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Demonstration of Fluidic Pulse Jet Mixing for a Horizontal Waste Storage Tank

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MASTER

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DEMONSTRATION OF FLUIDIC PULSE JET MIXING FOR A HORIZONTAL WASTE STORAGE TANK

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DEMONSTRATION OF FLUIDIC PULSE JET MIXING FOR A HORIZONTAL WASTE STORAGE TANK

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ABSTRACT

A fluidic pulse jet mixing system, designed and fabricated by AEA Technology of the United Kingdom, was successfully demonstrated for mobilization and retrieval of remote-handled transuranic (RH-TRU) sludge from a 50,000-gal horizontal waste storage tank at Oak Ridge National Laboratory (ORNL). The pulse jet system, consisting of seven modular equipment skids, was installed and commissioned in about 7 weeks and operated remotely for 52 days to remove about 88% of the sludge in the tank. The system used specially designed fluidic jet pumps and pulse 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 mixture. A total of 64,000 gal of liquid was required to transfer 6300 gal of sludge to the Melton Valley Storage Tanks (MVSTs) designated for consolidation of all ORNL RH-TRU sludges. Of the liquid used for the retrieval, 88% was existing or recycled tank supernate and only 7770 gal of additional process water was added to the system. Minimizing the addition of process water 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 campaigns, the manual sluicer was modified to provide a higher flow rate for removal of additional quantities of the remaining sludge heel. Six thousand gallons of process water was required to remove an additional 550 gal of sludge. After the manual sluicer 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 acid was mixed with the pulse jet system for several hours and 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 gallons of sludge remained in the tank after this operation.

The pulse jet system operated well during the demonstration and experienced no major equipment malfunctions. The modular design, use of quick-connect couplings, and low-maintenance aspects of the system allowed for maintaining radiation exposure well below expectations during installation and operations. The extent of sludge removal from tank W-21 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 more aggressive use of the manual sluicer (and associated water additions), or a more costly and elaborate robotic retrieval system. The results of this demonstration 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.

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. The 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 waste removal and processing the waste to stabilize the radioactive and hazardous components for long-term disposal. The heavy layer of sludge in these tanks must be mobilized in some way to remove it from the tanks. A preferred method involves mixing the sludge with existing tank liquids, rather than adding more liquids and 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 of the United Kingdom has developed pulse jet mixing system for tank waste that involves the use of fluidic pumps that have no moving parts and require very little maintenance. For the ORNL horizontal tanks, a single mixing system can be used for several tanks, and the system requires very little modification of the tank system. This type of system has been used in nuclear applications in the United Kingdom for many years. These advantages led to the decision to demonstrate AEA Technology'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 in the past for sludge mobilization and retrieval from horizontal storage tanks. These alternatives were limited by cost, maintenance requirements, extensive system modifications, and water usage.

Mixing the sludges with existing liquids in large storage tanks can be a challenge. At the Savannah River Site in South Carolina and 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 for the horizontal tanks.

Single-point sluicing was used at ORNL to mobilize and transfer sludges out of the vertical gunite tanks in the early 1980's.[1] 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 sludge 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 and 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 fluid. 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. The fluid in the tube falls back into the tank and imparts the mixing action.

The 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 vertically 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 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 to a "charge vessel" in place of the normally used pulse tube. The 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 sludge mixture reaches a predetermined level in the charge vessel, the vacuum pump is turned off. Air pressure is applied to the charge vessel to force the fluid back into the tank for mixing. 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 BVESTs 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, Building 2531, to reduce the volume for long-term storage. There are five BVESTs — numbered W-21, W-22, W-23, C-1, and C-2. In routine operations, W-22 serves as the feed tank for the evaporator system, while the other tanks store the LLLW concentrate. Tanks W-21 and W-23 may also serve as alternate feed tanks for the evaporator if W-22 is filled to capacity or out of service. Each tank has a capacity to hold 47,500 gal of liquid.

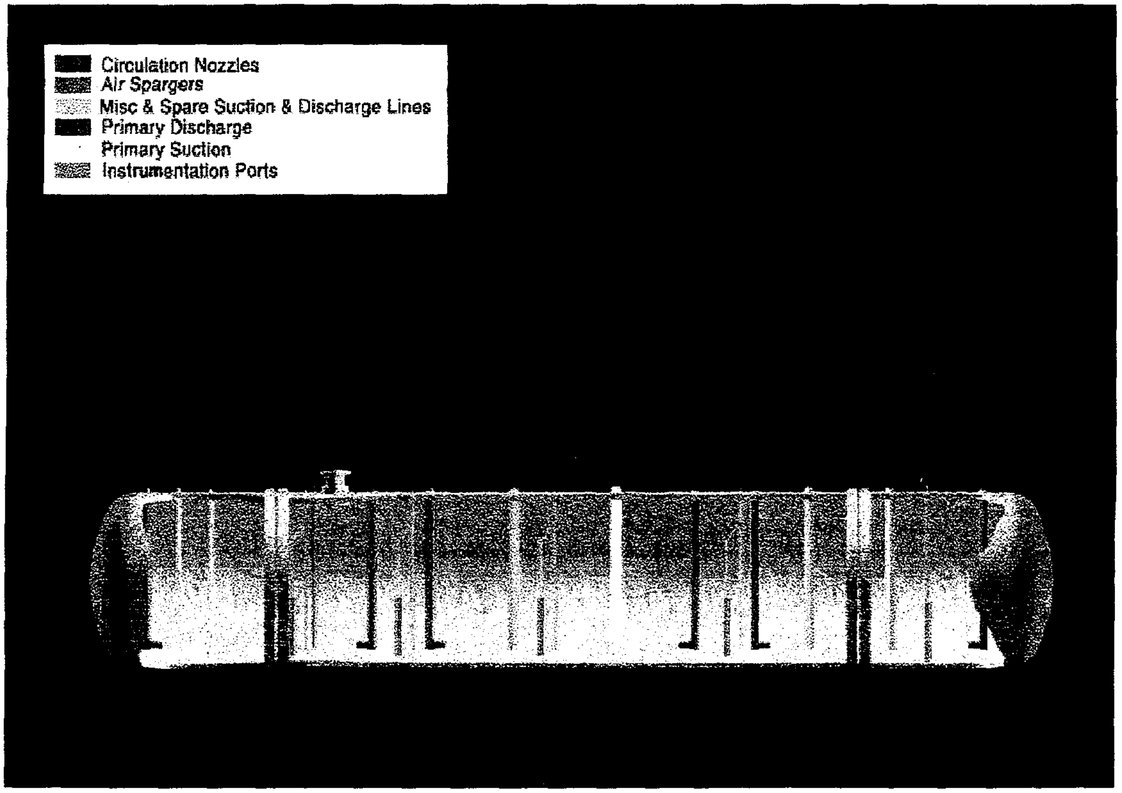
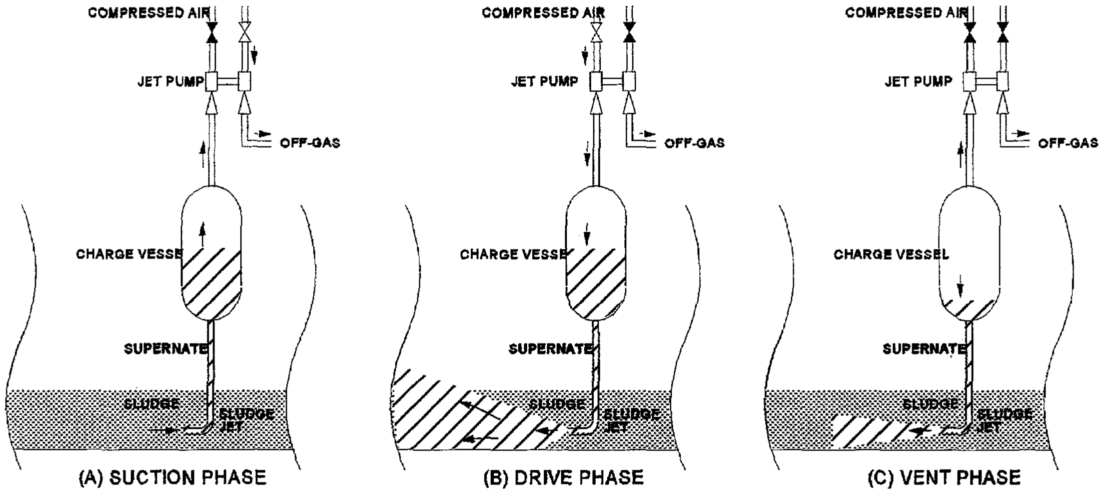


Fig. 1. Typical 50,000-gal horizontal waste storage tank at Oak Ridge.



(A) SUCTION PHASE (B) DRIVE PHASE (C) VENT PHASE

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. 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. The W-23 tank is located in a separate vault, west of W-21 and W-22.

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 the PVV. The vault floors and the walls are lined with 16-gauge stainless steel to a height of approximately 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 61ft, 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 BVESTs are connected by transfer pipelines to the Melton Valley Storage Tanks (MVSTs) located approximately 1 mile away. Liquid may be transferred from the BVEST to the MVST by using two progressive cavity (Moyno) pumps located in the PVV, situated between the tank vaults. The pumps are mounted longitudinally in the PVV approximately 2 ft, 4 in. apart. The PVV piping connects the W-21, W-22, and W-23 piping to these pumps. The pumps are designed to pump fluids to the MVST through a nominal 2-in. double-contained pipeline. The working pressure for the pipeline is 300 psi, and the pumps routinely operate at 240 psig at a flow of 60 gal/min. The equivalent length of the pipeline (actual length plus equivalent lengths to account for bends, valves, and other fittings) is about 7100 ft.

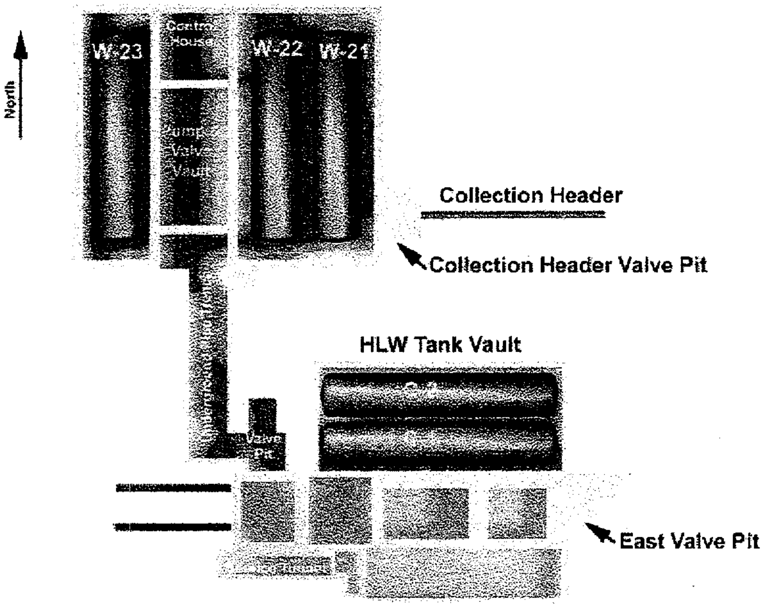


Fig. 3. Layout of Bethel Valley Evaporator Service Tanks at ORNL.

The 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 2-ft-deep concrete slabs with access 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 of the 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. The PVV is ventilated through an existing centralized off-gas system.

The six existing tank nozzles for all three tanks are connected by 3-in.-diam stainless steel pipelines back to a common mount point in the adjoining PVV. At the PVV, the pipe work ends in a series of blind four-bolt hole flanges.

5. BVEST W-21 SLUDGE CHARACTERISTICS

Tank W-21 is used to store concentrated LLLW generated at ORNL. The liquids and solids have separated and formed distinct layers in the tank. Based on level measurements, the volume of sludge was initially estimated to be 6700 gal. Table 1 provides sludge characterization information from sampling activities that took place in 1996.[2] The primary components of the sludge are metal nitrates, carbonates, and hydroxides. The pH of the supernate liquid is 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 sludge is 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 (RCRA). 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 (TRU) due to the plutonium and americium content, and it is considered remote handled (RH) due to the high gamma activity.

Table 1. BVEST W-21 waste characteristics

Parameter	1996 W-21 liquid	1996 W-21 sludge
pH	0.9 na	7.7 na
Density	1.27 g/mL	1.36 g/mL
Total solids (TS)	410 mg/mL	491 mg/g
Total suspended solids (TSS)	<1 mg/mL	nd mg/Kg
Total Organic Carbon (TOC)	533 mg/L	17,600 mg/Kg
Total activity (LSC)	610000 Bq/mL	3100000 Bq/g
Gross alpha	21000 Bq/mL	150000 Bq/g
^{244}Cm	18000 Bq/mL	100000 Bq/g
^{241}Am	1500 Bq/mL	12000 Bq/g
^{238}Pu	100 Bq/mL	15000 Bq/g
^{239}Pu	39 Bq/mL	6400 Bq/g
^{240}Pu	40 Bq/mL	4800 Bq/g
^{241}Pu	590 Bq/mL	100000 Bq/g
^{242}Pu	<0.1 Bq/mL	4.6 Bq/g
^{233}U	1800 Bq/mL	8500 Bq/g
^{234}U	27 Bq/mL	120 Bq/g
^{238}U	50 Bq/mL	330 Bq/g
^{60}Co	7900 Bq/mL	51000 Bq/g
^{90}Sr	87000 Bq/mL	580000 Bq/g
^{137}Cs	95000 Bq/mL	160000 Bq/g
^{152}Eu	190000 Bq/mL	930000 Bq/g
^{154}Eu	77000 Bq/mL	330000 Bq/g
^{155}Eu	21000 Bq/mL	90000 Bq/g
	Anions	
Bromide	109 mg/L	97 mg/Kg
Chloride	1170 mg/L	1370 mg/Kg
Fluoride	236 mg/L	23 mg/Kg
Nitrate	204000 mg/L	158000 mg/Kg
Nitrate	3.3 moles/L	mg/Kg
Sulfate	1400 mg/L	6030 mg/Kg
	Cations	
Al	299 mg/L	1230 mg/Kg
Ba	60 mg/L	82 mg/Kg
Ca	34500 mg/L	68300 mg/Kg
Cd	7.8 mg/L	38 mg/Kg
Cr	57 mg/L	229 mg/Kg
Cu	12 mg/L	83 mg/Kg
Fe	532 mg/L	2980 mg/Kg
Hg	1.3 mg/L	24 mg/Kg
K	6810 mg/L	11500 mg/Kg
Mg	3560 mg/L	11500 mg/Kg
Mn	32 mg/L	173 mg/Kg
Na	52200 mg/L	44000 mg/Kg
Ni	22 mg/L	104 mg/Kg
Pb	43 mg/L	394 mg/Kg
Sr	235 mg/L	266 mg/Kg
Th	507 mg/L	8650 mg/Kg
U	4030 mg/L	26300 mg/Kg

The rheological properties of the sludge were also evaluated.[2] Shear strength and viscosity data were collected for the sludge using a HAAKE Rotovisco RV30 Searle-type rotational controlled-rate rheometer. Every effort was made to minimize any disturbance to core samples obtained for the tests; however, removal of samples from containers and introduction of air complicated the effort. Shear strength information was obtained for core samples of the sludge taken at upper and lower depths of the sludge. A shear rate of 0.016 s^{-1} was applied to the sludge for periods ranging from 4 to 16 min. The maximum shear strength observed for the samples typically ranged between 4 and 8.5 Pa near the beginning of the test. After the first few minutes, the shear strength declined to a range of 0.5 to 5.0 Pa. Viscosity tests were performed using a W-21 sludge sample diluted 1:1 with tank supernate liquid, giving a slurry of 37.6% total solids and 13.5% undissolved solids. The HAAKE immersion sensor system was used for the tests. A hollow immersion tube with an inner diameter of 42 mm was used along with a modified cylindrical rotor with a diameter of 36.8 mm. The shear stress and viscosity were measured over a shear rate range of 0.0 to 450 s^{-1}. The viscosity data for the W-21 sample were very erratic and difficult to interpret. Shear stress versus shear rate data were also slightly erratic but showed a steadily increasing shear stress as shear rate was increased. These data were used to calculate an average viscosity of about 18 mPa/s.

6. COLD PILOT TEST EVALUATION

To evaluate the effectiveness of the conceptualized BVEST pulse jet system, pilot testing was performed by AEA Technology 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. 4) with the same diameter (12 ft) and one-third the length (20 ft) of the BVEST. Photographs of the charge

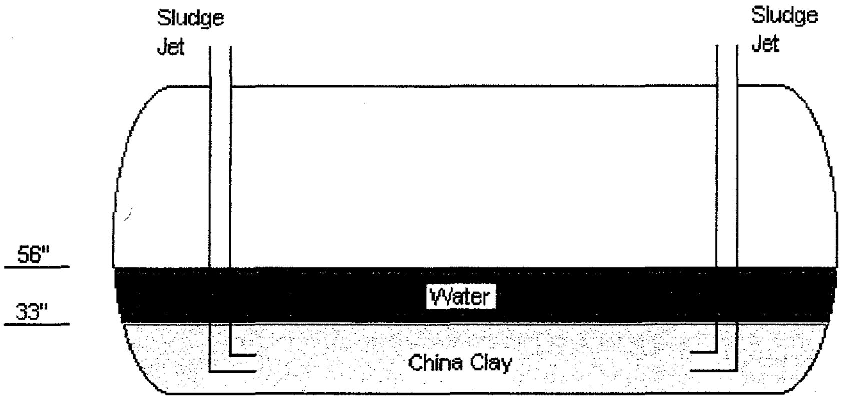


Fig. 4. Pilot tank for pulse jet system testing.

vessels and tank used for the testing are shown in Figs. 5 and 6, respectively. The tank contained two opposing jet nozzles configured the same as those in the BVESTs (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 the 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 the 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 the BVEST. The solids content and specific gravity of settled china clay are 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 of 19.5 wt % W-22 sludge correspond to those for a 22 to 30 wt % china clay slurry (maximum of 16-Pa shear strength and maximum of 40-mPa/s viscosity).[1] The specifications for the china clay are given in Table 2. 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.

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 3. The "drive time" (duration during which the charge vessel was pressurized with air) could not be set at 15 s initially because overblow of air

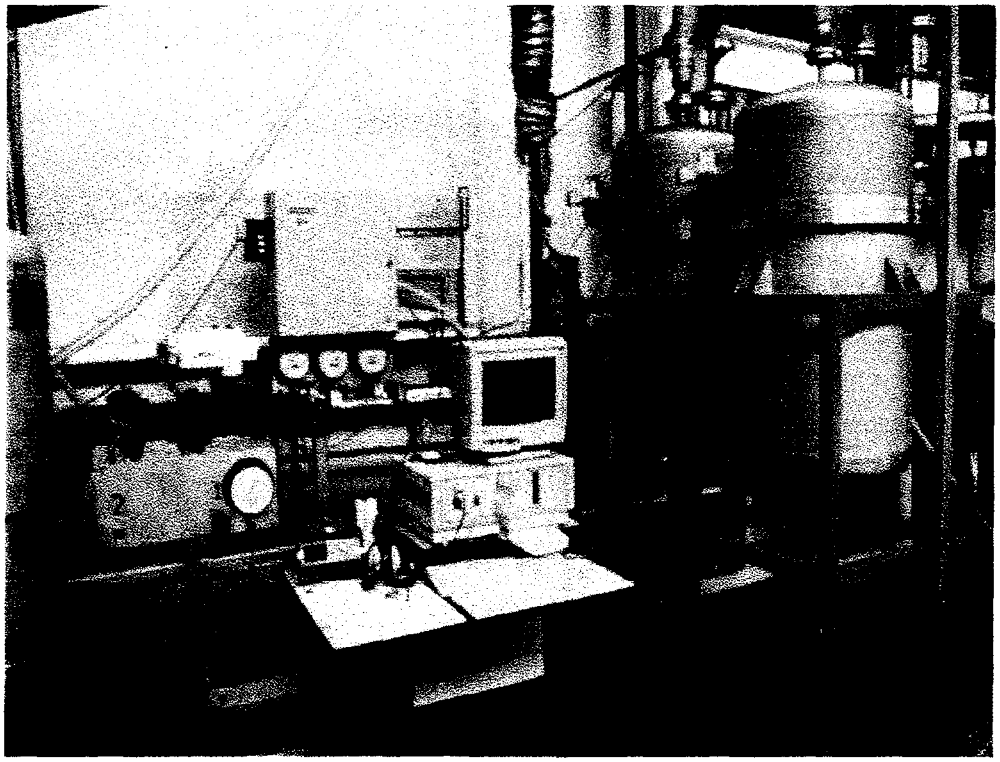


Fig. 5. Pilot test system charge vessels and controls.

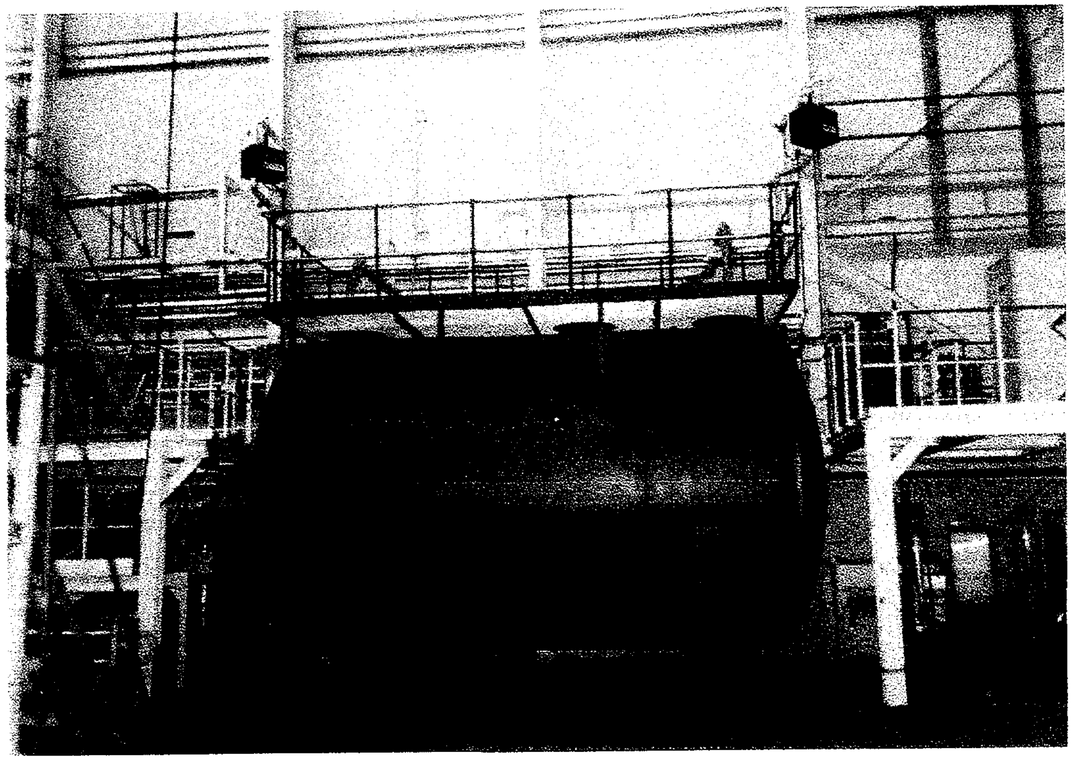


Fig. 6. Pilot test tank, one-third scale BVEST.

Table 2. Specifications and properties for Grade E china clay produced by ECC International

Brightness, ISO	77.0 ± 1.0
+300 mesh, % max.	0.05
+10 μm, % max.	35
−2 μm, % 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 3. 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

into the tank would occur. Overblow is 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 7 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 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 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.

Figure 8 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.

6.2 MASS BALANCE ON CLAY

$$\text{Clay}_{\text{init}} = (\text{Y} \times \text{wt }\%_{\text{remaining}}) + (\text{Total}_{\text{init}} - \text{Y}) \times \text{wt }\%_{\text{mixed}}$$

where

$\text{wt }\%_{\text{remaining}}$ = wt % solids in unmixed sludge,

$\text{wt }\%_{\text{mixed}}$ = wt % solids in mixed slurry,

$\text{Total}_{\text{init}}$ = total mass of water and clay at start of trial,

$\text{Clay}_{\text{init}}$ = mass of clay at start of trial,

Y = mass of sludge remaining.

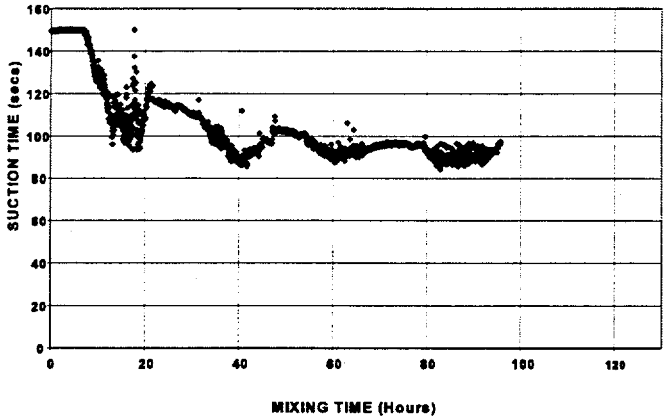


Fig. 7. Suction time versus mixing time for Test 1.

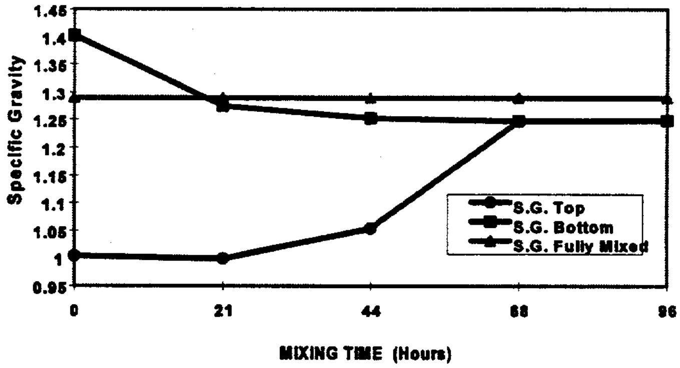


Fig. 8. Specific gravity versus mixing time.

$10{,}800 = (Y \times 0.53) + (28{,}800 - Y) \times 0.34.$

$Y = 5305$ 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.

Additional tests were performed where sludge conditions and system operating parameters were varied to determine favorable operating conditions for the W-21 mixing demonstration.

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. The data collected from this testing were used to set the initial operating conditions for the BVEST W-21 demonstration. AEA Technology is preparing a more detailed summary of the cold pilot testing, which will be published at a later date.

7. DESCRIPTION OF BVEST PULSE JET DEMONSTRATION SYSTEM

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 equally spaced jet nozzles, oriented to form three sets of opposing nozzles.

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 the control cubicle. The charge vessel skids were installed within the PVV. Other skids were located on or near the BVEST vault cover. 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 304L 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 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. 9.

Each charge vessel is a registered 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 system was designed to prevent the charge

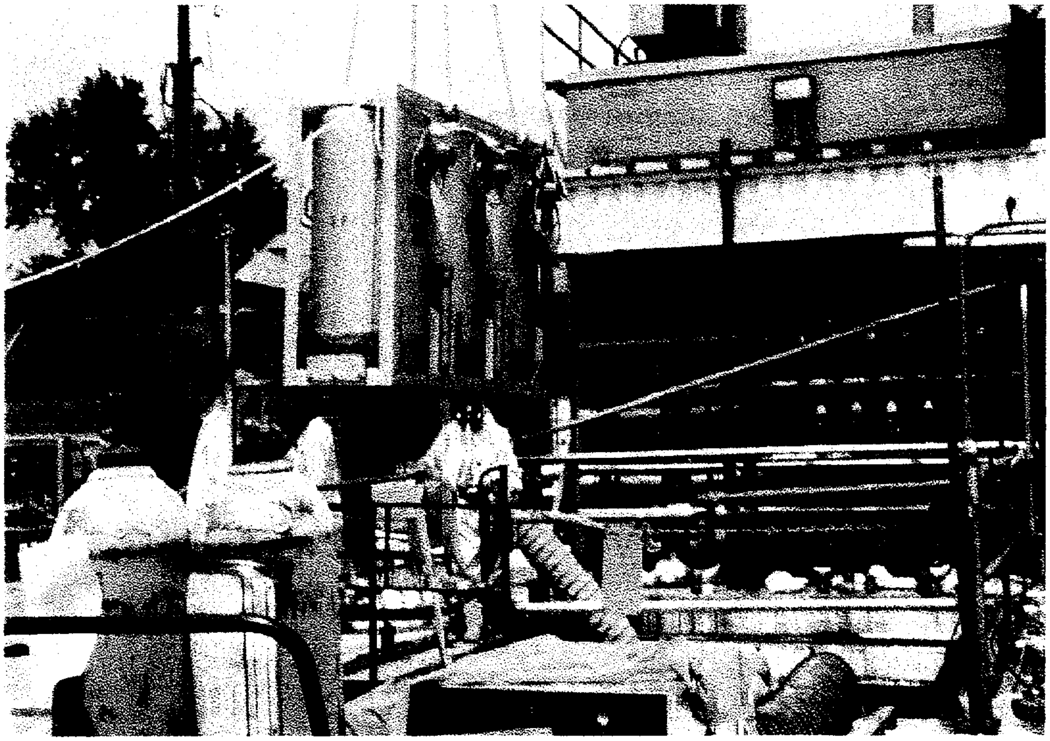


Fig. 9. Charge vessels being installed at the BVEST.

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 10 shows a photo of the jet pump skid being installed at the 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 11 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.

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

1. a demister to remove any liquid mists that may enter the charge vessel head space during filling;
2. a heater to increase the temperature of the off-gas to prevent condensation of water vapor, which could plug the air filters;

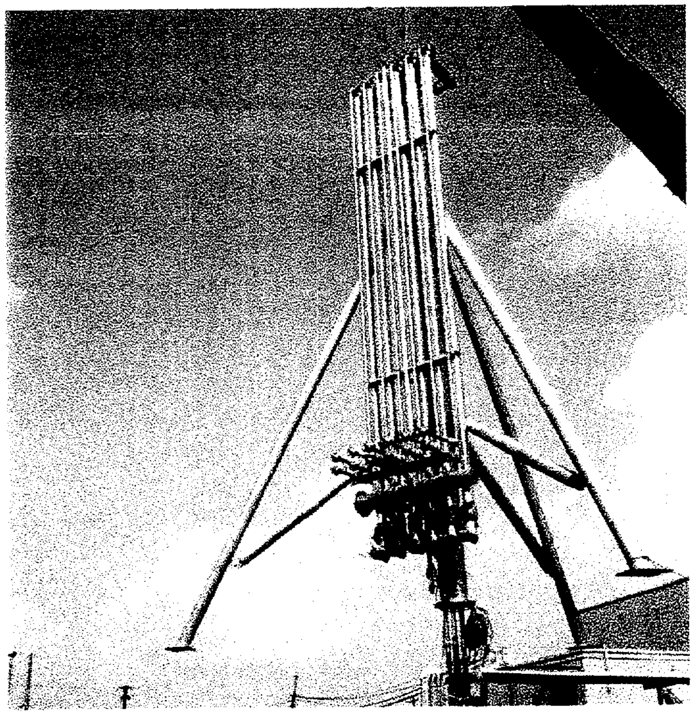
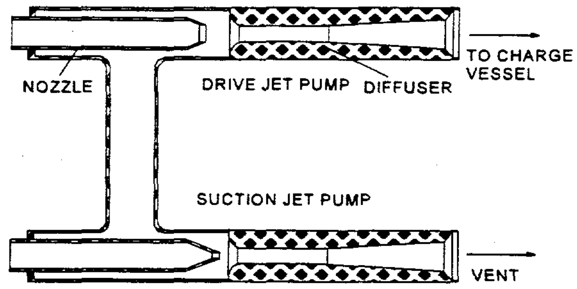
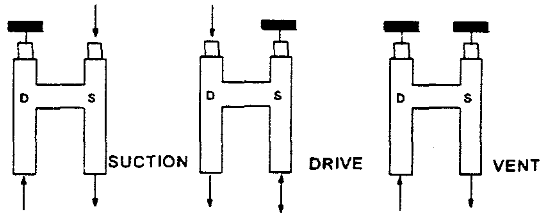


Fig. 10. Jet pump skid during installation.



(a) JET PUMP PAIR



(b) OPERATING MODES

Fig. 11. Jet pump operation.

3. a filter bank (including two stages of HEPA filters) to remove particulate matter;
4. makeup air inlet and prefilters;
5. fans to transport the air and maintain negative pressure on the system; and
6. a stack to discharge the treated off-gas.

The makeup air system includes two styles of roughing filters, a backflow-prevention HEPA, 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 system and the off-gas system. The Prescon system, provided and patented by AEA Technology, 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^{TM}-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:

1. 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.
2. A loss of negative pressure in the W-21 tank trips the main process air supply to the mixing system.
3. Tilt switches mounted on the jet pump skid close the main air and water supplies automatically during a seismic event.
4. 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 install the 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 hoses were connected to the W-21 jet nozzles. Photographs of the PVV, jet nozzle connections, and the installed charge vessels are shown in Figs. 12, 13, and 14.

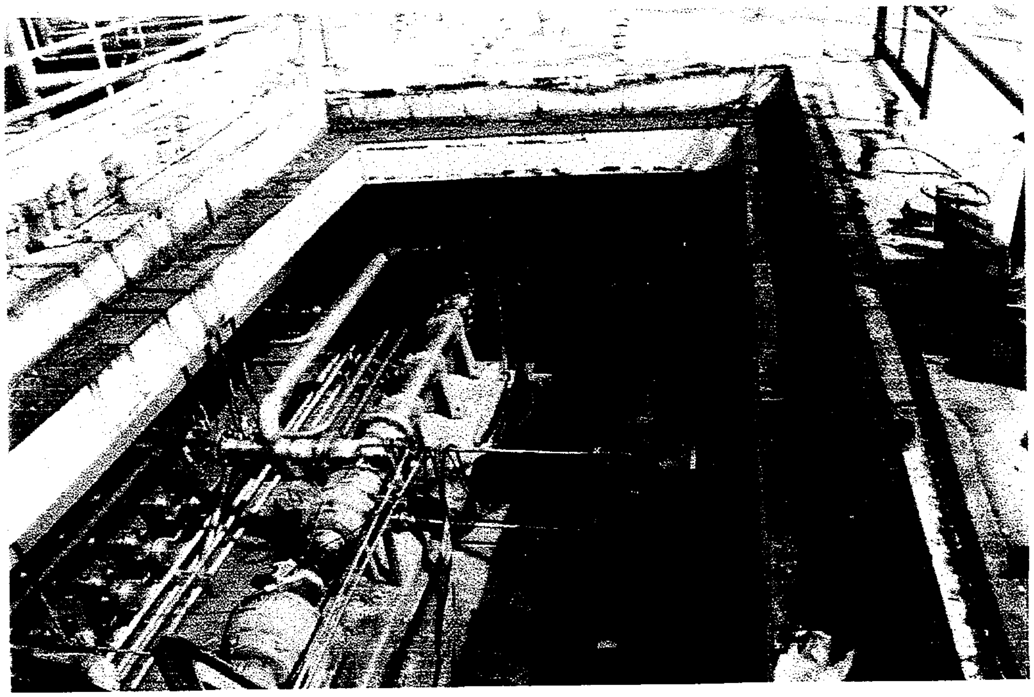


Fig. 12. BVEST pump and valve vault.

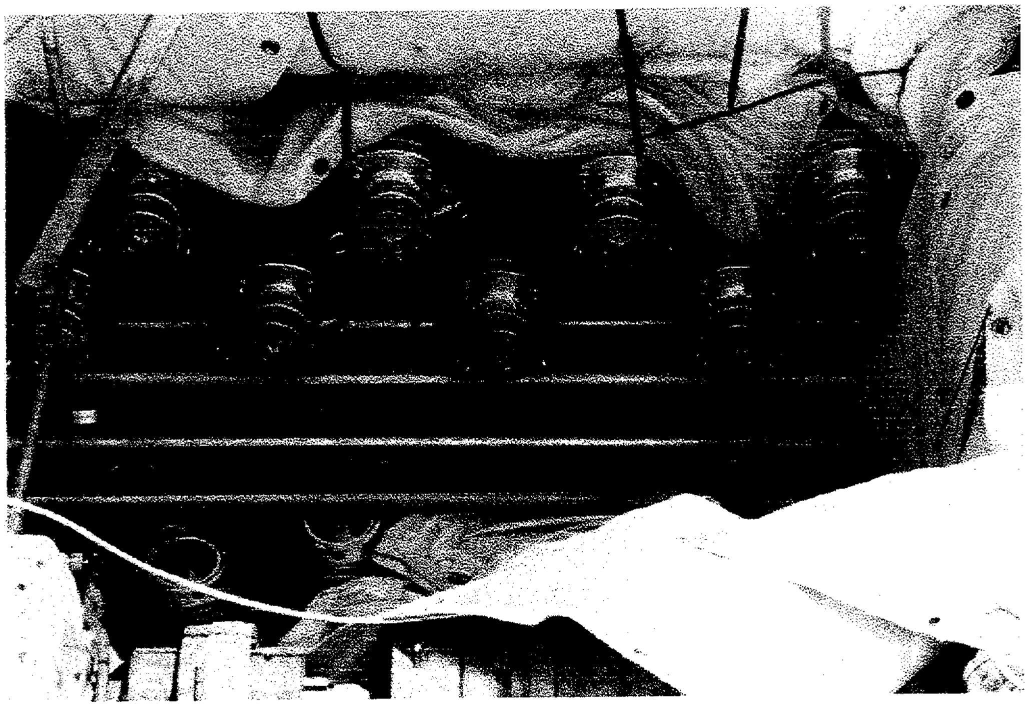


Fig. 13. Camlock connections for BVEST nozzles within the PVV.

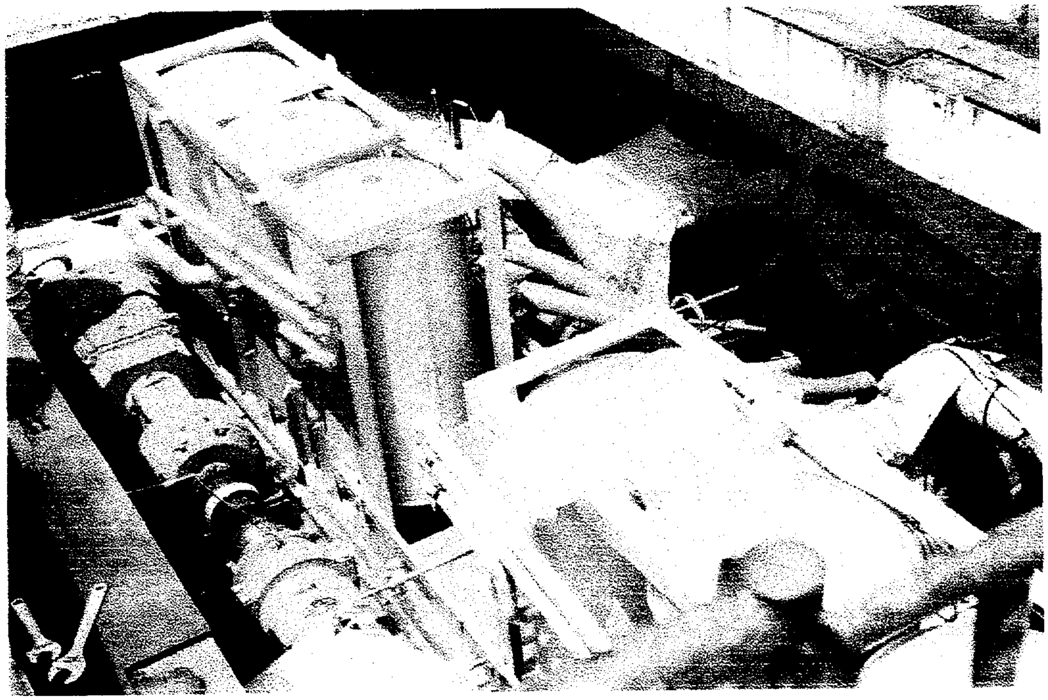


Fig. 14. Charge vessels installed in the PVV.

The vault plugs were replaced on the PVV. The middle concrete vault cover was replaced with a steel cover that included several 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 plug 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 video camera was also installed in the tank via an existing manway on the top of the tank connected to the vault roof by a new man way extension. Installation and shakedown activities were completed by August 4, 1997. A drawing and photograph of the installed system are provided in Figs. 15 and 16, respectively.

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 one of the tank jet nozzles via a charge vessel. This liquid, along with some entrained sludge, would then be drawn back into the charge vessel via the suction induced by the jet pump. Pressure would then be applied to the charge vessel, 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 vessel, and the suction/pulse cycles would be continued. When the desired sludge/supernate mixture composition is achieved, the mixture would be transferred to the MVSTs using the existing progressive cavity (Moyno) pumps. The targeted composition for transfer of the mixture is within the range of 5 to 10 wt % suspended solids slurry.

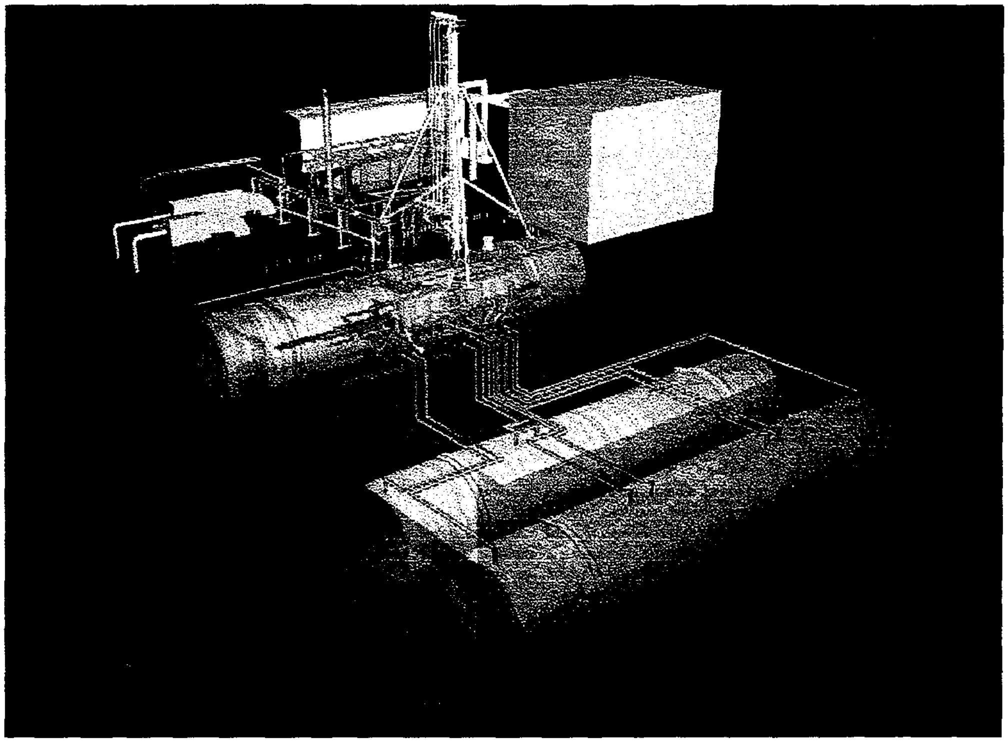


Fig. 15. Drawing of BVEST and pulse jet system layout.

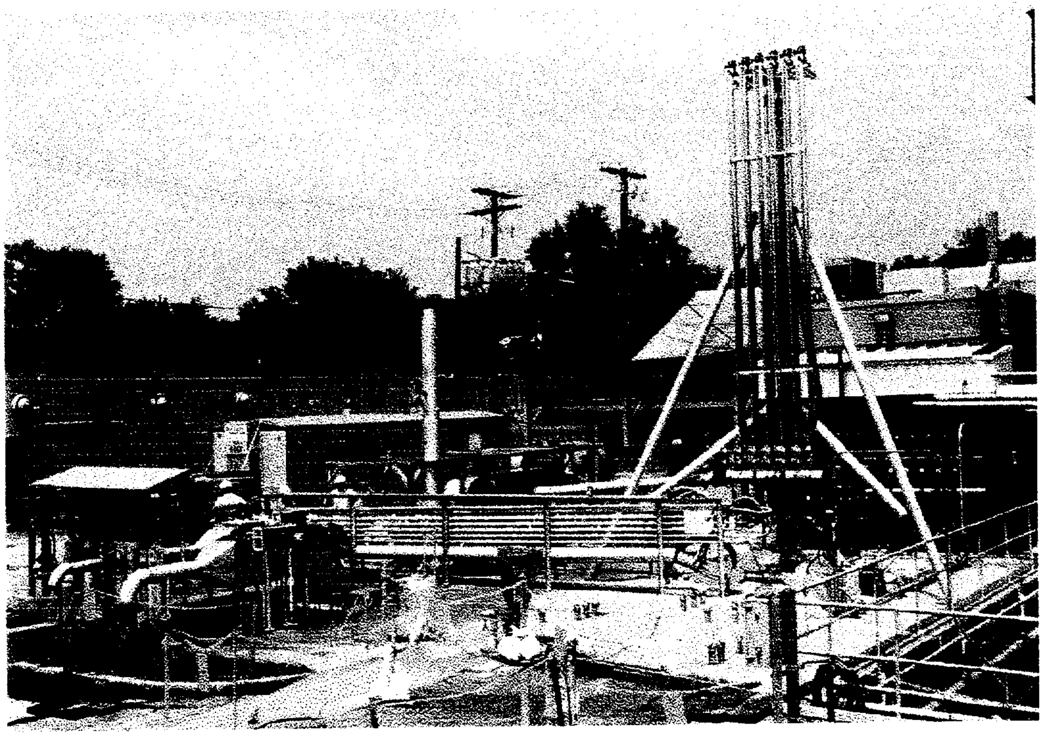


Fig. 16. Pulse jet system completed installation at the BVEST.

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.

Execution Plan Steps

Stage 1	Mix the center segment of W-21 using sludge jets A3 and A4 until a steady state is achieved.
Stage 2	Mix the northern segment of 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 W-21 using sludge jets A1 and A2. To keep the central and northern segments mixed, A3/A4 and A5/A6 nozzles will be pulsed periodically (see *Note*).
Stage 4	The operations manager will notify ORNL Waste Operations that the contents of W-21 are ready for transfer. This notification will be made verbally and recorded in the Operations Logbook. ORNL Waste Operations will then transfer the contents out of W-21 to the MVSTs.
Stage 5	ORNL Waste Operations will transfer supernate and/or water into the tank to mobilize the remaining sludge deposits.
Stage 6	Repeat stage 1.
Stage 7	Repeat stage 2.
Stage 8	Repeat stage 3.
Stage 9	Agitate the areas of W-21 between and behind sludge jets by operating three north-facing sludge jets (A1, A3, and A5) until steady-state conditions are reached, or for 24 h, whichever is longer.

Stage 10 Agitate the areas of 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 The operations manager will notify Waste Operations that the contents of W-21 are ready for transfer. This notification will be made verbally 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 Steps 4 and 12, the tank mixture is sampled prior to transfer to determine solids content of the mixture.

10. DEMONSTRATION OPERATIONS

The W-21 sludge retrieval demonstration required six mixing and transfer campaigns. The pulse jet system was used to mix and remove as much of the sludge as possible during each campaign. The extent of sludge mobilization was determined by monitoring the time required to fill the charge vessel to the level switch (suction time). Pilot testing indicated that suction time should decline and stabilize as mixing progresses and a uniform slurry is obtained. Once a stable mixture was achieved, it was sampled and analyzed for solids content to determine the amount of sludge suspended. When the concentration of suspended solids was acceptable, the mixture was transferred to the MVSTs using the Moyno pumps. 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 demonstration was terminated when it appeared that the amount of additional sludge being mobilized for transfer was relatively small. Table 4 provides a summary of the volumes of liquid and sludge used in the W-21 sludge-retrieval operation.

Table 4. Summary of

Transfer No.	Date completed	Starting volume (gal)	Starting level (in.)	Transferred volume (gal)	Final liquid level (in.)	Final volume as indicated by liquid level (gal)
1	9/17/97	40,000	108	37,700	14	2300
2	9/26/97	9,500	35	7,400	12	2100
3	10/06/97	6,900	24	4,850	12	2050
4	10/10/97	6,100	23	5,000	9.5	1100
5	10/14/97	9,000	34	7,700	10	1300
6	10/27/97	9,000	34	8,300	8	700
7	10/27/97	1,100	9.5	4,200	1300	1300
8	10/28/97	1,350	10	3,400	5	500
Total				78,550		

[a] The percent solids values for transfers 4 and 5 were not determined. For this calculat

[b] % suspended solids values are factored, based on bulk density of the slurry.

[c] Dilute liquid from W-22 had been used to fill W-21; % suspended solids value show

[d] The "weight of sludge" calculation assumes that the concentration of undissolved so

[e] Volume of sludge transferred assumes that the density of the sludge was 1.36 g/mL.

[f] Volume of sludge after transfer 8 was estimated at 350 gal. After transfer 5, an estim
estimate was 6700 gal, based on sludge depth measurement made in 9/96.

[g] DNR = did not record.

ixing and transfer data for W-21 Pulse Jet System Demonstration

Suspended solids[a,b,c] (%)	Density (g/mL)	Weight of sludge transferred[d] (lb)	Volume of sludge transferred[e] (gal)	Volume of sludge remaining[f]	Tank transferred to	Supernate from W-21 and other tanks (gal)	Sluice water added by sluicer (gal)	Flush water transferred to MVST	MVST transfer flow rate (gal/min)	MVST transfer pressure (psig)
2.16	1.221	29,672	2617	4853	W-24, -25	32,800	0	900	57	240
13.11	1.106	31,941	2817	1766	W-25	7,200	0	720	50	165
2.49	1.272	4,578	404	1362	W-25	4,870	1000	1050	57	DNR[g]
1.50	1.272	2,839	250	1112	W-25	2,960	2000	1100	57	DNR
0.75	1.272	2,186	193	919	W-25	6,030	1000		51	DNR
0.24	1.260	741	65	854	W-25, -28	6,300				
			250	604	W-23		3335			
			250	354	W-23		2650			
		71,957	6846			60,160	9985	3770		

n, the % suspended solids values were estimated, based on the values determined for transfer 3 and 6.

or transfer 2 is actually the total solids minus 2.4% to account for total solids in the original liquid. Total suspended solids for this transfer was actually 4.1 to 4.6%.
s was 28% in the original sludge (based on the last core sampling of W-21).
is is also based on the last core sampling of W-21.
d 800–1000 gal (use 900 gal) of sludge remained. Initial starting volume was generated by using volumes and % suspended solids transferred. Original volume

10.1 CAMPAIGN 1

The first campaign began on September 5, 1997, with a revised estimate of 7200 gal of sludge 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 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 initial 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 no. 1 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 no. 1 are given in Fig. 17 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.

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 %. This mixture (37,700 gal total) was successfully transferred to the MVSTs. 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 is 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 is 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 18 and 19 show photos of the west and east walls of the tank following the slurry transfer, respectively.

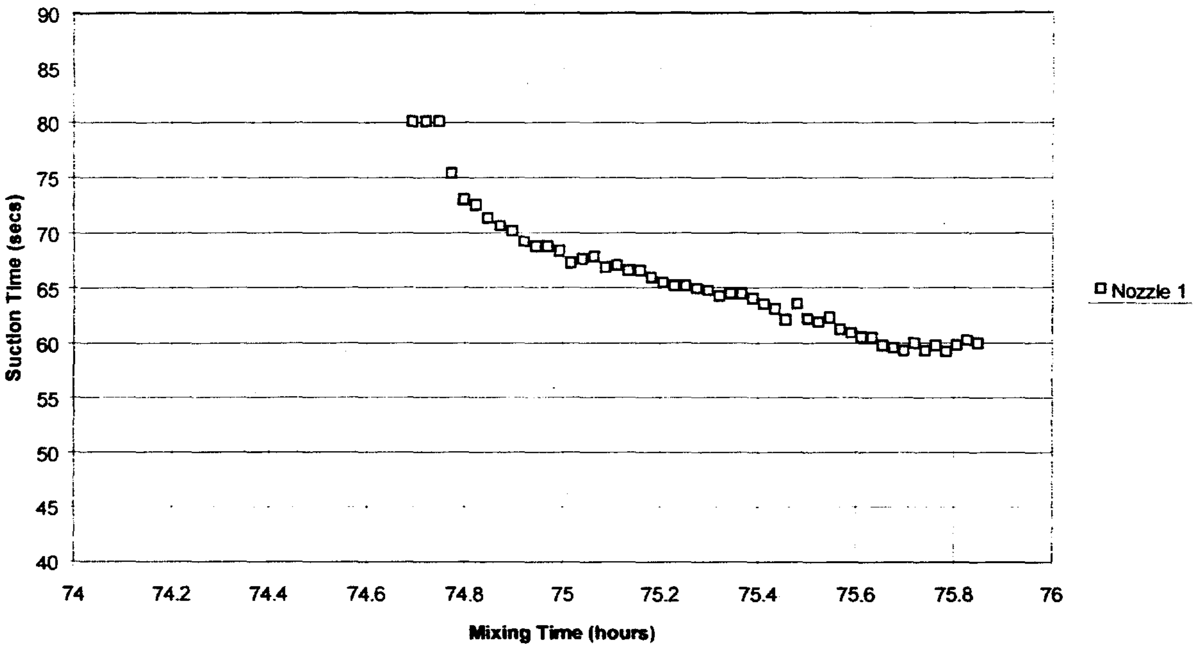


Fig. 17. W-21 mixing campaign #1 suction time versus time.

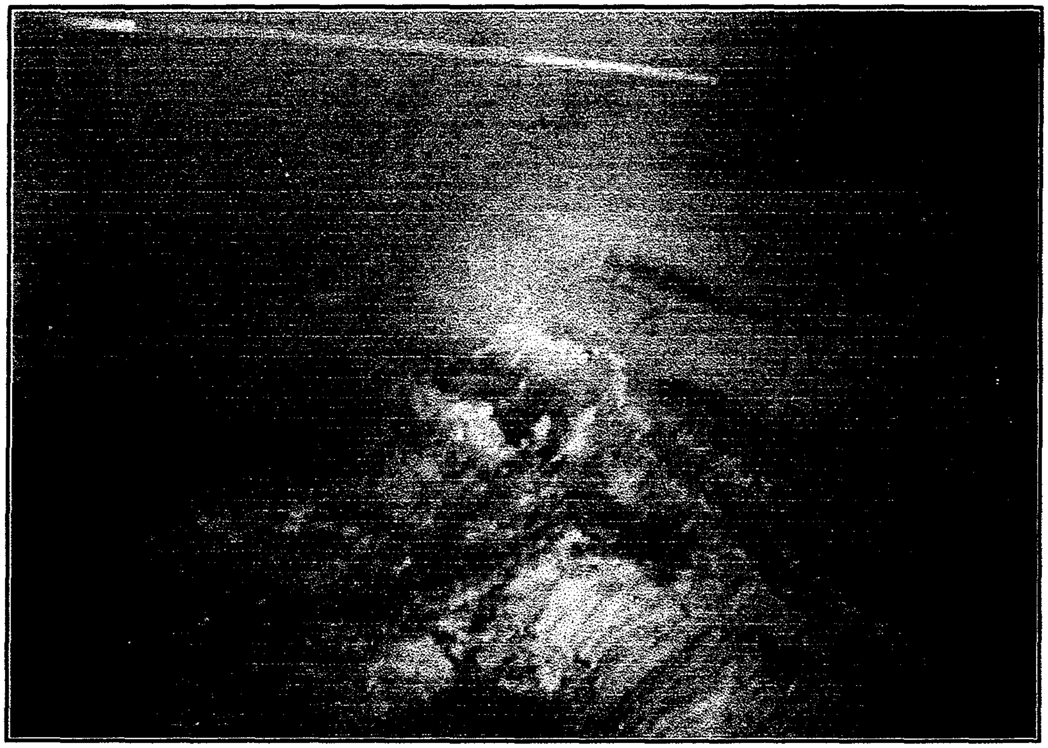


Fig. 18. W-21 west wall after Campaign 1 (BVST-0713_1).

Fig. 19. W-21 east wall after Campaign 1 (BVST-0710_1).

10.2 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 the MVST. The pulse jet system was operated for 4 days, and a sample of the liquid 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 the 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 is 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. no. 5 pipe nozzle was visible above the sludge level.

10.3 CAMPAIGN 3

Supernate from 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 4 days apart and indicated no change in solids content. This mixture was transferred to the MVSTs, 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 (nos. 5 and 4, nos. 2 and 3) and the north and south ends of the tank. The sludge between the nozzles had formed "dams" laterally across tank. These dams impeded mixing between sections of the tank and movement of the slurry to the transfer pump suction pipe located near the no. 3 nozzle. There was also a rather large sludge heel at the north and south ends of the tank. Figures 20 and 21 show photos of the east wall of the tank following the slurry transfer. Figure 22 shows a photo of the sludge dam created between nozzles 4 and 5.

To restore mixing across the jet nozzle pairs, a 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 sluicer operation is shown in Fig. 23. The sluicer operation added about 1000 gal of process water to the tank.

Figure 24 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 monitor, (3) results of sample analysis, and (4) the duration of mixing.

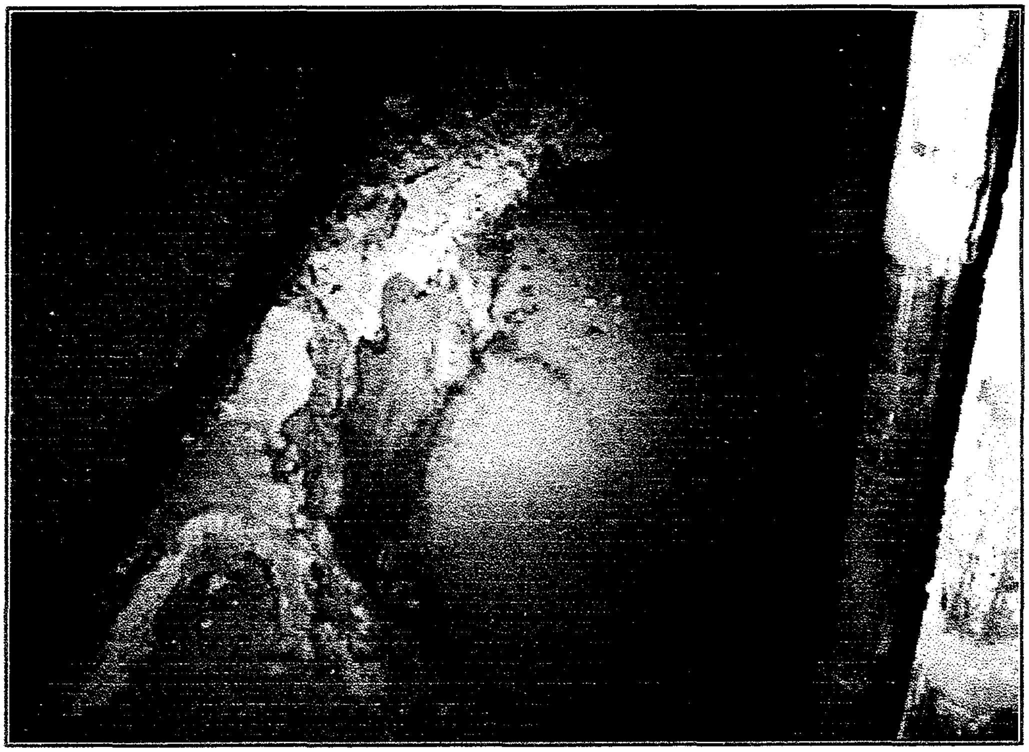


Fig. 20. W-21 east wall after Campaign 3 (BVST-0701_3).

Fig. 21. W-21 east wall after Campaign 3 (BVST-0702-3).

Fig. 22. W-21 east wall between the 4th and 5th nozzles after Campaign 3 (BEST-06707_3).

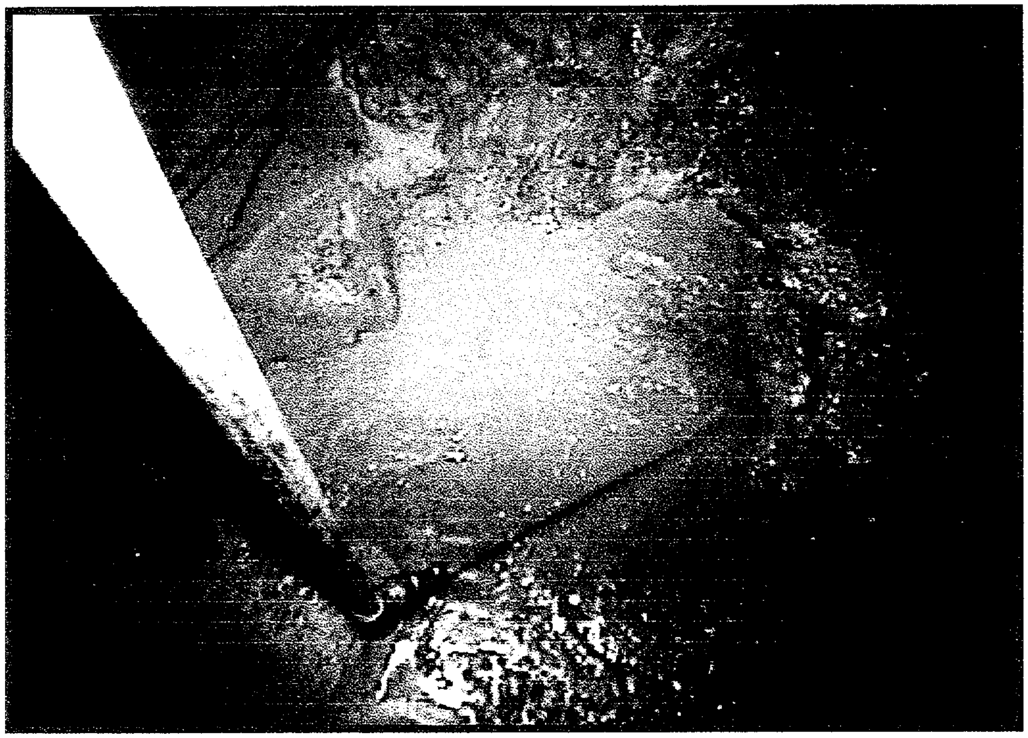


Fig. 23. Manual sluicing of buildup between nozzles 4 and 5 after Campaign 4 (BEST-0706_3).

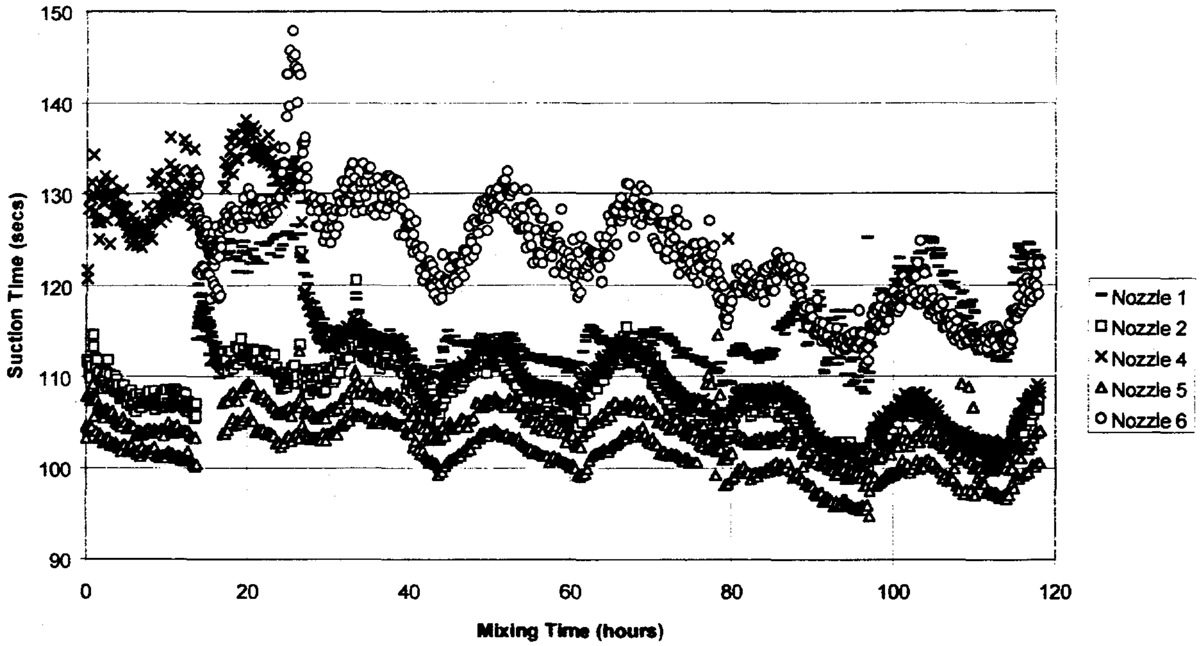


Fig. 24. W-21 Campaign 3 charge vessel suction time versus mixing time.

10.4 CAMPAIGN 4

About 2500 gal of supernate from tank C-1 was added to 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. A more extensive photographic recording of the tank interior was performed after this campaign. Figures 25 through 28 show the sludge remaining at both ends of the tank. Figures 29 and 30 show the east and west sides of the tank, respectively. Figures 31 through 34 show 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 jet pairs and at the north end of the tank into the remaining liquid in the tank. 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 6000 gal of supernate from tank C-1.

10.5 CAMPAIGN 5

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

10.6 CAMPAIGN 6

For the final campaign, 4600 gal of supernate from C-1 was transferred to 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 12 days, 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 the MVSTs, leaving about 850 gal (about 12% of the total sludge) in

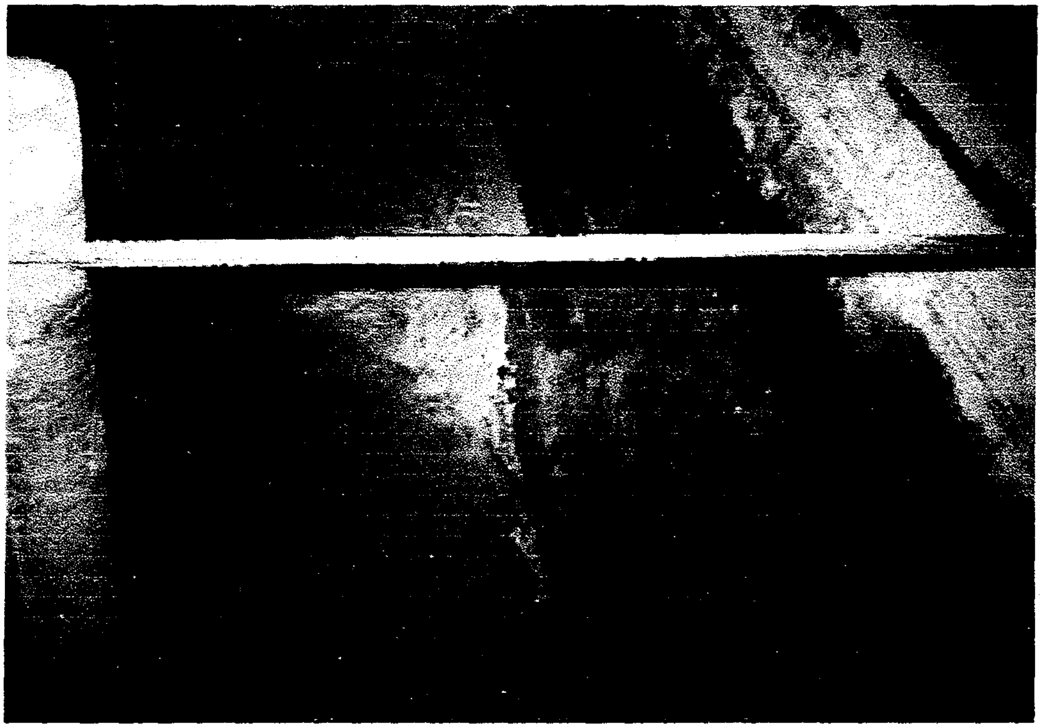


Fig. 25. Tank W-21 northeast corner after Campaign 4 (BVST-0715_4).

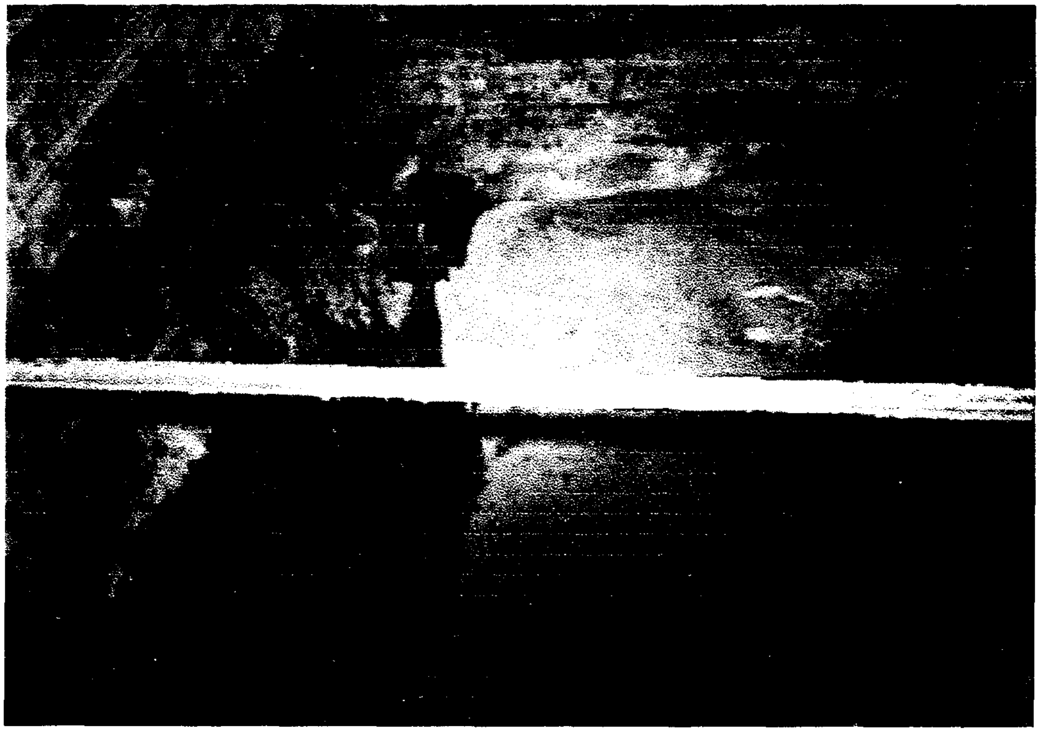


Fig. 26. Tank W-21 northwest corner after Campaign 4 (BVST-0725 4).

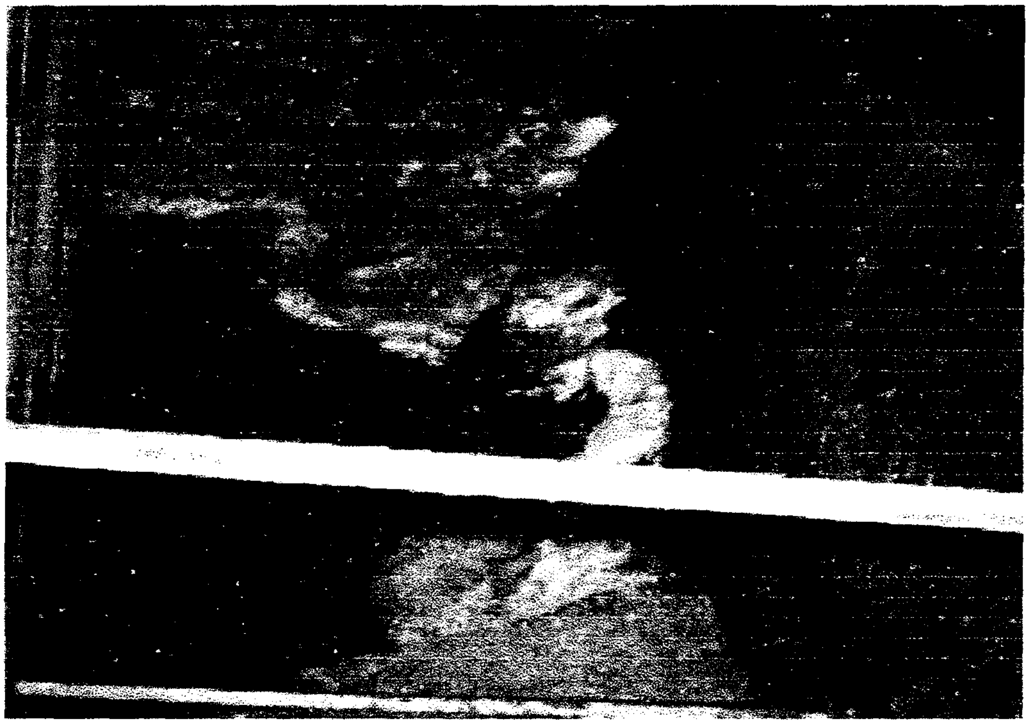


Fig. 27. Tank W-21 southwest corner after Campaign 4 (BVST-0723_4).

Fig. 28. Tank W-21 southeast corner after Campaign 4 (BVST-0718_4).

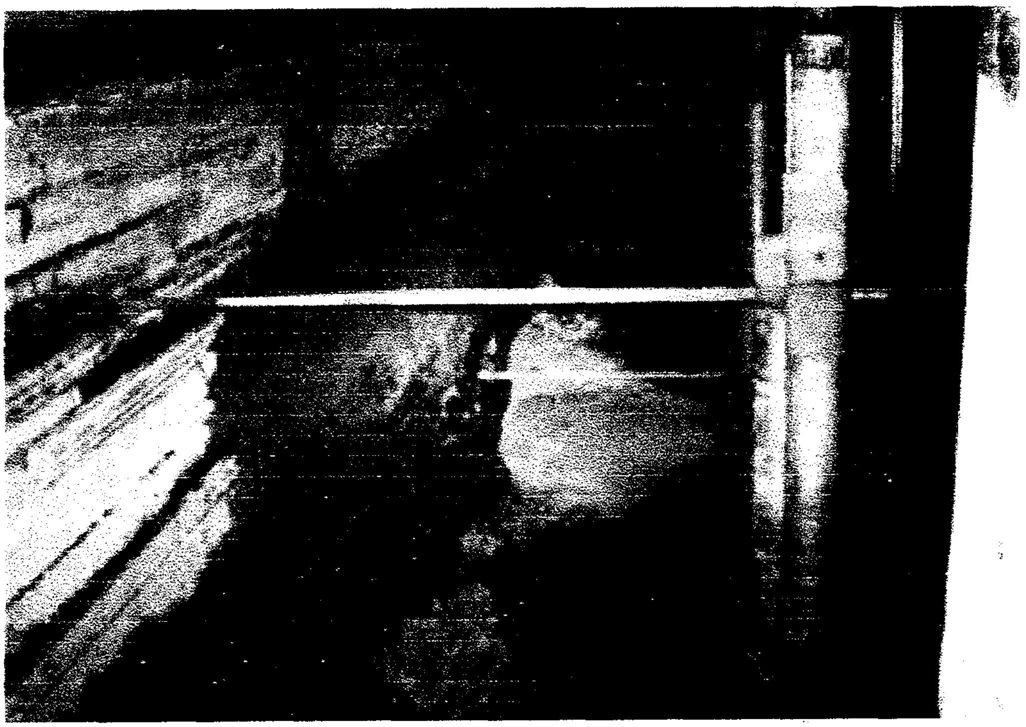


Fig. 29. Tank W-21 east side viewed south after Campaign 4 (BVST-0719 4).

Fig. 30. Tank W-21 west side viewed south after Campaign 4 (BVST-0721_4).

Fig. 31. W-21 nozzles 2 and 3 dam west side after Campaign 4 (BVST-0722 4).

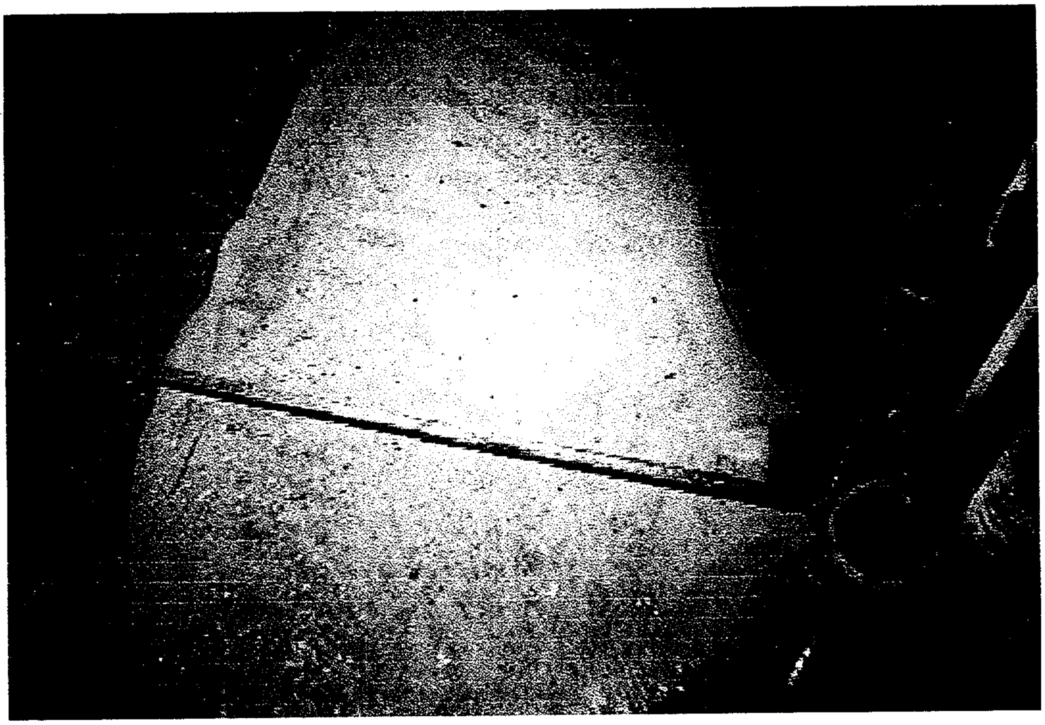


Fig. 32. Nozzles 4 and 5 dam east side after Campaign 4 (BVSWT-0714 4).

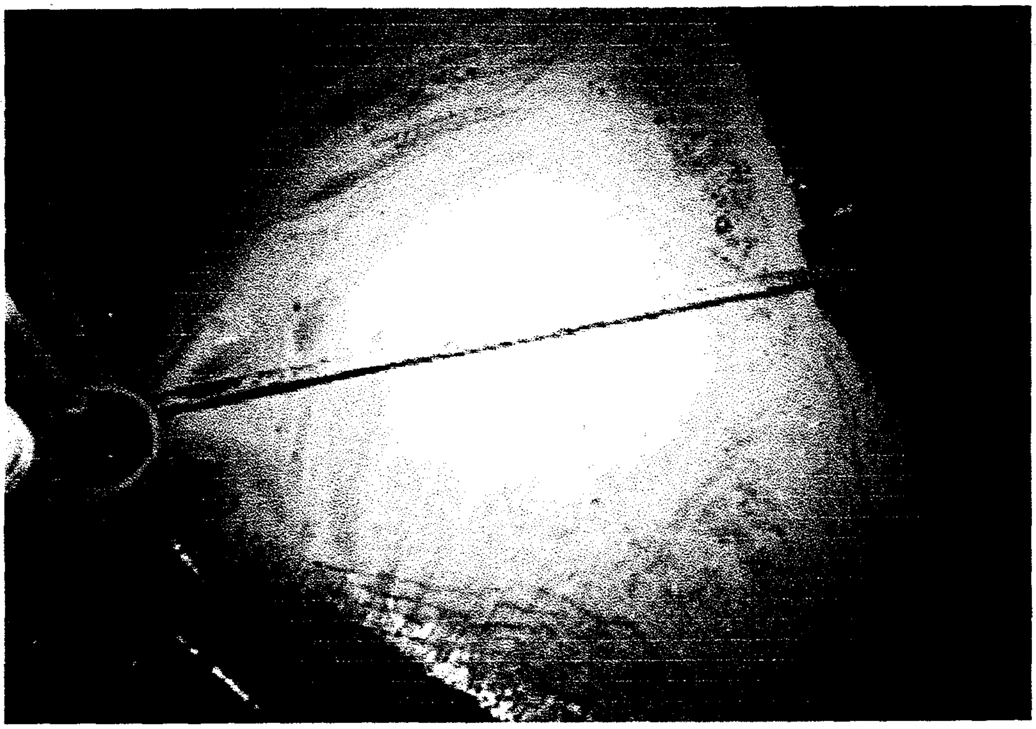


Fig. 33. Tank W-21 nozzles 4 and 5 dam west side after Campaign 4 (BVST-0720_4).

Fig. 34. Tank W-21 between nozzles 4 and 5 viewed from east after Campaign 4 (BVST-0716_4).

W-21. The remaining sludge solids had redeposited in the same areas as before. The percentage of suspended solids for this transfer was approximately one-tenth the suspended solids content of Campaign 3. Based on this percentage, the suspended solids contents for Campaigns 4 and 5 were estimated at 1.5 and 0.75%.

10.7 HEEL SLUICING

The remaining sludge in 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 a total of 1 h and 10 min in an effort to sluice the remaining heel out of the tank. The Moyno pump was operated continuously while transferring the slurry to W-23. Transfer of this slurry to the MVSTs was ruled out because of the lack of control of solids content for the slurry and the heavy nature of this sludge. A total of 5985 gal of process water was used during the final sluicing effort. The amount of sludge remaining in W-21 after the sluicing was estimated to be about 354 gal. The pulse jet system and the manual sluicer together removed 95% of the sludge from W-21. Figures 35 and 36 show the condition of the tank after sluicing.

Using the sluicer required that operators manually insert the pipe and nozzle through the existing W-21 manway from a location on top of the tank vault. The high activity of the tank contents prevented direct viewing of the sluicer position by the operators. The video camera inside the tank was used to view the sluicer. Radio communication from an operations supervisor stationed at the video monitor in the control trailer was used to direct the sluicer operators as to how the sluicer should be positioned. 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 ALARA (as low as reasonably achievable) Plan.

Fig. 35. W-21 views south after Campaign 5 improved sluicer operation and waste transfer.

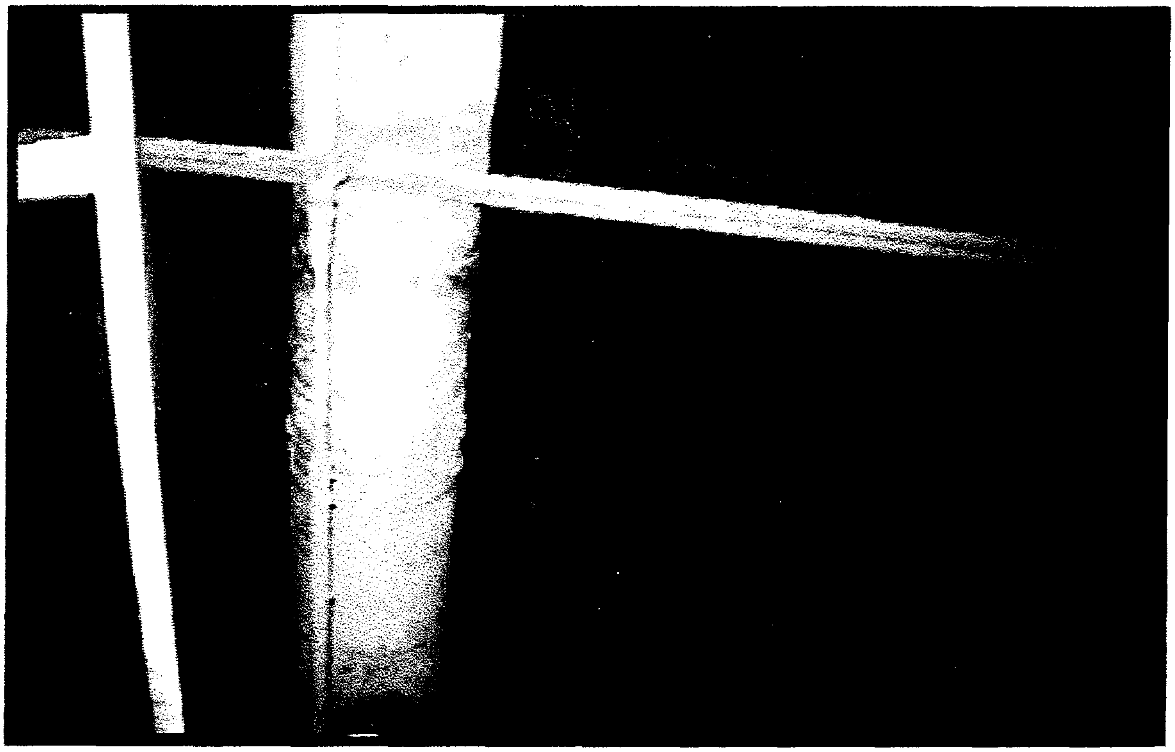


Fig. 36. W-21 northeast corner after Campaign 5 improved sluicer operation and waste transfer.

10.8 ACID DISSOLUTION OF HEEL

An effort was made to remove a large fraction of the remaining W-21 sludge heel by dissolving in a dilute solution of nitric acid. Prior to addition of acid to the tank, a sample of the remaining heel was obtained and characterized, then subjected dissolution tests using various concentrations of dilute nitric acid. This 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)* 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 the 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 the 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 W-21, which already contained about 350 gal of sludge and 1350 gal of liquid. The acid additions took place over a two-week period, with no mixing of the tank contents. On January 8, 2100 gal of supernate from another BVEST was added to W-21 to increase the volume to 5000 gal, the minimum volume required for use of the pulse jet system. On January 12, 1998, the pulse jet system was used to mix the W-21 contents for a 24-h time period, followed by transferring the mixture to tank W-22. Video inspection of the tank after the transfer indicated that approximately 100 gal of sludge remained in W-21. 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 Ca, Mg, Fe, and Sr, 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.

11. SAMPLE ANALYSIS

Samples of the mixture were taken periodically during the pulse jet demonstration project 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. An additional reason for sampling the mixture was to compare the composition of the mobilized sludge with that which had been 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 sample was obtained from a single location where a core sample of the sludge was obtained 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 tank was unknown at the time. However, comparing the composition of previous core sample to the composition of the mobilized sludge samples 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 transferred to W-21 were obtained from several different tanks and varied widely in composition. When transferred to W-21, 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. It was therefore 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 mixed sludge and core compositions was performed by first determining the ratio of low-solubility sludge components in each of the samples from the mixing campaigns, then comparing these ratios 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 mixed sludge (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 mixed sludge is somewhat lower than that in the core sample. The data also indicate that the ^{90}Sr content of the mixed sludge is slightly higher than that in the core sample.

12. PROJECT COST SUMMARY

Table 5 provides a general breakdown of the cost for this demonstration. The table reflects the funds provided to AEA Technology for equipment, installation, and operations. Costs for ORNL project oversite, sample analysis, and operational interfacing are not included.

Table 5. Pulse jet demonstration costs

Cost Element	Cost ($K)
Design, Fabricate, and Deliver Pulse Jet System	2392
Project Risk Management Study	250
Install at BVEST	679
Operations	466
Total	3787

13. SUMMARY AND CONCLUSIONS

The AEA Technology pulse jet system successfully removed about 88% of the sludge from a 50,000-gal horizontal storage tank using modular equipment and existing pipe nozzles for mixing the settled tank sludge with the existing tank supernate liquids. About 64,000 gal of liquid was used to transfer 6300 gal of sludge. Of the liquid used, 88% was existing or recycled tank supernate. Between pulse jet campaigns, 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 4000 gal of process water to the tank system. An additional 3770 gal of process water was added to the system as a consequence of charge vessel and pipeline flushing. After the pulse jet operations, the manual sluicer was modified and used at a higher flow rate to remove additional quantities of the remaining heel. This added another 6000 gal of process water to the tank and increased the total quantity of sludge removed from W-21 to about 6850 gal. 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. Greater than 98% of the sludge was removed from W-21 for all the retrieval operations.

The extent of sludge removal was limited by the constraints of using the existing jet configuration and the physical characteristics of the sludge. The ability to rotate the jet 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 sludge tended to settle more quickly than anticipated, forming sludge heels that were difficult to mobilize. Removal of greater than 98% of this sludge would require either much more aggressive use of the manual sluicer (and associated water additions) 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 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 pulse jet system required only about 7 weeks to install and test and was operated for a total 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. The 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 three lower than the ALARA plan estimate. The system operated well during the demonstration and experienced no major equipment malfunctions or unplanned maintenance outages.

These results 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. ACKNOWLEDGMENTS

Much of the information in this report was compiled from technical information provided by S. A. Taylor of AEA Technology, United Kingdom; J. W. Moore and J. L. Stellern of Lockheed Martin Central Engineering Services in Oak Ridge, Tennessee; and K. M. Billingsley of STEP Environmental in Oak Ridge, Tennessee. Taylor was the principal investigator for the cold pilot tests in the UK and was in charge of the pulse jet system operations at ORNL. Moore and Stellern contributed engineering support and project management for the demonstration. Billingsly was in charge of photographic and video coverage for the demonstration, provided the photos and some of the figures for the report, and contributed valuable editorial comments. Other organizations involved in the successful demonstration of this technology include the ORNL Liquid and Gaseous Waste Operations Section, who provided all of the necessary operations support for interfacing the pulse jet system with the existing operating system;

MK-Ferguson, who handled the installation of the pulse jet system and provided radiation protection and operations support; and the ORNL Radioactive Materials Analytical Laboratory, who provided timely analytical results for the sludge mixture samples taken during the demonstration.

15. REFERENCES CITED

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

Appendix A

Sample Analysis Data from W-21 Pulse Jet Demonstration Project

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

Component	Units	Concentration
Total activity (LSC)	Bq/mL	660000
Gross alpha	Bq/mL	8500
Acid	N	1.2
Total suspended solids	mg/L	8070
Total dissolved solids	mg/L	286000
Ag	mg/L	1.46
Al	mg/L	111
Ba	mg/L	30.6
Ca	mg/L	12200
Cd	mg/L	1.34
Cr	mg/L	7.78
Cu	mg/L	2.2
Fe	mg/L	108
K	mg/L	11900
Mg	mg/L	2100
Mn	mg/L	31.4
Na	mg/L	43400
Ni	mg/L	4.74
Sr	mg/L	<0.36
Th	mg/L	156
U	mg/L	3720
V	mg/L	3.6
Zn	mg/L	30.8

Table A-2. Sample analysis results from Campaign 1

		1997 Mixing Test					1996	1996	
Parameter	units	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 f35 (>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 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		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 f35 (>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[b]	
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 f35 (>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

		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		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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