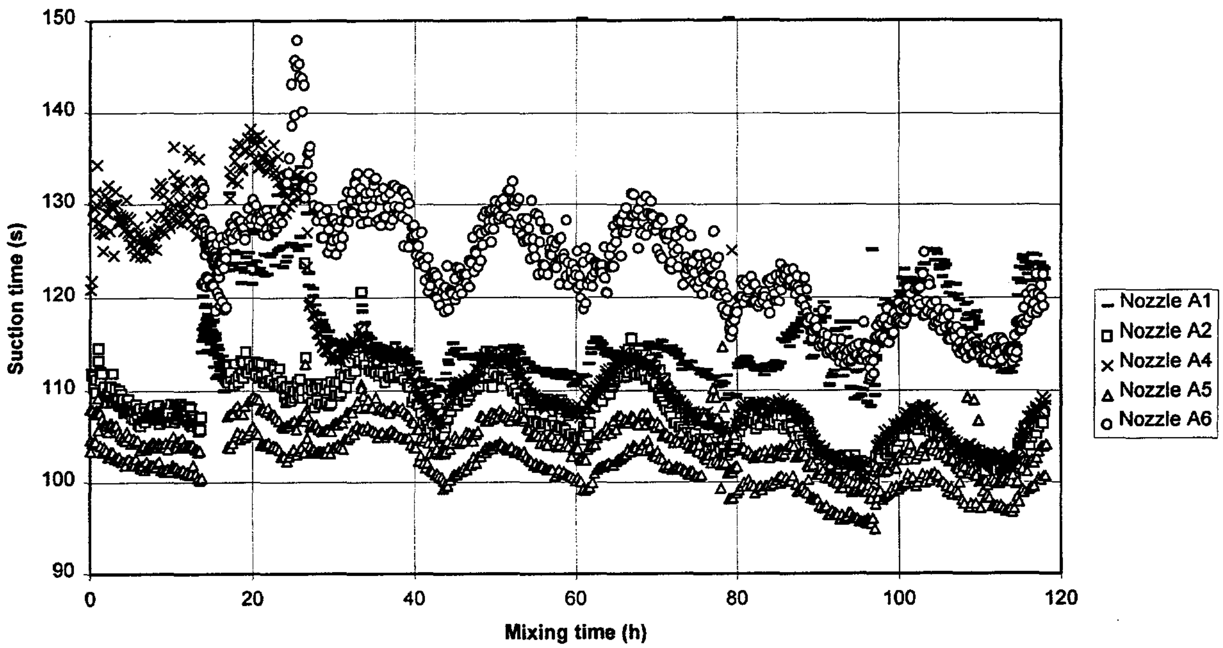



**Fig. 27. Tank W-21 Campaign 3 charge vessel suction times versus mixing time.**

### 10.1.4 Tank W-21, Campaign 4

About 4050 gal of supernate from tank C-1 was added to tank W-21 to increase the total volume to about 6100 gal for Campaign 4. The pulse jet system was operated for about 62 h for Campaign 4 and mobilized an estimated 250 gal of sludge into the supernate. Samples of the mixture were not taken during this campaign. After the transfer, the sludge had redeposited in same areas as before. The tank interior was inspected extensively after this campaign to help determine the amount of sludge remaining around the tank nozzles and at each end of the tank. Figure 28 shows the sludge remaining at both ends of the tank. Figures 20 and 21 show some additional views of the tank. Figure 25 shows various views of the sludge dams left between the nozzles.

A 90° elbow was added to the end of the manual sluicer to make it more effective at a greater distance. The sluicer was used to wash the piles of sludge from between the nozzle pairs and at the north end of the tank into the remaining tank liquid. This operation was much more effective than previous operations but added another 2000 gal of process water to W-21, increasing the total volume in W-21 to about 3000 gal. Prior to the next campaign, the tank was filled to the 9000-gal level using about 8000 gal of supernate from tank C-1.

### 10.1.5 Tank W-21, Campaign 5

The pulse jet system was operated for about 91 h during Campaign 5 and mobilized an estimated 193 gal of sludge into the supernate. No samples of the mixture were taken. After the

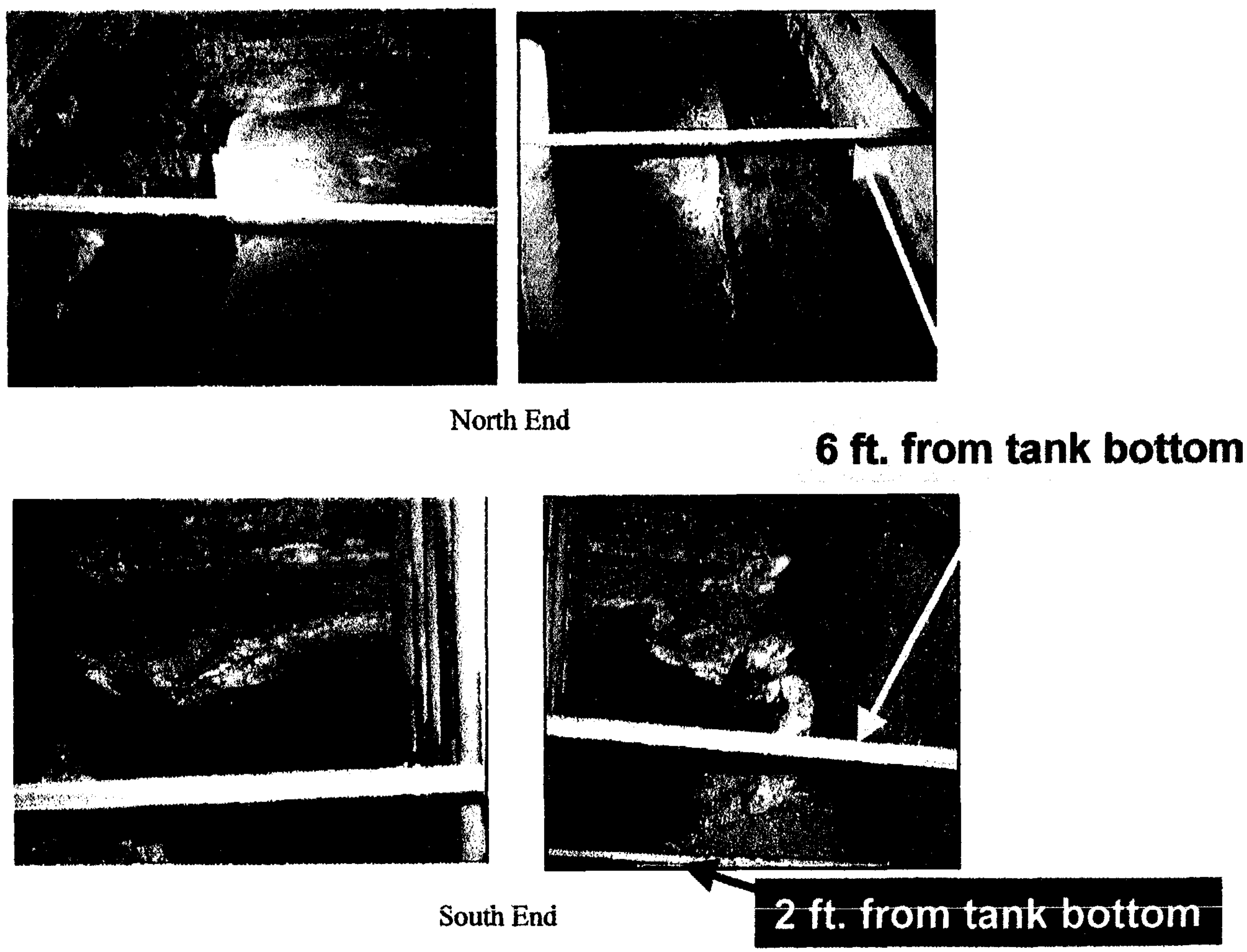



**Fig. 28. BVEST W-21 inspection following jet mixing Campaign 4, October 14, 1997.**

transfer, the remaining sludge was found to have redeposited in same areas as before, and the sluicer was used for a short period of time to disperse the sludge.

### 10.1.6 Tank W-21, Campaign 6

For this campaign, 8000 gal of supernate from tank C-1 was transferred to tank W-21, increasing the total volume in W-21 to 9000 gal, including about 915 gal of sludge. The pulse jet system was operated for about 288 h, mobilizing only about 65 gal of the remaining sludge. A sample was taken and indicated a very low suspended solids content of 0.24%. This mixture was successfully transferred to MVST, leaving about 850 gal (about 12% of the total sludge) in tank W-21. The remaining sludge solids had redeposited in the same areas as before. Based on sample results, the percentage of suspended solids for this transfer was approximately one-tenth the suspended solids content of Campaign 3. The suspended solids contents for Campaigns 4 and 5 were estimated at 1.5 and 0.75% based on the sample results from Campaigns 3 and 6.

### 10.1.7 Tank W-21 Sludge Heel Sluicing

The remaining sludge in tank W-21 appeared to be larger in particle size and settled quickly after mixing. In an attempt to remove the remaining sludge heel, a new manual sluicer was fabricated using 1.5-in.-diam pipe and a standard fire hose nozzle. The new sluicer was used at a flow rate of 85 gal/min in two short campaigns for approximately 1 h in an effort to sluice the remaining heel out of the tank. The Moyno pump operated continuously to transfer the slurry to tank W-23. This slurry was not transferred to MVST because of the lack of control of the solids content for the slurry and the heavy nature of this sludge. A total of 5985 gal of process water were used during the final sluicing effort. About 350 gal of sludge remained in tank W-21 after the sluicing activities. The pulse jet system and the manual sluicer together removed 95% of the sludge from tank W-21. Figure 20 shows the interior of the tank after the sluicing operation.

Sluicing operations required the operators to manually insert the pipe and nozzle through the existing tank W-21 manway located on top of the tank vault. Due to the high radiation activity of the tank contents, the opening was covered with lead blankets, and the video camera inside the tank was used to view the sluicing operations. An operations supervisor stationed at the video monitor in the control trailer used radio communication to direct the sluicer operators during the sluicing activities. This proved to be reasonably effective.

The total combined radiation dose received during all the sluicing operations was 375 mR. The total radiation dose received by workers for the entire project was 1230 mR. This was far less than the planned dose of 4000 mR estimated in the project as low as reasonably achievable plan.

### 10.1.8 Tank W-21 Acid Dissolution of Remaining Sludge Heel

An effort was made to remove a large portion of the remaining W-21 sludge heel by adding a dilute solution of nitric acid to dissolve the sludge. Prior to the addition of acid to the tank, a sample of the remaining heel was obtained and characterized and then subjected to dissolution tests using various concentrations of dilute nitric acid. These tests provided important information regarding the effectiveness and potential problems associated with this operation. The test program was designed to (1) determine the solubility of the sludge, (2) determine the amount of acid consumed, (3) evaluate the quantity and nature of off-gasses from the reaction, and (4) qualitatively evaluate the effectiveness under poor mixing conditions. The results of the lab work indicated that up to 70%

of the sludge heel would be soluble in nitric acid if an excess of 4 moles per liter (*M)* excess were maintained.

The source of the nitric acid was an existing waste liquid produced from the regeneration of ion-exchange resin used at the ORNL Process Waste Treatment Plant (PWTP). Part of the unreacted acid is recovered from the spent regenerant (eluate) by evaporation at PWTP prior to transfer of the liquid to the LLLW system. However, the eluate retains a free acid content of about 6 *M*. The volume of eluate produced at PWTP is about 300 gal per month. Two batches, or about 600 gal of the eluate, and about 600 gal of process water were added to approximately 350 gal of sludge and 1350 gal of liquid that remained in tank W-21. The acid additions took place over a 2-week period, with no mixing of the tank contents. On January 8, 1998, the volume in tank W-21 was increased by an addition of 2100 gal of supernate from another tank at BVEST. The total volume in W-21 was 5000 gal, which was the minimum volume required for effective use of the pulse jet system. On January 12, 1998, the pulse jet system was used to mix the W-21 contents for 24 h, and the mixture was transferred to tank W-22. Video inspection of the tank after the transfer indicated that approximately 100 gal of sludge remained in tank W-21. Figure 20 shows a photo of tank W-21 after the final slurry transfer. Table A-1 in Appendix A provides analytical data for a sample of the acid mixture following the operation. Since the PWTP eluate added to the tank contained high concentrations of calcium, magnesium, iron, and strontium, these cations cannot be used to determine the amount of sludge dissolved. However, alpha-emitting contaminants were probably not present in the PWTP eluate and at fairly low concentrations in the supernate liquid added prior to mixing. Calculating the quantity of sludge dissolved based on the gross alpha content of the final acid mixture gave a volume of 235 gal. Using the total suspended solids content of the sample to calculate the volume of sludge suspended gave an amount of 120 gal, for a total of 355 gal removed from the tank. This volume is larger than the estimated amount of sludge in the tank prior to the acid dissolution; however, the calculation and video inspection estimates are in reasonable agreement given the qualitative nature of both.

## 10.2 TANK W-22 OPERATIONS

The sludge retrieval effort for tank W-22 required five mixing and transfer campaigns. The time required to fill the charge vessels to the level switch was used to determine the readiness of the slurries for transfer. Based on the experience from the W-21 sludge mobilization activities, it was decided that tank W-22 would only be sampled for the first campaign unless the concentration of suspended solids in the first campaign was ≥5 wt %. An in-tank inspection was performed, with a video camera following each campaign. Table 7 shows the summary of mixing and transfer data for tank W-22 sludge retrieval activities. Photographs of tank W-22 at various stages of the sludge retrieval effort are shown in Figs. 29 through 34.

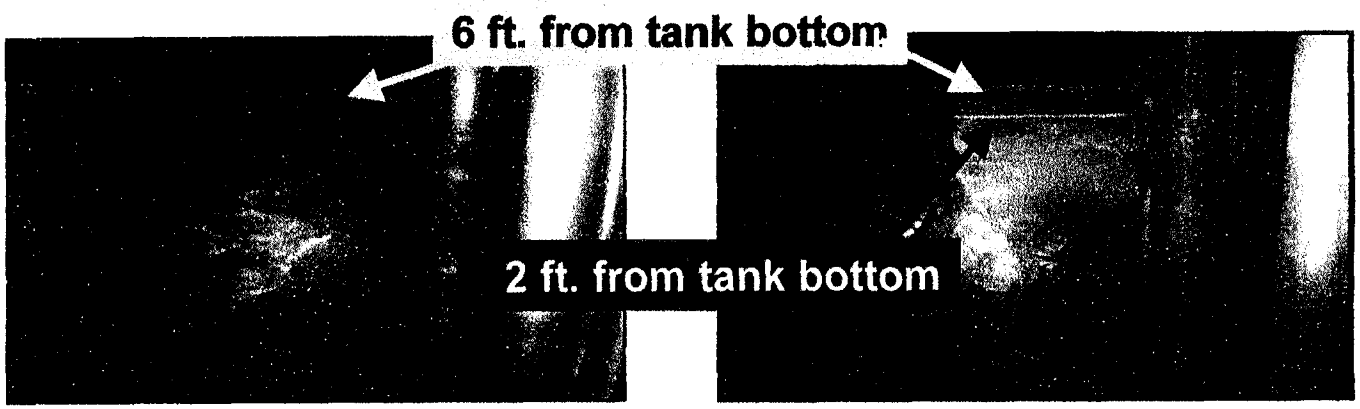
### 10.2.1 Tank W-22, Campaign 1

An estimated 7000 gal of sludge were stored in tank W-22 at the beginning of the first campaign. Before mobilization activities began, two 265 gal batches of 6 *M* nitric acid, which had been used as a flush of tank W-21, were transferred from tank W-21 into tank W-22. This was followed by a water flush and supernate addition, for a starting volume of approximately 30,200 gal. During the mobilization and mixing activity, large clumps of solids and foam were observed floating on the liquid surface (see Fig. 35).

## Table 7. Summary of mixing and transfer data for W-22 sludge retrieval activities

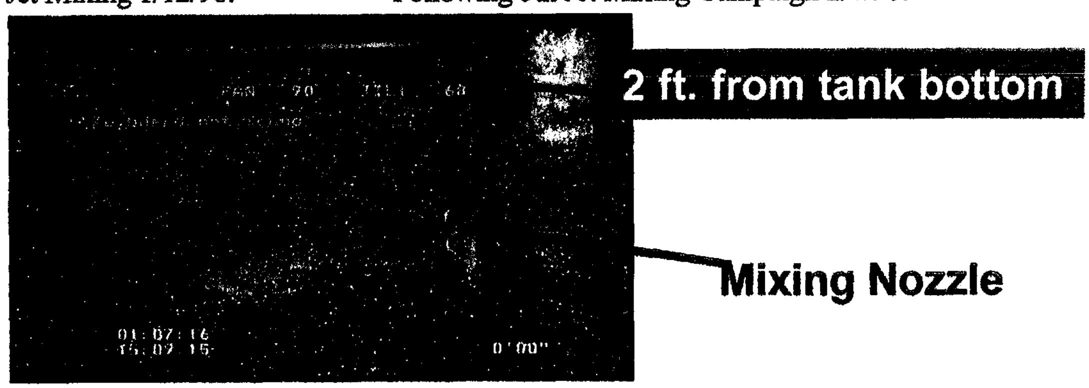
| Transfer No. | Date completed | Starting volume (gal) | Starting liquid level (in.) | Transferred volume (gal) | Final volume[a] (gal) | Suspended solids (wt %) | Density (g/mL) | Weight of sludge transferred (lb) | Volume of sludge transferred[b] (gal) | Volume of sludge remaining (gal) | Receiving tank | Flush water added to W-22 (gal) | MVST transfer flow rate (gal/min) | Transfer pressure (psig) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | 7000 | | 960[c] | | |
| 1 | 1/21/98 | 30200 | 84 | 28440 | 1760 | 4.30 | 1.170 | 42603 | 4258 | 2742 | W-24 | 250 | 50 - 60 | 165 - 190 |
| 2 | 1/26/98 | 14900 | 49 | 13660 | 1240 | | | | 1300 | 1442 | W-24, -25 | 250 | | |
| 3 | 1/30/98 | 7375 | 30 | 6690 | 685 | | | | 700 | 742 | W-25 | 515[d] | | |
| 4 | 2/2/98 | 5656 | 24 | 4825 | 831 | | | | 350 | 392 | W-25 | 515[d] | | |
| 5 | 2/9/98 | 6400 | 28 | 5315 | 1085 | | | | 190 | 202 | W-25 | 350[e] | | |
| Total | | | | | | | | | 6798 | | | | | |

[a]As indicated by liquid level instrumentation.
[b]Sludge volumes for transfers 2 through 5 are estimated based on video observation and using "landmarks" inside the tank for determining depth and size of the remaining sludge deposits.
[c]Volume includes two 265 gal acid additions plus two 135 gal dilution water additions from tank W-21, 100 gal transfer line flush, and 60 gal flush from AEA charge vessels.
[d]Volume includes 265 gal of regenerated acid plus 250 gal water flush.
[e]Approximately 100 gal of acid and 250 gal of flush water were added on 2/5/98.



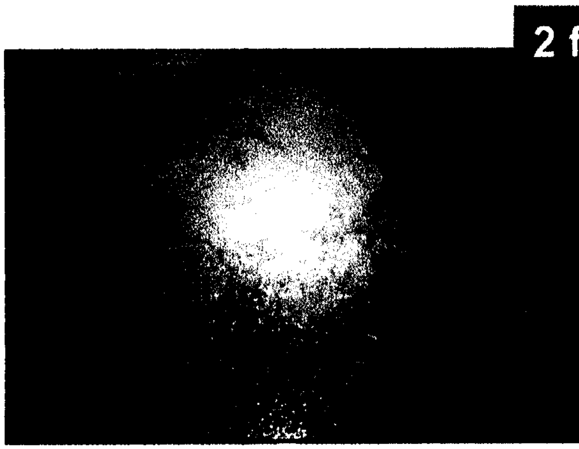

Initial Tank Inspection before Jet Mixing 1/12/98.

Following 5th Jet Mixing Campaign 2/2/98.



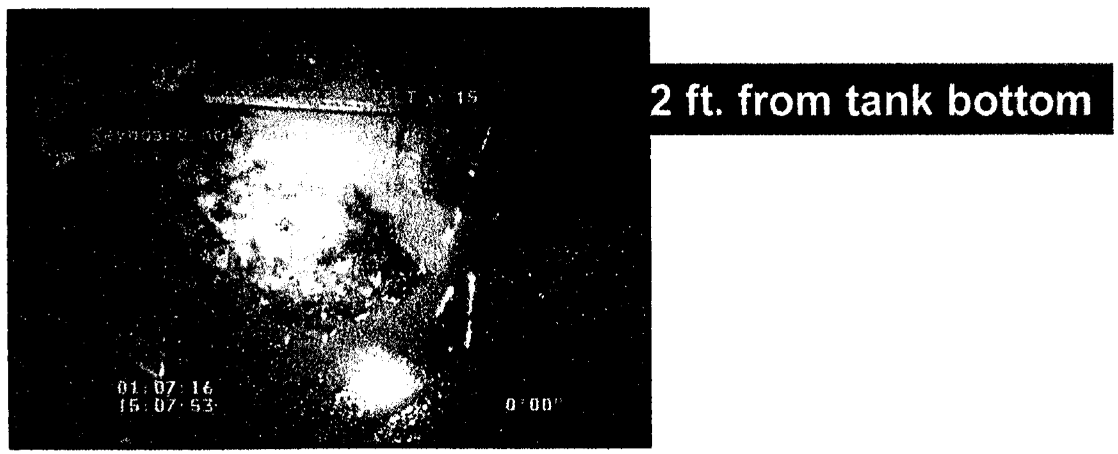

Following 6th Jet Mixing Campaign 2/9/98.

**Fig. 29. BVEST W-22 inspections: area east of nozzles 2 and 3 at various stages of bulk sludge removal.**



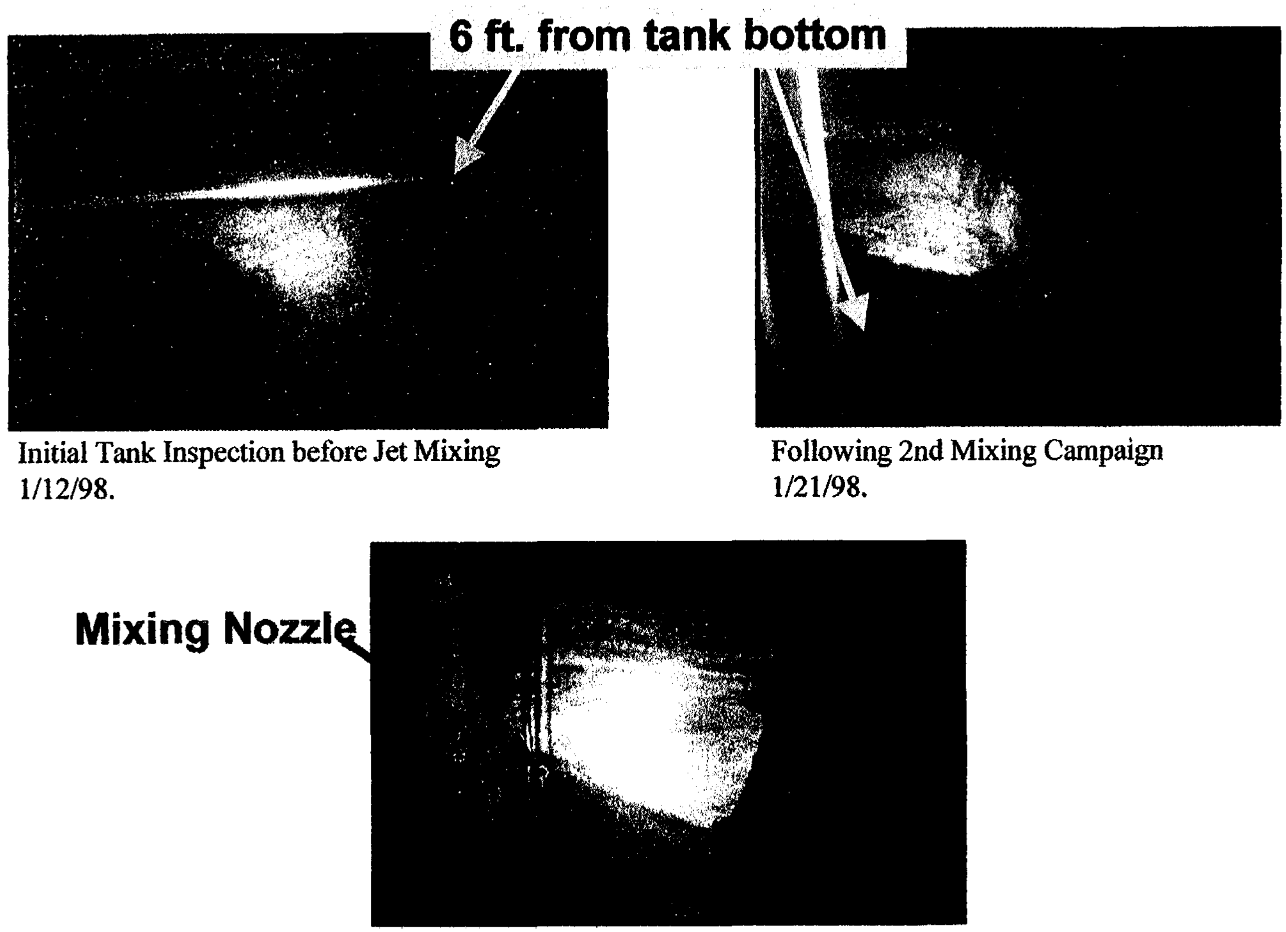

Following 3rd Jet Mixing Campaign 1/26/98.

Following 4th Jet Mixing Campaign 1/29/98.




Following 6thJet Mixing Campaign 2/9/98.

**Fig. 30. BVEST W-22 inspections: area around nozzles 4 and 5 at various stages of bulk sludge removal.**

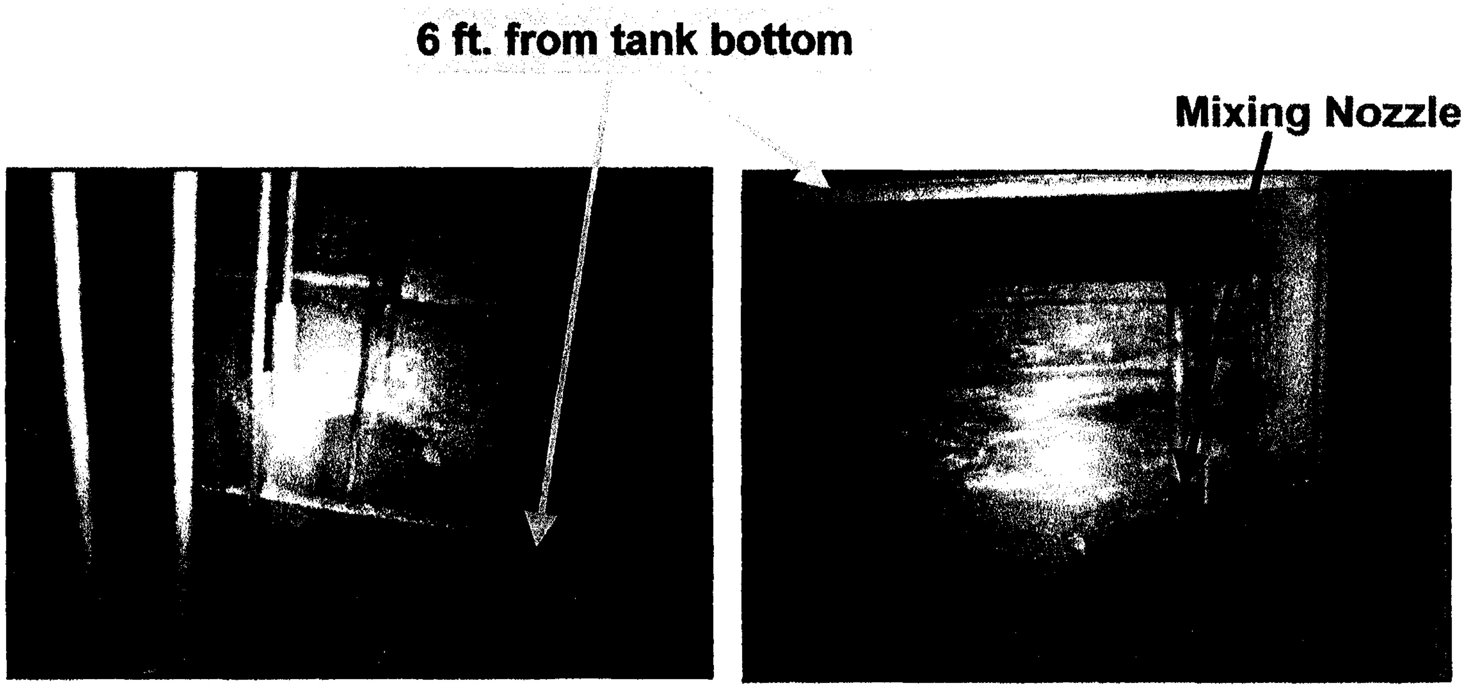



Initial Tank Inspection before Jet Mixing 1/12/98.

Following 2nd Mixing Campaign 1/21/98.

Final Tank Inspection 2/27/98.

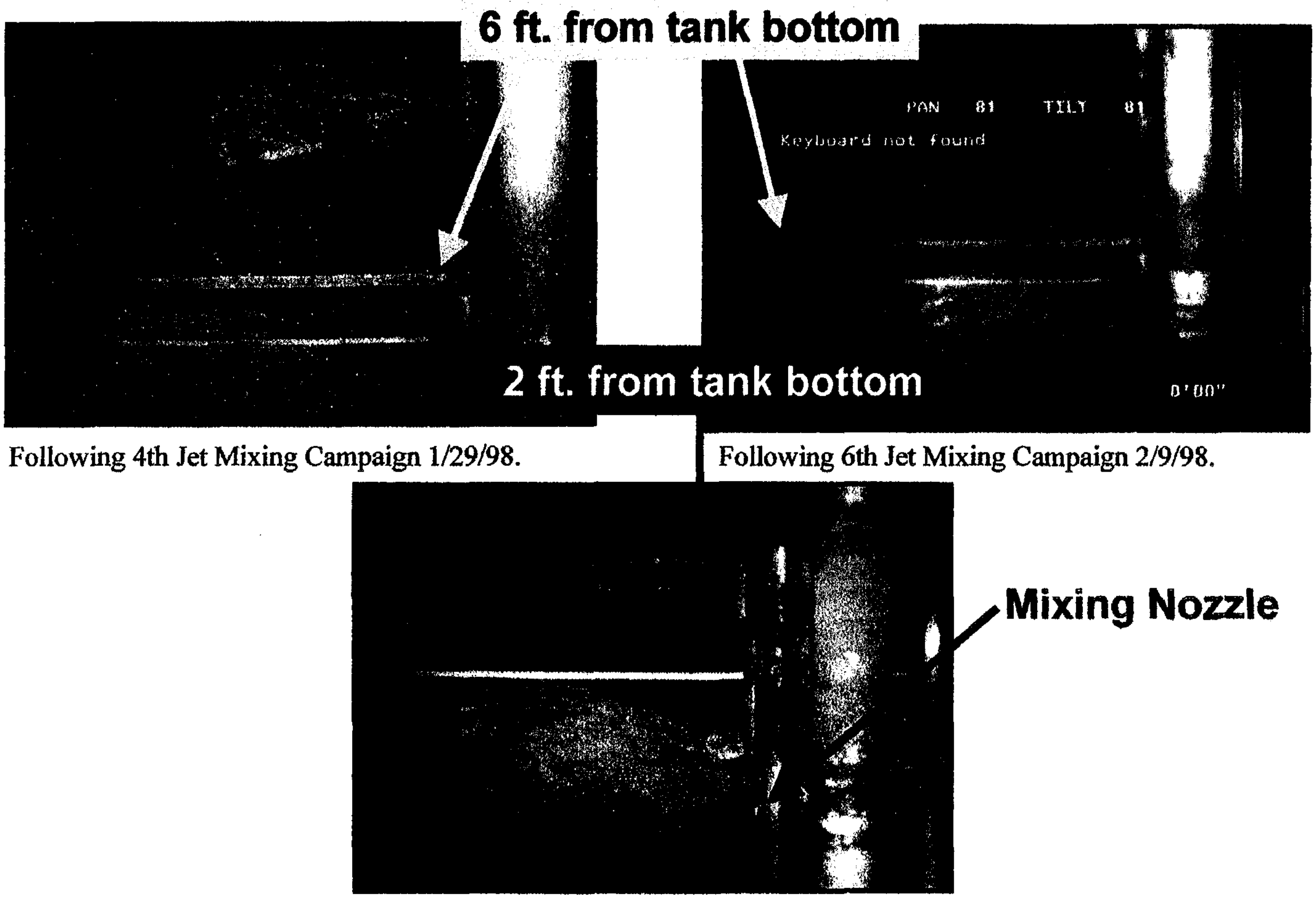
**Fig. 31. BVEST W-22 inspections: northeast corner of tank at various stages of bulk sludge removal.**




Following 4th Jet Mixing Campaign 1/29/98.

Final Tank Inspection 2/27/98.

**Fig. 32. BVEST W-22 inspections: northwest corner of tank at various stages of bulk sludge removal.**



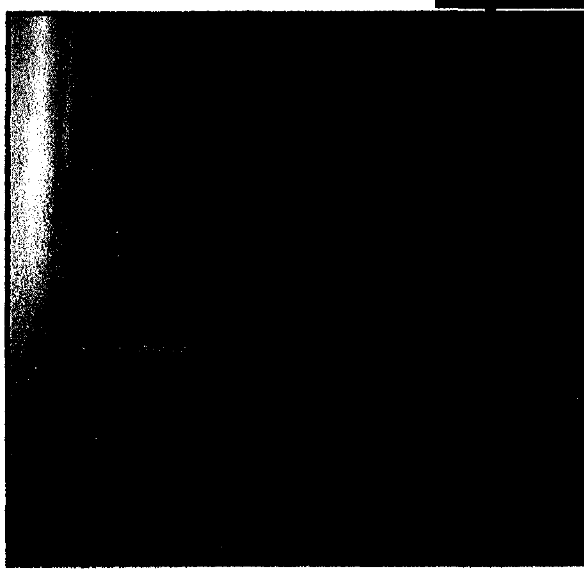

Following 4th Jet Mixing Campaign 1/29/98.

Following 6th Jet Mixing Campaign 2/9/98.

Final Tank Inspection 2/27/98.

**Fig. 33. BVEST W-22 inspections: southeast corner of tank at various stages of bulk sludge removal.**

2 ft. from tank bottom



Following 3rd Jet Mixing Campaign
1/26/98.

Final Tank Inspection 2/27/98.

**Fig. 34. BVEST W-22 inspections: southwest corner of tank at various stages of bulk sludge removal.**

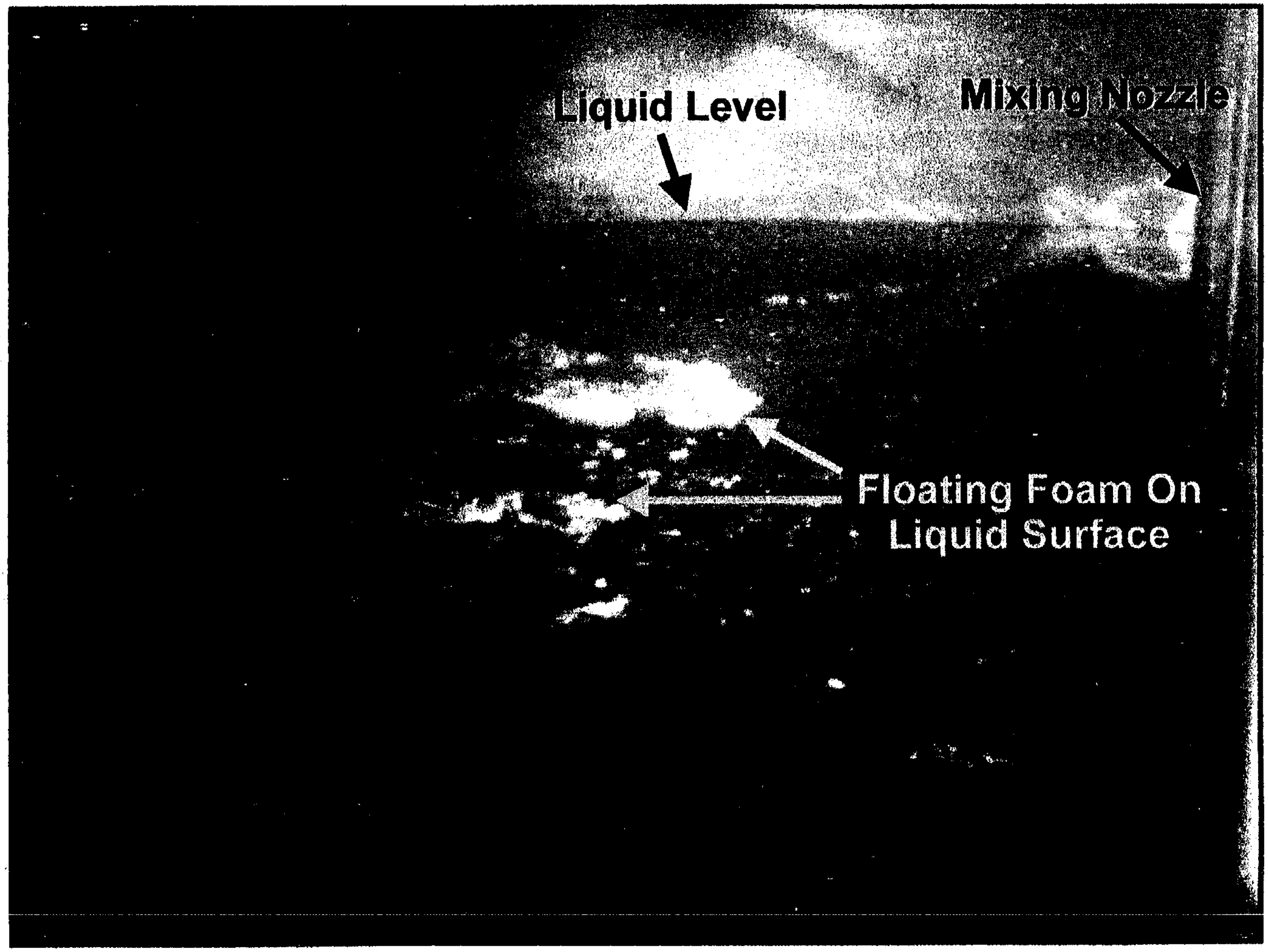



Fig. 35. Tank W-22, northwest corner of tank during jet mixing and acid dissolution, January 21, 1998.

The pulse jet system mixed the tank contents for 151 h. The slurry was sampled and analyzed for suspended solids concentration and density. The results indicated that the suspended solids concentration was 4.3 wt %, and the density was 1.17 g/mL, so no further samples would be taken from the tank. It is estimated that approximately 28,400 gal of slurry were transferred to tank W-24 at MVST. Based on visual observation of the tank after the transfer, about 2700 gal of sludge remained in tank W-22.

Figure 36 shows the time required for filling the charge vessels versus the operational mixing time for tank W-22. This graph shows the initial testing that was performed to obtain the parameter settings for the mixing equipment and the mixing period. There was a slow fill period for the charge vessels at the beginning, but similar to tank W-21, the time required to fill the charge vessels quickly reached an equilibrium.

### 10.2.2 Tank W-22, Campaign 2

Following the successful transfer of slurry from Campaign 1, supernate was transferred from MVST into tank W-22 for the second campaign. The starting volume was approximately 14,900 gal. The pulse jet system mixed the contents for 114 h. Upon receiving notification from AEAT that the tank contents were ready for transfer, approximately 13,700 gal of slurry were transferred to tanks W-24 (5500 gal) and W-25 (8200 gal) at MVST. Based on remote inspection of tank W-22 after the transfer, it was estimated that approximately 1440 gal of sludge remained in the tank.

### 10.2.3 Tank W-22, Campaign 3

Supernate was transferred from MVST to tank W-22 for the third campaign. The total starting volume in W-22 was approximately 7400 gal. The contents in the tank were mixed with the pulse jet system for 93 h, and then AEAT personnel indicated that the contents were ready for transfer. Approximately 6700 gal of slurry were transferred into tank W-25 at MVST. Based on a remote tank inspection, the volume of sludge remaining in W-22 was estimated to be 740 gal.

### 10.2.4 Tank W-22, Campaign 4

After the transfer of the Campaign 3 slurry to W-25, approximately 265 gal of regenerated acid were added to tank W-22 (plus 250 gal water). Supernate was transferred from MVST to bring the total volume in tank W-22 to approximately 5700 gal. The pulse jet system was operated for 70 h, and AEAT personnel indicated that the slurry was ready for transfer. Approximately 4800 gal of slurry were transferred into tank W-25 at MVST. A remote tank inspection was performed, and an estimated 390 gal of sludge remained in the tank.

### 10.2.5 Tank W-22, Campaign 5

Approximately 265 gal of regenerated acid and 250 gal of flush water were added to tank W-22 after Campaign 4. Supernate was transferred from MVST, for a total starting volume of 6400 gal. After mixing for approximately 72 h with the pulse jet system, the slurry was sampled and analyzed for free acid content. A second batch of acid (100 gal acid plus 250 gal water) was added to tank W-22. The contents were mixed for approximately 72 h, and the slurry was sampled and again analyzed for free acid content. Sample results indicated that free acid was available. During Campaign 5, the contents were mixed for a total of 168 h. Approximately 5300 gal of slurry were transferred to tank W-25 at MVST following the sludge mobilization and mixing activities. After

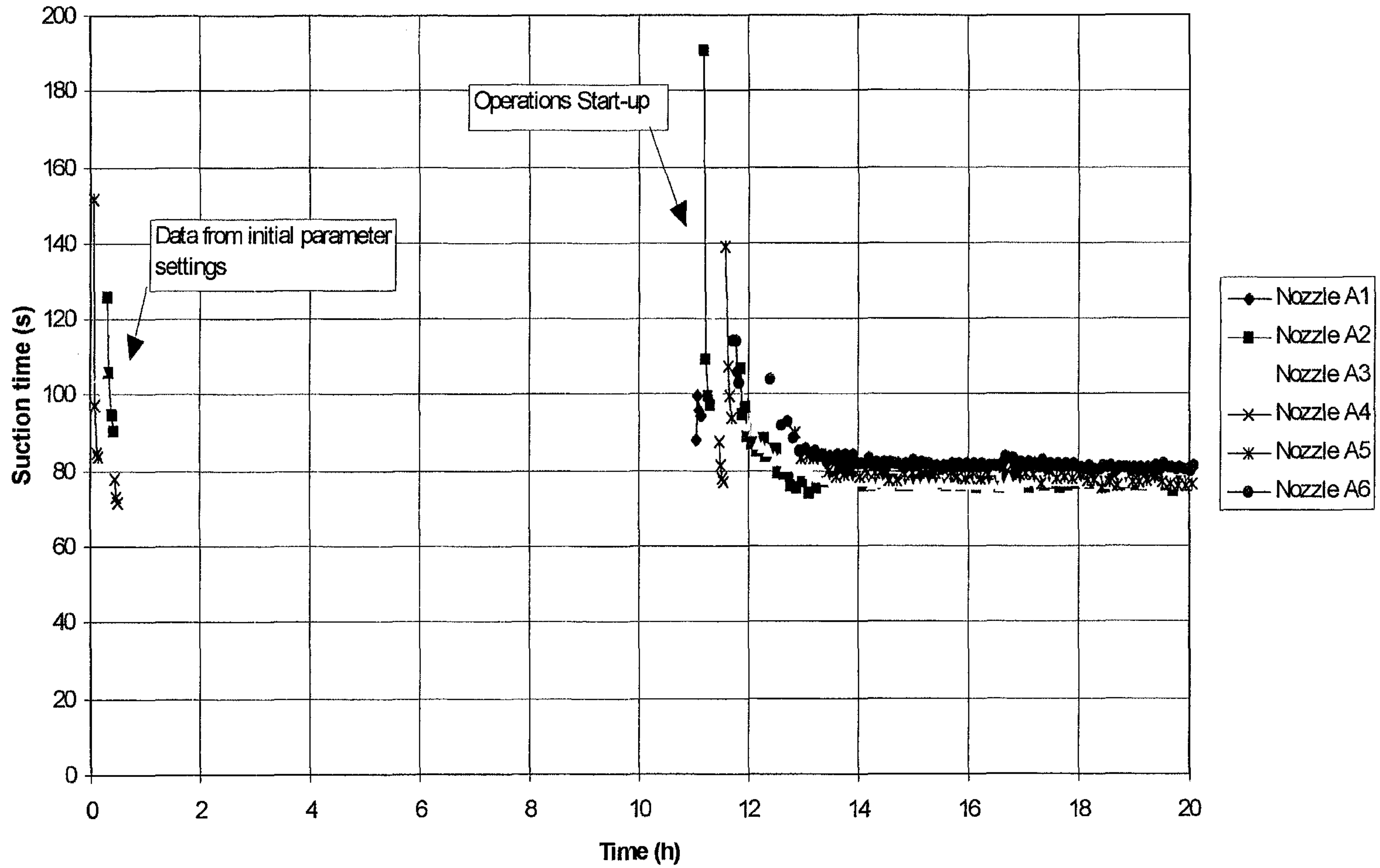



Fig. 36. W-22 mixing Campaign 1 charge vessel's suction times versus time.

the transfer, a remote tank inspection was performed. It was estimated that approximately 200 gal of sludge remained in the tank. The sludge removal effort for tank W-22 was deemed complete after the successful removal of approximately 97% of the sludge.

### 10.3 TANK W-23 OPERATIONS

The sludge retrieval effort for tank W-23 required three mixing and transfer campaigns. The times required to fill the charge vessels to the level switches were used to determine the readiness of the slurries for sampling, but as seen for tanks W-21 and W-22, this was a weak relationship for suspended solids concentration. For the purpose of inventory estimates, it was determined that each batch of slurry would be sampled and analyzed for solids content. The tank was inspected with the video camera following each campaign. Table 8 shows a summary of mixing and transfer data for the tank W-23 sludge retrieval activities. Photographs of tank W-23 at various stages of the sludge removal effort are shown in Figs. 37 and 38.

Since tank W-23 will receive slurries from two other tanks in BVEST (C-1 and C-2) that are scheduled for sludge retrieval activities, the goal of the W-23 sludge retrieval effort was to remove the bulk of the sludge, but not necessarily a complete retrieval. Slurries from these tanks will be transferred into W-23 rather than directly to MVST because of the small-diameter suction pipeline from tanks C-1 and C-2. The final sludge retrieval from tank W-23 will be accomplished in conjunction with the sludge retrieval from tanks C-1 and C-2.

#### 10.3.1 Tank W-23, Campaign 1

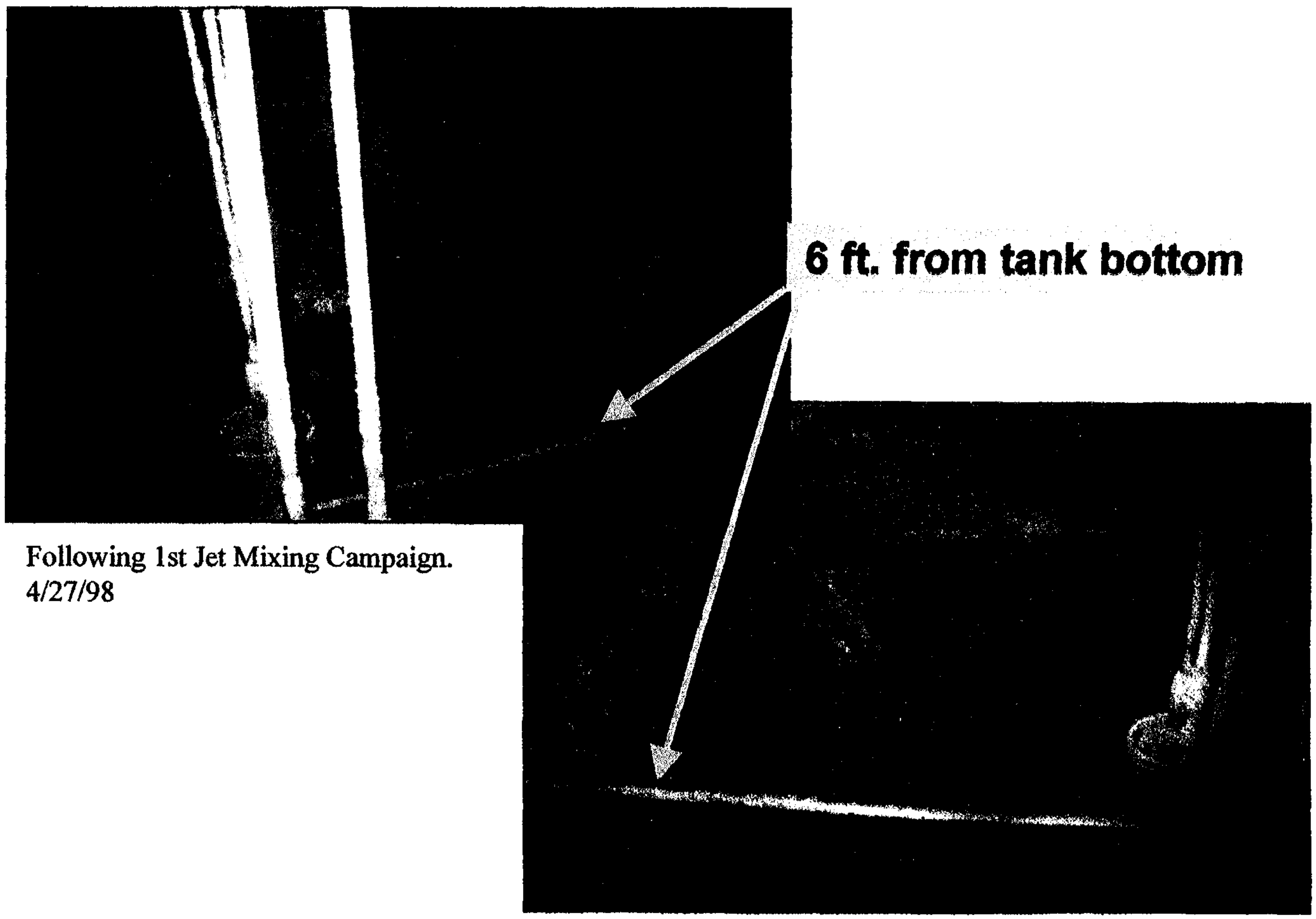
The estimated sludge volume in tank W-23 at the beginning of the campaign was 19,000 gal. Supernate was added to tank W-23 to bring the total volume to approximately 42,000 gal. Sludge mobilization activities started April 17, 1998. The tank slurry was sampled after notification by AEAT personnel that the contents appeared ready to transfer. The sample results indicated that the suspended solids concentration was 11.3 wt %, and the density was 1.28 g/mL. The suspended solids concentration was much higher than the target concentration of ≤5 wt %. The slurry was resampled and re-analyzed, and the suspended solids concentration result was 15.7 wt %. In an effort to reduce the suspended solids concentration, AEAT personnel turned off the pulsing from the charge vessels for the two nozzles on each end of the tank and mixed with only the two nozzles in the center of the tank for 48 h. The slurry was resampled, and the results indicated that the suspended solids concentration was still above 11 wt %. Staff of the Chemical and Analytical Sciences Division reported that the settling rate of the tank W-23 solid particles was much slower than that observed for the tank W-21 and tank W-22 slurry samples. Waste Management Operations recirculated the slurry in the tank using the progressive cavity pumps normally used for pipeline transfers. It was observed that the discharge pressure of the progressive cavity pump was reasonably low, indicating that the slurry did not behave like a heavy sludge. After consulting with technical staff and DOE, Bechtel Jacobs Company, and Lockheed Martin Energy Systems, Inc., management personnel, a decision was made to transfer the slurry to MVST. The slurry was transferred to tanks W-24 and W-25 on April 27, 1998, without difficulty. The pump discharge pressure ranged from 185 to 222 psig during the transfer, well below the 300 psi maximum.

The total duration of mixing in tank W-23 during Campaign 1 was 252 h. A remote camera inspection of the tank contents was performed following the transfer of the slurry, and the volume of sludge remaining in the tank was estimated to be approximately 6000 gal.

**Table 8. Summary of mixing and transfer data for W-22 sludge retrieval activities**

| Transfer No. | Date completed | Starting volume (gal) | Starting liquid level (in.) | Transferred volume (gal) | Final volume[a] (gal) | Suspended solids (wt %) | Density (g/mL) | Weight of sludge transferred (lb) | Volume of sludge transferred (gal) | Volume of sludge remaining[b] (gal) | Receiving tank | Flush water added to W-22 (gal) | Average MVST transfer flow rate (gal/min) | Transfer pressure (psig) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | 19000 | | | | |
| 1 | 4/27/98 | 42000 | 114 | 33780 | 8130 | 10.9 | 1.280 | 141187 | 12452 | 6000 | W-24, -25 | 150 | 50 | 185 - 222 |
| 2 | 5/1/98 | 20000 | 51 | 17000 | 3000 | 7.4 | 1.285 | 48087 | 4241 | 2000 | W-25 | 150 | 52 | 190 - 200 |
| 3 | 5/498 | 10000 | 37 | 7800 | 2200 | 5.9 | 1.262 | 17418 | 1536 | 750 | W-26 | 1480[c] | 55 | 190 - 200 |
| Total | | | | | | | | | 18229 | | | | | |

[a]As indicated by liquid level instrumentation.
[b]Sludge volumes are estimated based on video observation and using "landmarks" inside the tank for determining depth and size of the remaining sludge deposits.
[c]Volume includes 1000 gal water for flushing of transfer line and 480 gal for flushing of charge vessels.

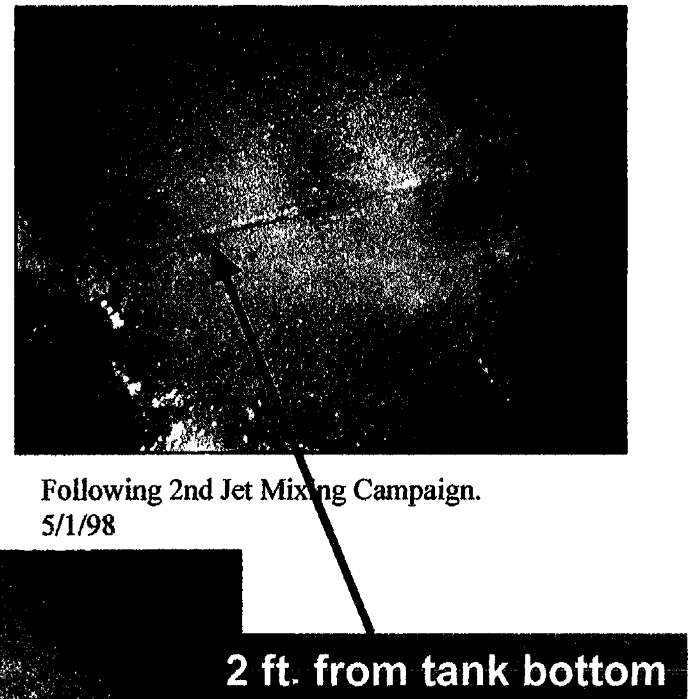



Following 1st Jet Mixing Campaign.
4/27/98

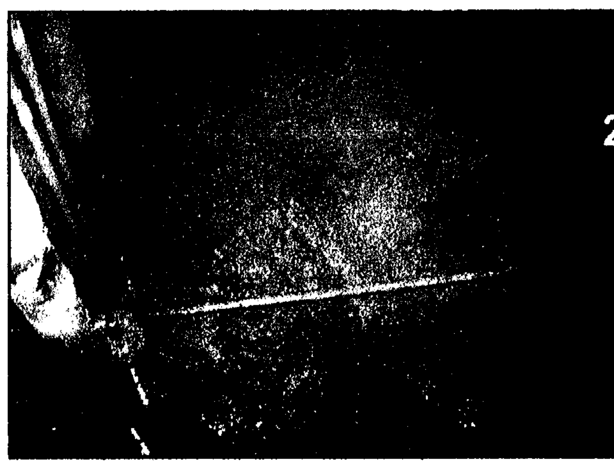
Following Final Jet Mixing Campaign. 5/5/98

**Fig. 37. BVEST W-23 inspections: north end of tank at various stages of bulk sludge removal.**

Following 1st Jet Mixing Campaign.
4/27/98




Following 2nd Jet Mixing Campaign.
5/1/98



Following Final Jet Mixing Campaign. 5/5/98

**Fig. 38. BVEST W-23 inspections: area around nozzles 4 and 5 at various stages of bulk sludge removal.**

Figure 39 shows the time required for filling the charge vessels versus the operation time period for tank W-23. Initially, the charge vessels did not completely fill within the preset time limit (200 s), so the charge vessels were emptied and the vacuum cycle reinitiated. Possible reasons that the initial suction times were longer for tank W-23 include the yield stress of the sludge was higher, the sludge depth was deeper, and the vacuum settings of the jet pumps may have been different. The graph shows that all the charge vessels were being completely filled after approximately 2.5 h of mixing time and that the suction time had reached an equilibrium within about 4 h. As indicated before, this did not mean that the concentration of suspended solids had reached an equilibrium. It can also be seen that the equilibrium time for filling the charge vessels for tank W-23 was about 40 s, as compared to approximately 80 s for tank W-22. The difference in charge vessel suction time is mainly attributable to the difference in vertical distance between the charge vessels and the tanks.

### 10.3.2 Tank W-23, Campaign 2

Supernate was added to tank W-23 at the completion of Campaign 1 to bring the total volume to approximately 20,000 gal. AEAT personnel began mixing operations on April 28, 1998. When AEAT personnel deemed that the slurry was ready for transport (based on suction time for the charge vessels), a sample was collected and analyzed for suspended solids concentration (9.5 wt %) and density (1.285 g/mL). Since the slurry from Campaign 1 was transferred without difficulty, the permissible suspended solids concentration was revised, and the Campaign 2 slurry was transferred to MVST W-25 on May 1, 1998. The transfer pressure ranged from 190 to 200 psig. The total mixing duration for the second campaign in W-23 was 80 h. A remote tank inspection was performed of W-23 after the transfer, and it was estimated that 2000 gal of sludge remained.

### 10.3.3 Tank W-23, Campaign 3

Supernate was added to tank W-23 to bring the total volume to approximately 10,000 gal before Campaign 3 began. Mixing operations restarted on May 1, 1998 and continued for 48 h. The slurry was sampled and analyzed for suspended solids concentration (7.5 wt %) and density (1.262 g/mL). The slurry was transferred to MVST W-26 on May 4, 1998, during which the transfer pressure ranged from 190 to 200 psig. The total duration of mixing in W-23 for this campaign was 67 h. An inspection of the tank after the transfer indicated that approximately 750 gal of sludge remained. This indicates that 96% of the sludge had been retrieved from tank W-23.

As previously discussed, the sludges in BVEST C-1 and C-2 will be retrieved and transferred into tank W-23 for subsequent transfer to MVST. Since tank W-23 is going to receive slurry from C-1 and C-2, it was not deemed necessary to expend a large effort to remove additional sludge from W-23. Therefore, the sludge retrieval of tank W-23 will be completed in conjunction with the sludge retrieval activities for the C-1 and C-2 tanks.

# 11. SAMPLE ANALYSIS

Samples of the waste slurries were taken periodically from tanks W-21, W-22, and W-23 during the pulse jet system operation to determine the density and suspended solids content at several depths in the liquid/sludge mixture. This information was used to estimate the amount of sludge mobilized into the supernate for the particular campaign. Slurry samples from tank W-21 were also

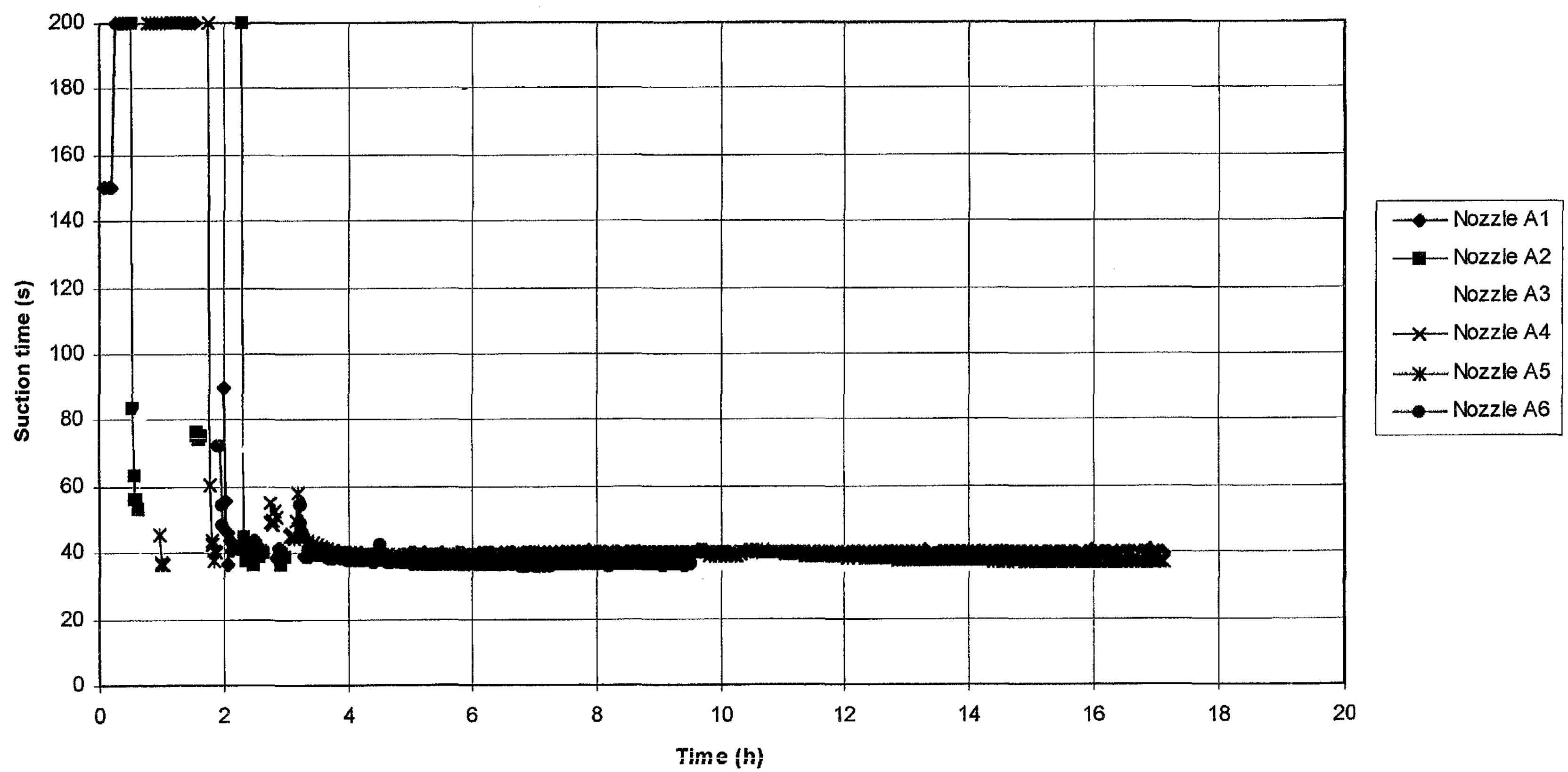



**Fig. 39. W-23 mixing Campaign 1 charge vessels suction times versus time.**

used to compare the composition of the mobilized sludge with the sludge composition determined from a previous core sample of the sludge. Tables A-2 through A-6 in Appendix A provide the results of the sample analysis and a comparison with the earlier core sample results. The previous core sample was obtained from a single location in the tank and analyzed. It was considered unlikely that the sludge composition was uniform throughout the tank, and the extent to which this core sample reflected the composition of the sludge in the entire tank was unknown at the time. Comparing the composition of the sludge core sample to the composition of the mobilized sludge samples taken during the mixing campaigns was complicated by the variation in solids content for the mixing campaign samples and also the use of different supernate compositions for each of the mixing campaigns. The liquids that were transferred to the tanks were obtained from several different storage tanks and varied widely in composition. When transferred to a tank at BVEST, these liquids mixed with the interstitial liquids of the sludge and the liquids remaining from the previous campaigns, which changed the composition of the soluble components of the sludge and made it impossible to track the liquid composition. Therefore, it was necessary to identify key sludge components that were present at high concentrations and were relatively insoluble so that the component concentration was not affected by the changing supernate composition.

A qualitative comparison of slurry samples and sludge core sample compositions was performed by first determining the ratio of low-solubility sludge components in each of the samples from the mixing campaigns. These ratios were compared to similar ratios for the core sample. Table A-7 in Appendix A shows these component ratios. This comparison indicates that, in general, the sludge suspended during the mixing campaign is similar in composition to the core sample. The ratio of the major nonradiological sludge components (calcium/uranium, uranium/thorium, magnesium/uranium, etc.) for the mixing campaign samples is reasonably close to the same ratios in the core sample. The ratio of gross alpha content to other components in the slurry samples (uranium, calcium, magnesium) is about a factor of two lower than the same ratio for the core sample. This indicates that the concentration of alpha-emitting components in the slurry is somewhat lower than that in the core sample. The data also indicate that the $^{90}Sr$ content of the slurry was slightly higher than that in the core sample.

# 12. PROJECT COST SUMMARY

Table 9 provides a general breakdown of the cost for this project. The table reflects the total costs for design, installation, startup, and operations for all three tanks.

**Table 9. Pulse jet deployment costs**

| Organization | Activities | Cost ($K) |
|---|---|---|
| AEA Technology | - Design, fabrication, and delivery of pulse jet system<br>- Installation management<br>- Operation of pulse jet system | 3900 |
| Lockheed Martin Energy Research and Energy Systems | - Design of BVEST installation interfaces<br>- Safety analysis<br>- Engineering support<br>- Field operations support<br>- Technical support and documentation | 950 |

Table 9 (continued)

| Organization | Activities | Cost ($K) |
|---|---|---|
| M. K. Ferguson | - Installation of pulse jet system<br>- Fabrication and operation of sluicer<br>- Radiation Protection support | 450 |
| Bechtel Jacobs Company LLC | - Project management<br>- Project financial control<br>- Field engineering support | 10 |
| Total | | 5310 |

# 13. SUMMARY AND CONCLUSIONS

The AEAT fluidic pulse jet mixing system successfully removed sludge from three 50,000-gal, horizontal storage tanks using modular equipment and existing pipe nozzles for mixing the settled tank sludge with existing tank supernate liquids. The pulse jet system designed, fabricated, installed, tested, and operated for sludge retrieval over an 18-month period. The equipment was used to retrieve bulk quantities of sludge from three 50,000 gal tanks.

For tank W-21, approximately 64,000 gal of liquid were used to transfer 7200 gal of sludge. Of the liquid used, 88% was existing or recycled tank supernate. Between pulse jet mixing campaigns in tank W-21, a manual sluicer was used to assist the mixing by washing mounds of settled sludge heels into the flow path of the tank nozzles. Manual sluicer operation during the pulse jet operation added about 10,000 gal of process water to the tank system, but it increased the total quantity of sludge that was retrieved. An additional 3770 gal of process water was added to the system for charge vessel and pipeline flushing. An acid dissolution operation performed over a several-week period removed an additional 250 gal of sludge, leaving about 100 gal of sludge in the tank. Waste retrieval operations for tank W-21 occurred over a period of 52 days, including a short amount of downtime and the manual sluicer operations. The pulse jet system was operated about 73% of the time, or 38 days. Greater than 98% of the sludge was removed from W-21 for all the retrieval operations.

For tank W-22, approximately 52,000 gal of liquid were used to mix and transfer approximately 6800 gal of sludge. Approximately 95% of the liquid used was existing or recycled tank supernate, and acid was occasionally included as part of the supernate. The pulse jet system was operated over a period of 19 days, with essentially no down time. Greater than 97% of the sludge was retrieved from tank W-22. Manual sluicing was not required in tanks W-22 and W-23.

For tank W-23, approximately 18,000 gal of sludge were mixed and transferred with approximately 45,000 gal of liquid. Approximately 96% of the liquid used was existing or recycled tank supernate. The pulse jet system was operated for 25 days, with essentially no down time. Approximately 96% of the sludge in tank W-23 was removed in three mixing campaigns. Additional sludge removal may have been possible, but operations were halted because W-23 will be used to receive sludges from the retrieval activities for tanks C-1 and C-2.

The maximum concentration of suspended solids, indicated by analyzed samples, that was obtained during the mixing campaigns for tanks W-21 and W-22 was approximately 5 wt %; however, the concentration of suspended solids in the W-23 slurries approached 16 wt %. Potential reasons for the higher concentration include (1) the tank contained more sludge than the others; (2) the vertical distance between the charge vessels and W-23's discharge nozzles was significantly closer than the other tanks; therefore, the cycle time for the charge vessels was shorter than the other tanks; (3) the chemical and physical characteristics of the sludge caused the tank W-23 solids to stay in suspension longer than the solids in tanks W-21 and W-22.

The extent of sludge removal was limited by the constraints of using the existing tank nozzle configuration and the physical characteristics of the sludge. The ability to rotate the tank nozzles would have significantly improved the effectiveness of the system, though this would have required significant mechanical work, expense, and radiation exposure. A significant fraction of the W-21 and W-22 sludges tended to settle more quickly than anticipated, forming sludge heels that were difficult to mobilize. Removal of greater than 98% of these sludges would require either much more aggressive use of the manual sluicer (and associated water additions), a shielded sluicing system that utilizes supernate from an existing inventory, or a more costly and elaborate robotic retrieval system.

The ability to determine the mixing conditions in the tank was compromised by inconsistent suction time data for the charge vessels. Cold tests of the pulse jet system indicated that suction time data could be used to determine when a uniform mixture was achieved. However, actual field suction time data was inconsistent and erratic, making it difficult to determine when or if a uniform mixture was achieved. This was likely due to differences between the physical characteristics of the actual sludge and the china clay used in the cold testing. Qualitative judgement of other operating parameters was used as an indication of adequate mixing. This resulted in successful pipeline transfer of the slurries; however, mixing times may have been much longer than necessary. The use of on-line monitoring instrumentation for continuous measurement of density and solids content of the slurry could likely have shortened mixing times, reduced operating costs, and provided greater assurance of adequate mixing.

The modular design of the system allowed for quick installation and minimized personnel exposure for work being performed in high-radiation areas. The total dose received by operations personnel was 1230 mR, including the manual sluicer activities, which is more than a factor of 3 lower than the as low as reasonably achievable plan estimate. The system operated well and experienced no major equipment malfunctions or unplanned maintenance outages.

These results and the fact that the system can be used to mix sludges in multiple tanks with simple hose change-out indicate that the pulse jet system should be seriously considered for mixing and bulk retrieval of sludges in horizontal tanks at ORNL and at other DOE sites such as Idaho and Savannah River.

## 14. REFERENCES


Weeren, H. O. 1984. *Sluicing Operations at Gunite Waste Storage Tanks*, ORNL/NFW-84/42, Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Keller, J. M., J. M. Giaquinto, and A. M. Meeks 1997. *Characterization of the BVEST Waste Tanks Located at ORNL*, ORNL/TM-13358, Oak Ridge Natl. Lab., Oak Ridge, Tenn.

# APPENDIX A

# ANALYSIS DATA FROM SLUDGE RETRIEVAL FROM TANK W-21

**Table A-1. Analysis of W-21 liquid sample following acid dissolution and mixing**

| Component | Units | Concentration |
|---|---|---|
| Total activity (LSC) | Bq/mL | 660,000 |
| Gross alpha | Bq/mL | 8,500 |
| Acid | N | 1.2 |
| Total suspended solids | mg/L | 8,070 |
| Total dissolved solids | mg/L | 286,000 |
| Ag | mg/L | 1.46 |
| Al | mg/L | 111 |
| Ba | mg/L | 30.6 |
| Ca | mg/L | 12,200 |
| Cd | mg/L | 1.34 |
| Cr | mg/L | 7.78 |
| Cu | mg/L | 2.2 |
| Fe | mg/L | 108 |
| K | mg/L | 11,900 |
| Mg | mg/L | 2,100 |
| Mn | mg/L | 31.4 |
| Na | mg/L | 43,400 |
| Ni | mg/L | 4.74 |
| Sr | mg/L | <0.36 |
| Th | mg/L | 156 |
| U | mg/L | 3,720 |
| V | mg/L | 3.6 |
| Zn | mg/L | 30.8 |

**Table A-2. Sample analysis results from Campaign 1**

| Parameter | units | 1997 Mixing Test | | | | | 1996 | 1996 | |
|---|---|---|---|---|---|---|---|---|---|
| | | W-21-B1 | W-21-M1 | W-21-T1 | avg. | %std | W-21 L | W-21 S | 96-S/avg |
| RMAL request number | | 8311 | 8311 | 8311 | | | 7772B | 7835A | |
| RMAL sample number | | -055 | -056 | -057 | | | -013 | -015 | |
| pH | na | 7.2 | 7.2 | 7.2 | 7.2 | 0.00% | 0.9 | 7.7 | |
| Density[a] | g/mL | 1.221 | 1.222 | 1.221 | 1.221 | 0.05% | 1.27 | 1.36 | |
| Total solids (TS) | mg/mL | 419 | 402 | 399 | 407 | 2.65% | 410 | 491 | |
| Suspended solids (TSS) | mg/mL | 26.0 | 27.9 | 25.4 | 26.4 | 4.94% | 0 | nd[b] | |
| Total activity (LSC) | Bq/mL | 880000 | 900000 | 890000 | 890000 | 1.12% | 610000 | 3100000 | 3.48 |
| Gross alpha | Bq/mL | 15000 | 15000 | 14000 | 14667 | 3.94% | 21000 | 150000 | 10.23 |
| $^{60}Co$ | Bq/mL | 10000 | 9900 | 10000 | 9967 | 0.58% | 7900 | 51000 | 5.12 |
| $^{90}Sr$[c] | Bq/mL | 120770 | 128165 | 117070 | 122002 | 4.63% | 87000 | 580000 | 4.75 |
| $^{134}Cs$ | Bq/mL | 8000 | 6700 | 7300 | 7333 | 8.87% | | | |
| $^{137}Cs$ | Bq/mL | 270000 | 270000 | 280000 | 273333 | 2.11% | 95000 | 160000 | 0.59 |
| $^{152}Eu$ | Bq/mL | 210000 | 210000 | 210000 | 210000 | 0.00% | 190000 | 930000 | 4.43 |
| $^{154}Eu$ | Bq/mL | 72000 | 73000 | 74000 | 73000 | 1.37% | 77000 | 330000 | 4.52 |
| $^{155}Eu$ | Bq/mL | 23000 | 25000 | 25000 | 24333 | 4.75% | 21000 | 90000 | 3.70 |
| $^{233/234}U$ | Bq/mL | | | | | | | | |
| $^{238}Pu$ | Bq/mL | | | | | | | | |
| $^{239/240}Pu$ | Bq/mL | | | | | | | | |
| $^{241}Am$ | Bq/mL | 3000 | 2100 | 2600 | 2567 | 17.57% | | | 0.00 |
| $^{244}Cm$ | Bq/mL | | | | | | | | |
| Al | mg/L | 219 | 214 | 208 | 214 | 2.58% | 299 | 1230 | 5.76 |
| Ba | mg/L | 32 | 31 | 32 | 32 | 1.58% | 60 | 82 | 2.59 |
| Ca | mg/L | 25600 | 25300 | 25900 | 25600 | 1.17% | 34500 | 68300 | 2.67 |
| Cr | mg/L | 36 | 36 | 37 | 36 | 1.39% | 57 | 229 | 6.34 |
| Cu | mg/L | 13 | 13 | 13 | 13 | 1.75% | 12 | 83 | 6.30 |
| Fe | mg/L | 487 | 487 | 487 | 487 | 0.00% | 532 | 2980 | 6.12 |
| K | mg/L | 8900 | 8700 | 8880 | 8827 | 1.25% | 6810 | 11500 | 1.30 |
| Mg | mg/L | 3230 | 3180 | 3300 | 3237 | 1.86% | 3560 | 11500 | 3.55 |
| Mn | mg/L | 50 | 51 | 52 | 51 | 2.85% | 32 | 173 | 3.40 |
| Na | mg/L | 54900 | 53800 | 55200 | 54633 | 1.35% | 52200 | 44000 | 0.81 |
| Ni | mg/L | 17 | 16 | 17 | 17 | 1.81% | 22 | 104 | 6.27 |
| Pb | mg/L | 40 | 39 | 40 | 40 | 1.52% | 43 | 394 | 9.97 |
| Sr | mg/L | 167 | 169 | 163 | 166 | 1.84% | 235 | 266 | 1.60 |
| Th | mg/L | 1910 | 1850 | 1780 | 1847 | 3.52% | 507 | 8650 | 4.68 |
| U | mg/L | 5520 | 5710 | 5650 | 5627 | 1.73% | 4030 | 26300 | 4.67 |
| $^{233}U$ | atom % | 0.0866 | 0.0884 | 0.0948 | 0.0899 | 4.79% | 0.128 | 0.093 | |
| $^{234}U$ | atom % | 0.0023 | 0.0001 | 0.0001 | 0.0008 | 152.42% | 0.003 | 0.002 | |
| $^{235}U$ | atom % | 0.2642 | 0.2582 | 0.26 | 0.2608 | 1.18% | 0.254 | 0.253 | |
| $^{236}U$ | atom % | 0.0057 | 0.0059 | 0.0008 | 0.0041 | 69.88% | 0.006 | 0.005 | |
| $^{238}U$ | atom % | 99.6412 | 99.6475 | 99.6444 | 99.6444 | 0.00% | 99.609 | 99.647 | |
| $^{238}U/^{233}U$ (>200) | | 837 | 828 | 770 | 812 | 4.48% | 575 | 793 | |
| $^{238}U/^{235}U$ (>110) | | 317 | 323 | 316 | 319 | 1.19% | 287 | 326 | |
| $^{238}U/^{235}U/35$ (>110) | | 265 | 268 | 261 | 265 | 1.33% | 237 | 267 | |

[a]Density measured at 31°C.
[b]nd: not determined.
[c]The activity for each W-21 slurry sample was estimated from the total activity.

## Table A-3. Sample analysis results from Campaign 2

| Parameter | units | 1997 Mixing Test | | | | | | 1996 | 1996 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | W-21-1 | W-21-2 | W-21-3 | W-21--4 | avg. | %std | W-21 L | W-21 S | 96-S/avg |
| RMAL request number | | 8357 | 8357 | 8357 | 8357 | | | 7772B | 7835A | |
| RMAL sample number | | -013 | -014 | -015 | -016 | | | -013 | -015 | |
| pH | na | 8.5 | 9.0 | 9.0 | 9.0 | 8.9 | 2.77% | 0.9 | 7.7 | |
| Density[a] | g/mL | 1.106 | 1.106 | 1.105 | 1.106 | 1.106 | 0.05% | 1.27 | 1.36 | |
| Total solids (TS) | mg/mL | 169 | 170 | 169 | 170 | 170 | 0.34% | 410 | 491 | |
| Suspended solids (TSS) | mg/mL | 51.0 | 48.5 | 50.4 | 45.2 | 48.8 | 5.35% | 0 | nd[b] | |
| Total activity (LSC) | Bq/mL | 1200000 | 1200000 | 1200000 | 1200000 | 1200000 | 0.00% | 610000 | 3100000 | 2.58 |
| Gross alpha | Bq/mL | 36000 | 32000 | 30000 | 33000 | 32750 | 7.63% | 21000 | 150000 | 4.58 |
| $^{60}$Co | Bq/mL | 9400 | 9000 | 9500 | 9600 | 9375 | 2.81% | 7900 | 51000 | 5.44 |
| $^{90}$Sr[c] | Bq/mL | 251660 | 254560 | 248490 | 249410 | 251030 | 1.08% | 87000 | 580000 | 2.31 |
| $^{134}$Cs | Bq/mL | 4100 | 4500 | 4700 | 4100 | 4350 | 6.90% | | | |
| $^{137}$Cs | Bq/mL | 320000 | 320000 | 320000 | 320000 | 320000 | 0.00% | 95000 | 160000 | 0.50 |
| $^{152}$Eu | Bq/mL | 200000 | 210000 | 210000 | 210000 | 207500 | 2.41% | 190000 | 930000 | 4.48 |
| $^{154}$Eu | Bq/mL | 64000 | 64000 | 66000 | 64000 | 64500 | 1.55% | 77000 | 330000 | 5.12 |
| $^{155}$Eu | Bq/mL | 22000 | 17000 | 23000 | 22000 | 21000 | 12.90% | 21000 | 90000 | 4.29 |
| $^{233/234}$U | Bq/mL | 2400 | 1500 | 1900 | 1900 | 1925 | 19.15% | 1800 | 8500 | 4.42 |
| $^{238}$Pu | Bq/mL | 2900 | 1500 | 500 | 1800 | 1675 | 58.98% | 99 | 15000 | 8.96 |
| $^{239/240}$Pu | Bq/mL | 2500 | 1800 | 1200 | 1400 | 1725 | 33.26% | 69 | 11000 | 6.38 |
| $^{241}$Am | Bq/mL | 2400 | 2900 | 2800 | 3300 | 2850 | 12.97% | 1500 | 12000 | 4.21 |
| $^{244}$Cm | Bq/mL | 26000 | 24000 | 24000 | 25000 | 24750 | 3.87% | 18000 | 100000 | 4.04 |
| Al | mg/L | 328 | 320 | 325 | 318 | 323 | 1.42% | 299 | 1230 | 3.81 |
| Ba | mg/L | 15 | 16 | 16 | 15 | 15 | 1.53% | 60 | 82 | 5.31 |
| Ca | mg/L | 11400 | 9120 | 11700 | 11100 | 10830 | 10.77% | 34500 | 68300 | 6.31 |
| Cr | mg/L | 60 | 60 | 61 | 60 | 60 | 0.96% | 57 | 229 | 3.82 |
| Cu | mg/L | 23 | 23 | 23 | 23 | 23 | 0.92% | 12 | 83 | 3.65 |
| Fe | mg/L | 359 | 358 | 363 | 355 | 359 | 0.92% | 532 | 2980 | 8.31 |
| K | mg/L | 5390 | 4380 | 5570 | 5330 | 5168 | 10.35% | 6810 | 11500 | 2.23 |
| Mg | mg/L | 3090 | 2510 | 3190 | 3040 | 2958 | 10.31% | 3560 | 11500 | 3.89 |
| Mn | mg/L | 66 | 67 | 67 | 66 | 67 | 1.05% | 32 | 173 | 2.59 |
| Na | mg/L | 28100 | 23000 | 28900 | 27700 | 26925 | 9.89% | 52200 | 44000 | 1.63 |
| Ni | mg/L | 16 | 16 | 16 | 16 | 16 | 1.06% | 22 | 104 | 6.47 |
| Pb | mg/L | 70 | 70 | 71 | 69 | 70 | 1.29% | 43 | 394 | 5.63 |
| Sr | mg/L | 47 | 48 | 49 | 47 | 48 | 1.64% | 235 | 266 | 5.60 |
| Th | mg/L | 2550 | 1930 | 2480 | 2460 | 2355 | 12.14% | 507 | 8650 | 3.67 |
| U | mg/L | 10900 | 8840 | 11400 | 11100 | 10560 | 11.03% | 4030 | 26300 | 2.49 |
| $^{233}$U | atom % | 0.0668 | 0.0759 | 0.0651 | 0.0692 | 0.0693 | 6.85% | 0.128 | 0.093 | |
| $^{234}$U | atom % | 0.0000 | 0.0027 | 0.0000 | 0.0015 | 0.0011 | 124.54% | 0.003 | 0.002 | |
| $^{235}$U | atom % | 0.2890 | 0.2971 | 0.2979 | 0.2872 | 0.2928 | 1.87% | 0.254 | 0.253 | |
| $^{236}$U | atom % | 0.0000 | 0.0000 | 0.0000 | 0.0016 | 0.0004 | 200.00% | 0.006 | 0.005 | |
| $^{238}$U | atom % | 99.6442 | 99.6243 | 99.6369 | 99.6405 | 99.6365 | 0.01% | 99.609 | 99.647 | |
| $^{238}$U/$^{233}$U (>200) | | 1043 | 907 | 1055 | 1010 | 1004 | 6.70% | 575 | 793 | |
| $^{238}$U/$^{235}$U (>110) | | 303 | 289 | 295 | 304 | 298 | 2.38% | 287 | 326 | |
| $^{238}$U/$^{235}$U$_f$35 (>110) | | 267 | 253 | 262 | 266 | 262 | 2.43% | 237 | 267 | |

[a]Density measured at 31°C.
[b]nd: not determined.
[c]The activity for each W-21 slurry sample was estimated from the total activity.

## Table A-4. Sample analysis results from Campaign 3, first sampling

| | | 1997 Mixing Test | | | | | | 1996 | 1996 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Parameter | units | W-21-1 | W-21-2 | W-21-3 | W-21--4 | avg. | %std | W-21 L | W-21 S | 96-S/avg |
| RMAL request number | | 8359 | 8359 | 8359 | 8359 | | | 7772B | 7835A | |
| RMAL sample number | | -029 | -030 | -031 | -032 | | | -013 | -015 | |
| pH | na | 8.6 | 8.6 | 8.5 | 8.6 | 8.6 | 0.44% | 0.9 | 7.7 | |
| Density[a] | g/mL | 1.259 | 1.264 | 1.263 | 1.265 | 1.263 | 0.21% | 1.27 | 1.36 | |
| Total solids (TS) | mg/mL | 429 | 429 | 430 | 428 | 429 | 0.19% | 410 | 491 | |
| Suspended solids (TSS) | mg/mL | 33.3 | 31.3 | 39.1 | 31.2 | 33.7 | 11.01% | 0 | nd | |
| Total activity (LSC) | Bq/mL | 1200000 | 1200000 | 1200000 | 1100000 | 1175000 | 4.26% | 610000 | 3100000 | 2.64 |
| Gross alpha | Bq/mL | 18000 | 19000 | 18000 | 18000 | 18250 | 2.74% | 21000 | 150000 | 8.22 |
| $^{60}$Co | Bq/mL | 7300 | 7500 | 7300 | 6800 | 7225 | 4.13% | 7900 | 51000 | 7.06 |
| $^{90}$Sr[c] | Bq/mL | 225680 | 224435 | 225495 | 176610 | 213055 | 11.41% | 87000 | 580000 | 2.72 |
| $^{134}$Cs | Bq/mL | 4800 | 4900 | 5300 | 4700 | 4925 | 5.34% | | | |
| $^{137}$Cs | Bq/mL | 490000 | 490000 | 490000 | 490000 | 490000 | 0.00% | 95000 | 160000 | 0.33 |
| $^{152}$Eu | Bq/mL | 110000 | 110000 | 110000 | 110000 | 110000 | 0.00% | 190000 | 930000 | 8.45 |
| $^{154}$Eu | Bq/mL | 34000 | 35000 | 33000 | 34000 | 34000 | 2.40% | 77000 | 330000 | 9.71 |
| $^{155}$Eu | Bq/mL | 13000 | 13000 | 14000 | 12000 | 13000 | 6.28% | 21000 | 90000 | 6.92 |
| $^{233/234}$U | Bq/mL | 1100 | 1400 | 1300 | 1100 | 1225 | 12.24% | 1800 | 8500 | 6.94 |
| $^{238}$Pu | Bq/mL | 1400 | 2000 | 2300 | 2200 | 1975 | 20.41% | 99 | 15000 | 7.59 |
| $^{239/240}$Pu | Bq/mL | 2000 | 2200 | 2000 | 2100 | 2075 | 4.61% | 69 | 11000 | 5.30 |
| $^{241}$Am | Bq/mL | 2900 | 2600 | 1600 | 2000 | 2275 | 25.72% | 1500 | 12000 | 5.27 |
| $^{244}$Cm | Bq/mL | 11000 | 11000 | 11000 | 11000 | 11000 | 0.00% | 18000 | 100000 | 9.09 |
| Al | mg/L | 240 | 188 | 218 | 189 | 209 | 12.00% | 299 | 1230 | 5.89 |
| Ba | mg/L | 10 | 12 | 12 | 12 | 11 | 10.29% | 60 | 82 | 7.24 |
| Ca | mg/L | 9520 | 11500 | 13500 | 11800 | 11580 | 14.09% | 34500 | 68300 | 5.90 |
| Cr | mg/L | 32 | 22 | 21 | 21 | 24 | 21.40% | 57 | 229 | 9.60 |
| Cu | mg/L | 11 | 6 | 6 | 6 | 7 | 33.46% | 12 | 83 | 11.13 |
| Fe | mg/L | 270 | 329 | 383 | 331 | 328 | 14.07% | 532 | 2980 | 9.08 |
| K | mg/L | 22000 | 23600 | 28200 | 24900 | 24675 | 10.67% | 6810 | 11500 | 0.47 |
| Mg | mg/L | 2960 | 3470 | 4080 | 3590 | 3525 | 13.05% | 3560 | 11500 | 3.26 |
| Mn | mg/L | 45 | 38 | 38 | 38 | 39 | 8.68% | 32 | 173 | 4.38 |
| Na | mg/L | 79500 | 89800 | 106000 | 94000 | 92325 | 11.88% | 52200 | 44000 | 0.48 |
| Ni | mg/L | 8 | 10 | 10 | 10 | 9 | 12.63% | 22 | 104 | 11.24 |
| Pb | mg/L | 72 | 76 | 75 | 75 | 75 | 2.36% | 43 | 394 | 5.28 |
| Sr | mg/L | 61 | 60 | 60 | 62 | 61 | 1.65% | 235 | 266 | 4.38 |
| Th | mg/L | 2200 | 1090 | 1530 | 1430 | 1563 | 29.75% | 507 | 8650 | 5.54 |
| U | mg/L | 4780 | 5800 | 7850 | 7050 | 6370 | 21.27% | 4030 | 26300 | 4.13 |
| $^{233}$U | atom % | 0.0658 | 0.0687 | 0.0663 | 0.0657 | 0.0666 | 2.11% | 0.128 | 0.093 | |
| $^{234}$U | atom % | 0.0023 | 0.0027 | 0.0029 | 0.0021 | 0.0025 | 14.61% | 0.003 | 0.002 | |
| $^{235}$U | atom % | 0.2693 | 0.2673 | 0.2673 | 0.2707 | 0.2687 | 0.62% | 0.254 | 0.253 | |
| $^{236}$U | atom % | 0.0058 | 0.0064 | 0.0056 | 0.0061 | 0.0060 | 5.86% | 0.006 | 0.005 | |
| $^{238}$U | atom % | 99.6567 | 99.655 | 99.6579 | 99.6554 | 99.6563 | 0.00% | 99.609 | 99.647 | |
| $^{238}$U/$^{233}$U (>200) | | 1092 | 1051 | 1088 | 1093 | 1081 | 1.86% | 575 | 793 | |
| $^{238}$U/$^{235}$U (>110) | | 326 | 327 | 328 | 325 | 327 | 0.40% | 287 | 326 | |
| $^{238}$U/$^{235}$U$_f$35 (>110) | | 282 | 281 | 283 | 281 | 282 | 0.34% | 237 | 267 | |

[a]Density measured at 31°C.
[b]nd: not determined.
[c]The activity for each W-21 slurry sample was estimated from the total activity.

## Table A-5. Sample analysis results from Campaign 3, second sampling

| Parameter | units | 1997 Mixing Test W-21-1 | W-21-2 | W-21-3 | W-21--4 | avg. | %std | 1996 W-21 L | 1996 W-21 S | 96-S/avg |
|---|---|---|---|---|---|---|---|---|---|---|
| RMAL request number | | 8366 | 8366 | 8366 | 8366 | | | 7772B | 7835A | |
| RMAL sample number | | -029 | -030 | -031 | -032 | | | -013 | -015 | |
| pH | na | 8.6 | 8.7 | 8.6 | 8.6 | 8.6 | 0.58% | 0.9 | 7.7 | |
| Density[a] | g/mL | 1.272 | 1.268 | 1.274 | 1.272 | 1.272 | 0.20% | 1.27 | 1.36 | |
| Total solids (TS) | mg/mL | 430 | 432 | 431 | 431 | 431 | 0.19% | 410 | 491 | |
| Suspended solids (TSS) | mg/mL | 33.8 | 30.4 | 31.0 | 31.6 | 31.7 | 4.68% | 0 | nd[b] | |
| Total activity (LSC) | Bq/mL | 1100000 | 1100000 | 1100000 | 1100000 | 1100000 | 0.00% | 610000 | 3100000 | 2.82 |
| Gross alpha | Bq/mL | 15000 | 15000 | 15000 | 14000 | 14750 | 3.39% | 21000 | 150000 | 10.17 |
| $^{60}$Co | Bq/mL | 7700 | 7300 | 6900 | 6800 | 7175 | 5.73% | 7900 | 51000 | 7.11 |
| $^{90}$Sr[c] | Bq/mL | 170585 | 172260 | 184705 | 185205 | 178189 | 4.40% | 87000 | 580000 | 3.25 |
| $^{134}$Cs | Bq/mL | 5200 | 4700 | 4600 | 4600 | 4775 | 6.02% | | | |
| $^{137}$Cs | Bq/mL | 500000 | 500000 | 480000 | 480000 | 490000 | 2.36% | 95000 | 160000 | 0.33 |
| $^{152}$Eu | Bq/mL | 110000 | 110000 | 110000 | 110000 | 110000 | 0.00% | 190000 | 930000 | 8.45 |
| $^{154}$Eu | Bq/mL | 35000 | 34000 | 33000 | 33000 | 33750 | 2.84% | 77000 | 330000 | 9.78 |
| $^{155}$Eu | Bq/mL | 13000 | 12000 | 12000 | 12000 | 12250 | 4.08% | 21000 | 90000 | 7.35 |
| $^{233/234}$U | Bq/mL | 1000 | 960 | 1100 | 970 | 1008 | 6.35% | 1800 | 8500 | 8.44 |
| $^{238}$Pu | Bq/mL | 400 | 1400 | 1000 | 500 | 825 | 56.31% | 99 | 15000 | 18.18 |
| $^{239/240}$Pu | Bq/mL | 1700 | 1800 | 1700 | 1700 | 1725 | 2.90% | 69 | 11000 | 6.38 |
| $^{241}$Am | Bq/mL | 3200 | 2100 | < 2600 | 3000 | 2767 | 21.18% | 1500 | 12000 | 4.34 |
| $^{244}$Cm | Bq/mL | 8700 | 8700 | 8600 | 7900 | 8475 | 4.56% | 18000 | 100000 | 11.80 |
| Al | mg/L | 111 | 102 | 98 | 96 | 102 | 6.58% | 299 | 1230 | 12.10 |
| Ba | mg/L | 11 | 11 | 11 | 11 | 11 | 1.99% | 60 | 82 | 7.39 |
| Ca | mg/L | 10900 | 10400 | 9850 | 9980 | 10283 | 4.61% | 34500 | 68300 | 6.64 |
| Cr | mg/L | 22 | 21 | 21 | 21 | 21 | 2.44% | 57 | 229 | 10.92 |
| Cu | mg/L | 8 | 7 | 7 | 7 | 7 | 4.10% | 12 | 83 | 11.22 |
| Fe | mg/L | 324 | 300 | 288 | 290 | 301 | 5.50% | 532 | 2980 | 9.92 |
| K | mg/L | 22900 | 21600 | 20600 | 20800 | 21475 | 4.86% | 6810 | 11500 | 0.54 |
| Mg | mg/L | 3250 | 3060 | 2920 | 2950 | 3045 | 4.90% | 3560 | 11500 | 3.78 |
| Mn | mg/L | 38 | 37 | 37 | 36 | 37 | 2.03% | 32 | 173 | 4.70 |
| Na | mg/L | 81000 | 76900 | 73200 | 74100 | 76300 | 4.60% | 52200 | 44000 | 0.58 |
| Ni | mg/L | 15 | 15 | 15 | 15 | 15 | 1.50% | 22 | 104 | 7.02 |
| Pb | mg/L | 82 | 80 | 79 | 77 | 80 | 2.45% | 43 | 394 | 4.95 |
| Sr | mg/L | 70 | 65 | 63 | 63 | 65 | 4.74% | 235 | 266 | 4.09 |
| Th | mg/L | 1820 | 1830 | 1750 | 1780 | 1795 | 2.06% | 507 | 8650 | 4.82 |
| U | mg/L | 6840 | 6260 | 5820 | 5790 | 6178 | 7.95% | 4030 | 26300 | 4.26 |
| $^{233}$U | atom % | 0.0666 | 0.0640 | 0.0661 | 0.0643 | 0.0653 | 1.98% | 0.128 | 0.093 | |
| $^{234}$U | atom % | 0.0025 | 0.0021 | 0.0021 | 0.0035 | 0.0026 | 25.91% | 0.003 | 0.002 | |
| $^{235}$U | atom % | 0.2702 | 0.2640 | 0.2667 | 0.2676 | 0.2671 | 0.96% | 0.254 | 0.253 | |
| $^{236}$U | atom % | 0.0056 | 0.0051 | 0.0046 | 0.0058 | 0.0053 | 10.19% | 0.006 | 0.005 | |
| $^{238}$U | atom % | 99.6551 | 99.6648 | 99.6605 | 99.6589 | 99.6598 | 0.00% | 99.609 | 99.647 | |
| $^{238/233}$U (>200) | | 1078 | 1134 | 1093 | 1121 | 1107 | 2.31% | 575 | 793 | |
| $^{238/235}$U (>110) | | 325 | 334 | 329 | 330 | 330 | 1.12% | 287 | 326 | |
| $^{238/235}$U $f35$ (>110) | | 281 | 289 | 284 | 285 | 285 | 1.16% | 237 | 267 | |

[a]Density measured at 31°C
[b]nd: not determined.
[c]The activity for each W-21 slurry sample was estimated from the total activity.

**Table A-6. Sample analysis results from Campaign 6**

| Parameter | units | 1997 Mixing Test W-21-1 | 1996 W-21 L | 1996 W-21 S |
|---|---|---|---|---|
| RMAL request number | | 8456 | 7772B | 7835A |
| RMAL sample number | | -17 | -013 | -015 |
| pH | na | 8.6 | 0.9 | 7.7 |
| Density[a] | g/mL | 1.26 | 1.27 | 1.36 |
| Total solids (TS) | mg/mL | 414 | 410 | 491 |
| Suspended solids (TSS) | mg/mL | 3.0 | 0 | nd[b] |

[a]Density measured at 31°C.
[b]nd: not determined.

**Table A-7. Component ratios for mixed sludge samples and 1996 core sample**

| Component Ratios[a] | Campaign 1 Samples | Campaign 2 Samples | Campaign 3 Samples set 1 | Campaign 3 Samples set 2 | Avg | '96 Core Sample | %Variation |
|---|---|---|---|---|---|---|---|
| Ca/U | 4.55 | 1.03 | 1.82 | 1.66 | 2.26 | 2.60 | -12.80 |
| Ca/Fe | 52.57 | 30.19 | 35.28 | 34.22 | 38.06 | 22.92 | 66.07 |
| Ca/Mg | 7.91 | 3.66 | 3.29 | 3.38 | 4.56 | 5.94 | -23.25 |
| Ca/Gr Alpha | 1.75 | 0.33 | 0.63 | 0.70 | 0.85 | 0.46 | 87.10 |
| Ca/Th | 13.86 | 4.60 | 7.41 | 5.73 | 7.90 | 7.90 | 0.05 |
| U/$^{238}$Pu | | 6.30 | 3.23 | 7.49 | 4.25 | 1.75 | 142.65 |
| U/Gr Alpha | 0.38 | 0.32 | 0.35 | 0.42 | 0.37 | 0.18 | 110.16 |
| U/Th | 3.05 | 4.48 | 4.08 | 3.44 | 3.76 | 3.04 | 23.74 |
| U/Ca | 0.22 | 0.98 | 0.55 | 0.60 | 0.59 | 0.39 | 52.29 |
| U/Fe | 11.55 | 29.44 | 19.41 | 20.56 | 20.24 | 8.83 | 129.31 |
| Gr Alpha/Ca | 0.57 | 3.02 | 1.58 | 1.43 | 1.65 | 2.20 | -24.79 |
| Gr Alpha/Mg | 4.53 | 11.07 | 5.18 | 4.84 | 6.41 | 13.04 | -50.88 |
| Gr Alpha/U | 2.61 | 3.10 | 2.86 | 2.39 | 2.74 | 5.70 | -51.96 |
| Gr Alpha/Th | 7.94 | 13.91 | 11.68 | 8.22 | 10.44 | 17.34 | -39.82 |
| Gr Alpha/$^{238}$Pu | | 19.55 | 9.24 | 17.88 | 11.67 | 10.00 | 16.68 |
| Th/Ca | 0.07 | 0.22 | 0.13 | 0.17 | 0.15 | 0.13 | 18.26 |
| Th/Mg | 0.57 | 0.80 | 0.44 | 0.59 | 0.60 | 0.75 | -20.25 |
| Th/U | 0.33 | 0.22 | 0.25 | 0.29 | 0.27 | 0.33 | -17.37 |
| Th/Gr Alpha | 0.13 | 0.07 | 0.09 | 0.12 | 0.10 | 0.06 | 75.63 |
| Th/$^{238}$Pu | | 1.41 | 0.79 | 2.18 | 1.09 | 0.58 | 89.58 |
| Mg/Ca | 0.13 | 0.27 | 0.30 | 0.30 | 0.25 | 0.17 | 48.49 |
| Mg/U | 0.58 | 0.28 | 0.55 | 0.49 | 0.48 | 0.44 | 8.72 |
| Mg/Th | 1.75 | 1.26 | 2.26 | 1.70 | 1.74 | 1.33 | 30.90 |
| Mg/Gr A | 0.22 | 0.09 | 0.19 | 0.21 | 0.18 | 0.08 | 131.71 |
| Mg/Fe | 6.65 | 8.24 | 10.74 | 10.13 | 8.94 | 3.86 | 131.68 |
| $^{90}$Sr/Gr A | 8.32 | 7.67 | 11.67 | 12.08 | 9.93 | 3.87 | 156.93 |
| $^{90}$Sr/Ca | 4.77 | 23.18 | 18.40 | 17.33 | 15.92 | 8.49 | 87.45 |
| $^{90}$Sr/Mg | 37.69 | 84.88 | 60.44 | 58.52 | 60.38 | 50.43 | 19.73 |
| $^{90}$Sr/U | 21.68 | 23.77 | 33.45 | 28.84 | 26.94 | 22.05 | 22.14 |
| $^{90}$Sr/Th | 66.07 | 106.59 | 136.36 | 99.27 | 102. | 67.05 | 52.23 |

[a]Where radiological and nonradiological components are used for the ratios, the ratios were calculated using mixed units (i.e., Bq/L divided by mg/L).

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