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**CASE STUDY TO REMOVE RADIOACTIVE HAZARDOUS SLUDGE
FROM LONG HORIZONTAL STORAGE TANKS**

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CASE STUDY TO REMOVE RADIOACTIVE HAZARDOUS SLUDGE FROM LONG HORIZONTAL STORAGE TANKS

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ABSTRACT

The removal of radioactive hazardous sludge from waste tanks is a significant problem at several U.S. Department of Energy (DOE) sites. The use of submerged jets produced by mixing pumps lowered into the supernatant/sludge interface to produce a homogeneous slurry is being studied at several DOE facilities. The homogeneous slurry can be pumped from the tanks to a treatment facility or alternative storage location. Most of the previous and current studies with this method are for flat-bottom tanks with vertical walls. Because of the difference in geometry, the results of these studies are not directly applicable to long horizontal tanks such as those used at the Oak Ridge National Laboratory. Mobilization and mixing studies were conducted with a surrogate sludge (e.g., kaolin clay) using submerged jets in two sizes of horizontal tanks. The nominal capacities of these tanks were 0.87 m³ (230 gal) and 95 m³ (25,000 gal). Mobilization efficiencies and mixing times were determined for single and bidirectional jets in both tanks with the discharge nozzles positioned at two locations in the tanks. Approximately 80% of the surrogate sludge was mobilized in the 95-m³ tank using a fixed bidirectional jet (inside diameter = 0.035 m) and a jet velocity of 6.4 m/s (21 ft/s).

INTRODUCTION

The removal of radioactive hazardous sludge from waste tanks is a significant problem at several U.S. Department of Energy (DOE) sites. The waste typically originates as acidic liquid, which is neutralized to protect the storage tanks from corrosion. The neutralization process also causes the metals dissolved in the acidic waste to precipitate and form a sludge layer in the bottom of the storage tanks.

Most storage tanks at DOE facilities are vertical cylindrical-shaped tanks; however, the waste storage tanks at the Oak Ridge National Laboratory (ORNL) are typically long horizontal cylinders. The typical waste tank at ORNL is constructed from stainless steel and contains multiple risers that provide services to the tank (e.g., liquid addition, liquid removal, and sparging). Although the tanks range up to ~18 m (60 ft) in length, only one manhole opening is usually installed in each tank. The manhole typically has a diameter of ~0.5 m (19 in.), but it is not necessarily located in the center of the tank. The tank diameters range up to 3.6 m (12 ft).

Direct access to the tanks is restricted because of the radioactive nature of the waste; as a result, a remote method is required to remove the sludge from the tanks. Past practice at ORNL for removing sludge from vertical cylindrical tanks involved the use of a sluicing nozzle positioned at the top of the tank to mobilize and suspend the sludge for transport as a slurry (Weeren, 1984). Although the actual method is more complicated, the layperson can visualize this method as analogous to using a fire hose to suspend the settled solids. The Hanford Site has also used this method to remove radioactive sludge from its tanks (Rasmussen, 1980). This method requires that the liquid level in the tank be very low; otherwise, the liquid absorbs some of the impinging energy.

Researchers at the Savannah River Site evaluated the use of submerged jets to mobilize the sludge in tanks at that location. They originally used water as the mobilizing stream; however, it became apparent that this significantly increased the volume of waste. The submerged jet system was modified to use existing supernatant for sludge mobilization (Bradley et al., 1977). This procedure evolved into the development of submerged rotational mixing pumps for mobilizing sludge. Savannah River, Hanford, and West Valley have used mixing pumps for mobilizing sludge; however, it is important to note that all the waste storage tanks at these facilities are flat-bottom vertical cylinders.

Very few studies have been conducted that investigate mixing and mobilization in horizontal cylindrical tanks. A previous study at ORNL investigated the mixing of fluids in horizontal cylindrical tanks with submerged jets, and an empirical correlation was found to predict the time required to mix the contents of these tanks (Perona et al., 1994). This paper describes an ORNL study to determine the feasibility of using submerged jets for removing sludge from its long horizontal cylindrical tanks. Because only a small distance existed between the sides of the tanks, rotating the submerged nozzle was unnecessary. The experimental studies reported in this paper were all performed with fixed-position nozzles.

The use of an external mixer pump offers some advantages over the use of an internal mixer pump. Likewise, the internal mixer pump offers some advantages over the external mixer pump. A comparison and contrast of the two methods follows.

- The internal mixer pump keeps the radioactive fluid within the confines of the tank until the slurry is ready to be transported to the treatment facility or alternate storage location. The external mixer pump requires that the slurry be brought outside the tank and returned to the tank,

which presents a potential risk of personnel and environmental exposure. Double-wall piping and radiation shielding can be utilized as engineering methods to reduce the risk.

- The required suction head is an important parameter for any pump. The internal mixer pump essentially eliminates this parameter because the pump is submersed in the fluid. The external mixer pump is typically limited to suction heads less than 10 m (33 ft).
- The cost of equipment is always a concern to any process. The cost of the internal mixer pump is typically much higher than that for an external mixer pump, but the cost comparison should not be limited to the cost of the pumps. An internal pump also requires that a structure be built over the tank to support and lower the pump in the tank, whereas, the external pump system requires double-wall piping and radiation shielding.
- The internal mixer pump must be slowly lowered into the tank and allowed to clear out its path as it is lowered to prevent overloading the pump with a high concentration of undissolved (suspended) solids. The cost of adjusting the depth of the pump is high. The suction nozzle for the external mixer pump may be placed practically anywhere in the tank supernatant layer.

THEORY

Four flow regions have been described for turbulent flow of Newtonian fluids through jets (Green, 1984). Within the first five nozzle diameters of the jet, the flow has about the same velocity as the initial discharge velocity. A transition region exists for approximately eight nozzle diameters, followed by a region of established flow. The centerline velocity drops off rapidly past the region of established flow. The region of established flow is of most interest since most of the sludge

mobilization occurs here. An equation was developed for the velocity profile along the x-axis in the established flow region of a jet (Albertson et al., 1950) and may be represented as

$$V_x = \frac{C_1 D V_o}{x} e^{-C_2 (r/x)^2} \quad (1)$$

where

- V_x = velocity at point x ,
- C_1, C_2 = constants,
- V_o = initial discharge velocity,
- D = nozzle diameter,
- x = distance from nozzle, and
- r = radial distance from jet axis.

The angle at which the jet expands affects constants C_1 and C_2 , but equation (1) indicates that the velocity at any distance from the jet nozzle (in the established flow region) is proportional to the product of the nozzle diameter and the initial fluid velocity at the jet (DV_o). When the jet impacts perpendicularly to the surface of the sludge, the force of the impact is given by

$$F = \frac{\rho V_x^2 A}{2 g_c} , \quad (2)$$

where

- F = force of the jet striking the sludge,
- ρ = fluid density,
- A = area of impact, and
- g_c = gravitational constant.

Typically the sludge in waste storage tanks exhibits a yield stress, and the rheology of the sludge can be characterized by a Bingham plastic model (Selby, 1981; Ceo et al., 1990; Youngblood et al., 1994). For a Bingham plastic material, the force required to begin movement is considered the product of the yield stress (τ_o) and the cross-sectional area (A).

Churnetski equated the force from the jet with the force required to overcome the yield stress of the sludge and determined the jet velocity required for sludge movement (Churnetski, 1981a). This value was then substituted into equation (1) to give the following equation for calculating the distance at which the sludge will be mobilized. This distance was called the effective cleaning radius (*ECR*):

$$ECR = KDV_o \left(\frac{\rho}{2\tau_o g_c} \right)^{1/2}, \quad (3)$$

where

$$K = C_1 e^{-C_2(r/x)^2}. \quad (4)$$

The above equations suggest that the *ECR* is approximately proportional to the product of the nozzle diameter and the initial jet velocity as expressed in equation (5) for a system in which the density of the fluid and the yield stress of the sludge are constant:

$$ECR = KDV_o. \quad (5)$$

The value of *K* depends on the type of material to be mobilized, and it is equivalent to the slope of the line when plotting *ECR* versus *DV_o*.

This proportionality relationship has been confirmed to some extent in experimental studies with various nozzle sizes and jet velocities (Churnetski, 1981b). In one test, a 1/4-in.-diam jet operated at 650 ft/s and 3000 psia gave essentially the same cleaning radius as a 1.5-in.-diam nozzle operated at 100 ft/s and 100 psia. These two nozzles had the same *DV_o* product (Bradley et al.,

1977). The preceding equations do not consider factors such as tank geometry, effect of settling, obstacles in the path of the jet, or the effect of erosion and eddies on sludge removal. Also, studies by Hamm et al. at Savannah River indicate that the cleaning radius continues to increase with time although the sludge removal rate may become very slow (Hamm et al., 1989). The effect of the impact of jet forces on tank components has also been studied (Bamberger et al., 1992). No information has been found for the effect of geometry on the jet velocity profile in horizontal tanks.

If the jet velocity of a submerged jet is not sufficient to mobilize the sludge all the way to the end of the tank, the sludge profile will typically have the appearance of a beach or a bank, as illustrated in Fig. 1. Since no distinct vertical wall of sludge is present, the beach profile complicates the determination of the jet effectiveness. Bradley defined the jet effectiveness as the distance cleaned to the extent that less than 1/8 in. of sludge remained after the slurry had been removed, and he equated this distance to the *ECR* (Bradley et al., 1977). Since the submerged jets were fixed in position (i.e., they did not rotate) for the tests described in this report, it was reasonable to define a similar quantity known as the effective cleaning length (*ECL*). This definition is shown schematically in Fig. 1.

This study simulated the effect that a submersible mixer pump would have with kaolin clay in a horizontal tank. A mixer pump was simulated by installing the pump discharge and pump suction at the same point in the tank. This study also addressed the possibility of using an external pump with suction and discharge nozzles located on opposite ends of the tank.

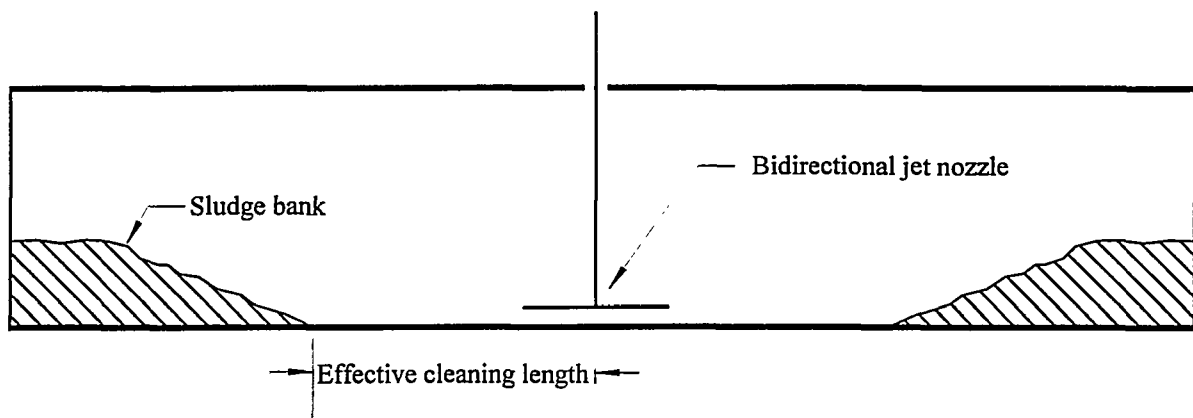


Fig. 1. Schematic of tank illustrating leftover sludge bank after a mobilization test and the definition of effective cleaning length.

EXPERIMENTAL

Mobilization and mixing experiments were conducted with surrogate materials in two tanks. The use of surrogate materials was necessary because of the radioactive nature of the actual waste. The first tank, constructed from Plexiglas, had a capacity of $\sim 0.87 \text{ m}^3$ (230 gal). It was 3.05 m (10 ft) long and 0.6 m (2 ft) in diameter. Kaolin clay was used as a surrogate material to represent the sludge in both tanks. In addition, a mixture of compounds was prepared that chemically represented the sludge and supernatant contents of one of the waste tanks and was also used as a surrogate in the 0.87-m^3 tank. This surrogate was originally used in a slurry transport study (Hylton et al., 1994). Principal components of the sludge phase included calcium carbonate, calcium hydroxide, magnesium hydroxide, aluminum hydroxide, and silicic acid. The supernatant phase was composed of sodium nitrate, potassium nitrate, sodium carbonate, sodium chloride, and sodium hydroxide.

The experimental setup for the 0.87-m^3 tank was a simple recirculation loop; however, the discharge and suction nozzles were reconfigured in various positions as required. A typical setup is shown in Fig. 2, and a list of the mobilization and mixing tests performed in this tank is provided in Table 1.

The 95-m^3 tank was configured to provide a large amount of versatility for the mobilization tests, as shown in Fig. 3. Three discharge nozzles and three suction nozzles were installed in the tank. Except when the objective was to mobilize all the sludge, only one discharge nozzle and one suction nozzle were used for each mobilization test. Bidirectional submerged nozzles were installed approximately at the 1/4-, 1/2-, and 3/4-tank-length positions at $\sim 0.15 \text{ m}$ (6 in.) from the bottom.

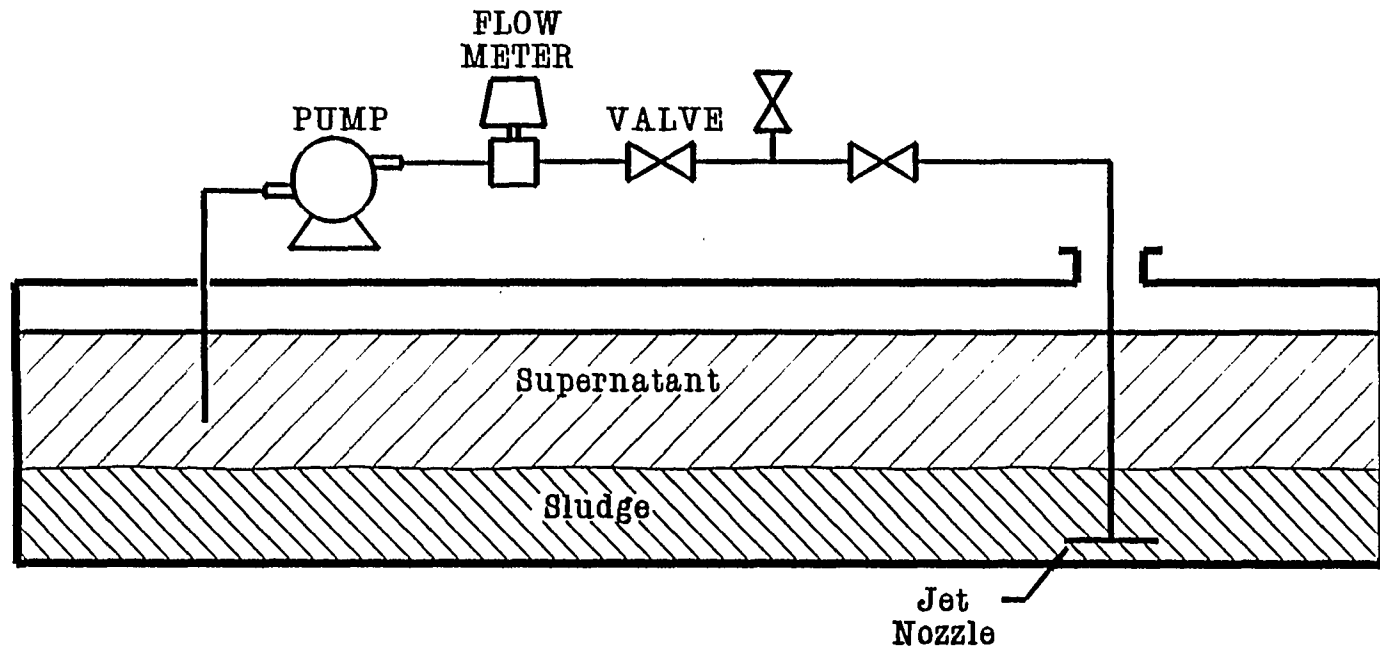


Fig. 2. Example of experimental setup for the 0.87-m³ tank.

Table 1. Test conditions and results for sludge mobilization runs in the 0.87-m³ tank

Run Number	Surrogate Material	Jet Type ^a	Jet Discharge Location ^b	Suction Location ^c	Jet Velocity ^d (m/s)	DV_o Product ^e (m ² /s)	ECL^f (m)	Jet Reynolds Number	Length of run (min)	Percent Mobilized
1	Kaolin	B	~1/4 L	~7/8 L	3.0	0.065	NA ^g	65,000	30	85
2	Kaolin	B	~1/4 L	~7/8 L	1.5	0.033	NA ^g	33,000	30	55
3	Kaolin	B	~1/4 L	~7/8 L	0.7	0.016	NA ^g	16,000	30	38
4	Kaolin	U	~1/4 L	~7/8 L	5.9	0.131	1.3	131,000	15	85
5	Kaolin	B	Center	Center	2.6	0.058	NA ^g	58,000	30	99
6	Chem. mix.	B	Center	Center	2.5	0.055	0.6	55,000	30	68
7	Chem. mix.	B	Center	Center	2.5	0.055	0.6	55,000	45	63
8	Chem. mix.	B	Center	Center	3.4	0.076	0.9	76,000	60	83
9	Chem. mix.	B	Center	Center	3.4	0.076	0.9	76,000	150	80
10	Chem. mix.	B	~1/4 L	Center	3.8	0.084	1.4	84,000	120	88

^aB = bidirectional; U = unidirectional. All nozzles had an inside diameter of 0.022 m (0.87 in.).

^b~1/4 L = ~1/4 tank length from the end of the tank.

^c~7/8 L = ~7/8 tank length from the same end of the tank referenced for the discharge nozzle.

^dMultiply values by 3.281 to convert unit from m/s to ft/s.

^eMultiply values by 10.764 to convert unit from m²/s to ft²/s.

^fECL = Effective cleaning length. Multiply values by 3.281 to convert unit from m to ft.

^gNA = not available.

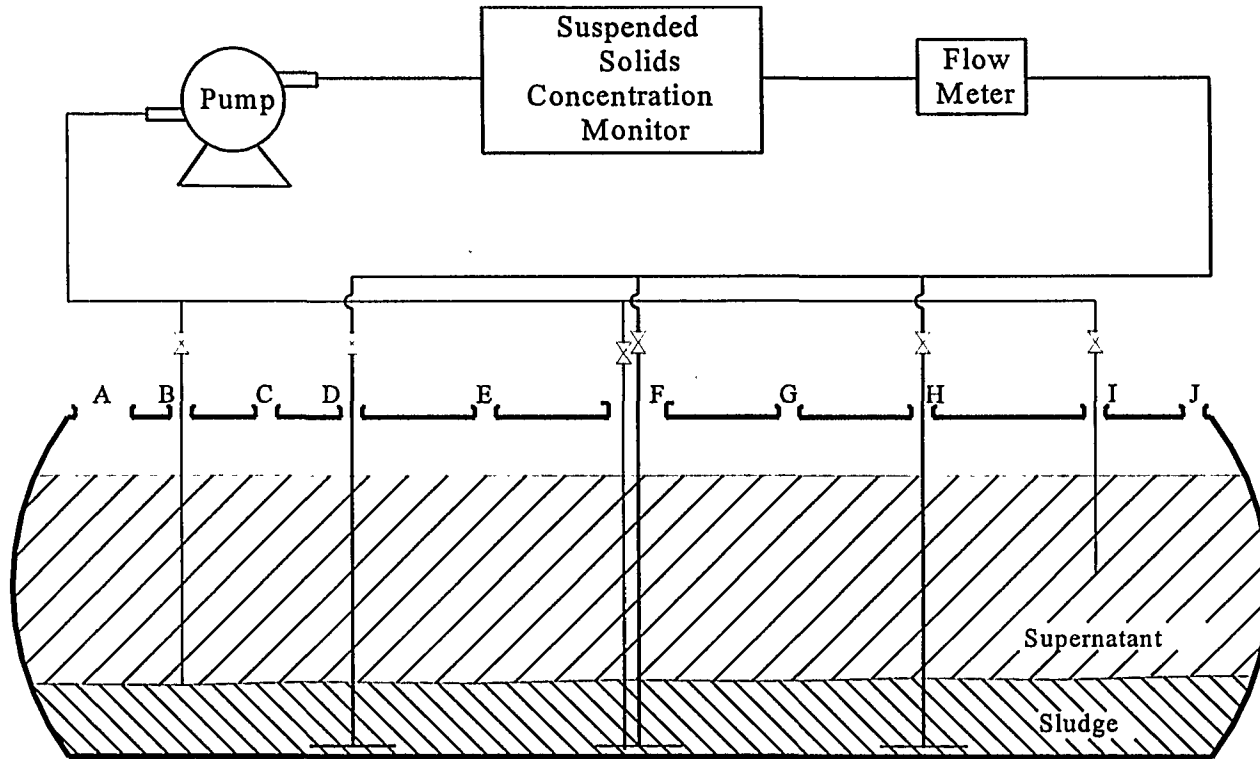


Fig. 3. Experimental setup for the 95-m³ tank.

These nozzles were constructed from 1.25-in. Schedule 40 pipe and sized to give a jet velocity of ~6 m/s (20 ft/s). Suction legs were installed approximately at the 1/8-, 1/2-, and 7/8-tank-length positions. The depths of the suction legs (referenced to the bottom of the tank) were as follows: 0.5 m (20 in.) at the 1/8 position, 0.05 m (2 in.) at the 1/2 position, and 1.1 m (44 in.) at the 7/8 position. A list of the experimental runs performed in the 95 m³-tank is shown in Table 2.

The *ECL* was visually determined in the 0.87-m³ tank after allowing the suspended solids to resettle following a mobilization test. The theory was that the depth of settled sludge would be more shallow in the mobilized area than in the unmobilized areas. In actuality, the *ECL* was difficult to detect with this method since there was not much difference in the depth of settled sludge after an experiment; however, a small valley or ridge could usually be observed.

This method was also tried with the 95-m³ tank. In this case, an instrument with an infrared detector determined the depth of the sludge liquid interface. However, the results indicated that the sludge resettled to the same depth regardless of whether it had been mobilized in a particular area. Another method was devised to determine the *ECL* in the 95-m³ tank. The tank contained approximately ten access points (i.e., locations for risers). At the end of a mobilization test, samples were collected from the bottom of the tank at each riser with a long tube, a vacuum flask, and a vacuum pump. The samples were analyzed for suspended solids concentration. If the results showed that the suspended solids concentration was the same as the suspended solids concentration in the recirculation stream, then the sampling point was considered to be within the *ECL* of the submerged nozzle. A concentration higher than that in the recirculation stream indicated that sludge was still present in the location and that the sampling point was outside the *ECL* of the submerged nozzle.

Table 2. Test conditions and results for the mobilization runs with kaolin in the 95-m³ tank

Run Number	Settling Time ^a (h)	Jet Discharge Location ^b	Suction Location ^c	Jet Velocity ^d (m/s)	DV _o Product ^d (m ² /s)	Minimum ECL ^e (m)	Jet Reynolds Number	Mixing Time (min)	Quantity Mobilized (wt %)
K-0	900	Varied ^f	Varied ^f	6.54	0.229	NA ^g	231,000	NA ^g	70.0
K-1	210	Port F	Port F	6.54	0.229	ND ^g	231,000	660	66.1
K-2	280	Port D	Port I	6.54	0.229	ND ^g	231,000	155	60.5
K-3	280	Port H	Port B	6.54	0.229	3.2	231,000	185	60.3
K-4	260	Port F	Port I	6.54	0.229	3.2	231,000	280	59.8
K-5	300	Port F	Port F	6.54	0.229	3.2	231,000	525	58.6
K-6	300	Port D	Port I	3.27	0.115	1.4	116,000	ND ^g	35.0 ^h
K-7	130	Varied ^f	Varied ^f	6.54	0.229	NA ^g	231,000	NA ^g	91.6
K-8	300	Port F	Port F	6.54	0.229	3.2	231,000	ND ^g	81.4 ^h
K-9	300	Port H	Port B	6.54	0.229	3.2	231,000	130	81.4
K-10	300	Port H	Port B	3.27	0.115	1.6	116,000	ND ^g	49.0 ^h
K-11	300	Port H	Port B	4.90	0.172	3.2	173,000	300	77.2

^aAmount of time that the solids settled prior to this run.

^bAll discharge nozzles were bidirectional and constructed from 1.25-in. Schedule 40 pipe. See Fig. 3 for location of ports.

^cAll suction legs were constructed from 3-in. Schedule 40 pipe. See Fig. 3 for visual location of ports.

^dMultiply values by 3.281 to convert unit from m/s to ft/s. Multiply values by 10.76 to convert unit from m²/s to ft²/s.

^eECL = effective cleaning length. The exact distance could not necessarily be determined because of the distance between ports; consequently, the value shown for the ECL is the minimum distance.

^fThis run used all the discharge nozzles and suction legs to mobilize the maximum quantity of sludge.

^gND = not determined; NA = not applicable.

^hEstimated value based on the concentration of samples taken from inside the tank.

The test plan for the mixing and mobilization experiments in the 95-m³ tank called for the following steps.

1. Select a specific discharge nozzle, a specific suction leg, and the desired flow rate.
2. Perform mobilization and mixing test.
3. Allow suspended solids to resettle into a sludge layer for 7 days, and measure sludge profile at the various riser locations.
4. If the depth of sludge was significantly uneven, perform a mobilization run using all the discharge nozzles and suction legs to mobilize the maximum amount of sludge and to obtain a near-homogeneous slurry mixture. Theoretically, the sludge would resettle in an even depth profile. If the sludge depth was uniform, then restart with step 1.

After the first mobilization test, it became apparent that the sludge was still settling significantly after 7 days; consequently, the settling time was increased to 14 days. Measurements of the sludge profile indicated that the sludge depth was consistent across the tank. A video camera was submerged into the tank for visual inspection of the sludge layer. The sludge layer appeared to be level with small ripples. It was decided that a mobilization run was not necessary to obtain an even depth profile between test runs.

After several test runs, the sludge in some portions of the tank was significantly thicker than in other portions of the tank. The thicker sludge was found in areas that had not been mobilized during the previous test (i.e., those areas with greater than 14 days of settling time), which allowed the solid particles to become more compact. In an attempt to make the sludge in the tank homogeneous for comparison, a mobilization run using all of the discharge nozzles and suction legs in various configurations was performed approximately 14 days prior to runs K-8 through K-11. The final version of the test plan consisted of the following steps.

1. Select a specific discharge nozzle, a specific suction leg, and the desired flow rate.
2. Perform mobilization and mixing test.
3. Obtain samples from the bottom of tank at each riser location, and analyze for suspended solids concentration.

4. Conduct a mobilization run using all the discharge nozzles and suction legs to mobilize the maximum amount of sludge and to obtain a near-homogeneous slurry mixture. Allow the suspended solids to resettle for 14 days, and then restart with step 1.

RESULTS

The data obtained from the experimental tests were evaluated and compared with equation (5) to determine the correlation, if any, between the *ECL* and the product of the nozzle diameter and the jet velocity (DV_o) for the kaolin clay and the chemical mixture. The results are plotted in Fig. 4. Although some scatter was found in the results, Fig. 4 shows that the relationship between these quantities is similar to the type of data determined for the vertical flat-bottom tanks. The slope of the line for kaolin shown in Fig. 4 indicates that the value of the proportionality constant, *K*, is $\sim 14 \text{ s} \cdot \text{m}^{-1}$. Experimental data obtained by researchers at Savannah River and Hanford have shown the proportionality constant to range between 6 and $8 \text{ s} \cdot \text{m}^{-1}$. A review of the experimental programs indicates that the likely reasons for the difference in the proportionality constant for kaolin are (1) the much longer length of the ORNL nozzles, which allowed the jet to fully develop, and (2) the effect that the geometry of the tank may have imposed. The line shown for the chemical mixture in Fig. 4 is a linear regression based on the data obtained with the 0.87-m^3 tank. The value of the proportionality constant, *K*, is $\sim 22 \text{ s} \cdot \text{m}^{-1}$. Additional data at higher values of DV_o are needed to confirm this value.

By monitoring the height of the suspended solids interface under the various risers, it was also found that the height of the suspended solids interface was approximately the same at any given time during the run; however, the concentration of suspended solids varied across the tank until the submerged jet had mobilized as much as it was going to mobilize and the slurry

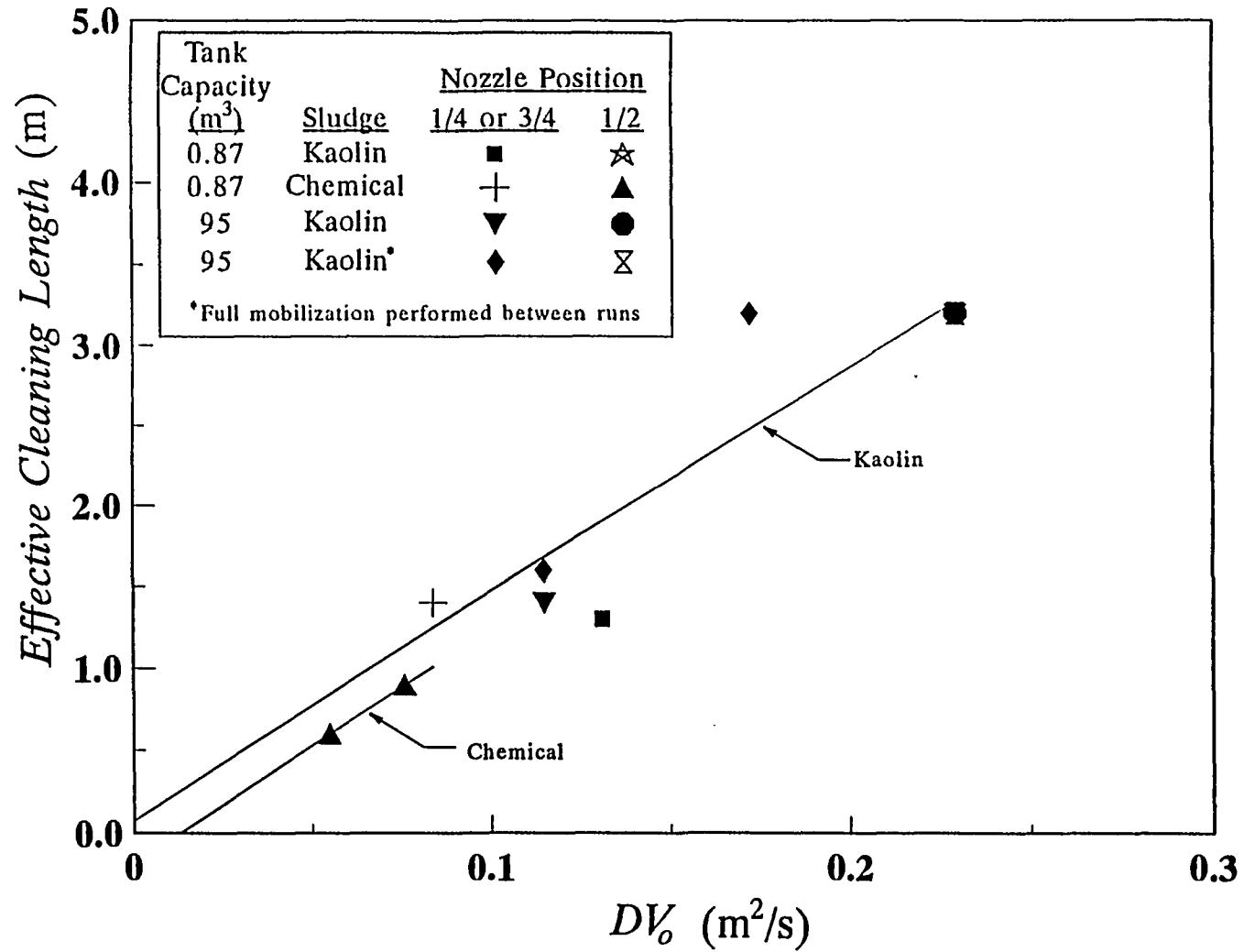


Fig. 4. Correlation of experimental data.

phase had reached an equilibrium concentration of suspended solids. Figure 5 shows the results from measuring the height of suspended solids in the tank at the various riser locations at various times during a particular run.

SUMMARY

The results presented in this paper demonstrate that it is feasible to use submerged jets for sludge mobilization in long horizontal cylindrical tanks. The size of the pump and the jet diameter can be predicted by determining the relationship between the effective cleaning length and the DV_o product. This study also indicates that a long jet nozzle allows the jet to fully develop and increases its effective cleaning distance. In comparing and contrasting internal and external mixer pumps, it was determined that the use of an external pump may be more advantageous for applications that involve a suction head less than 10 m (33 ft).

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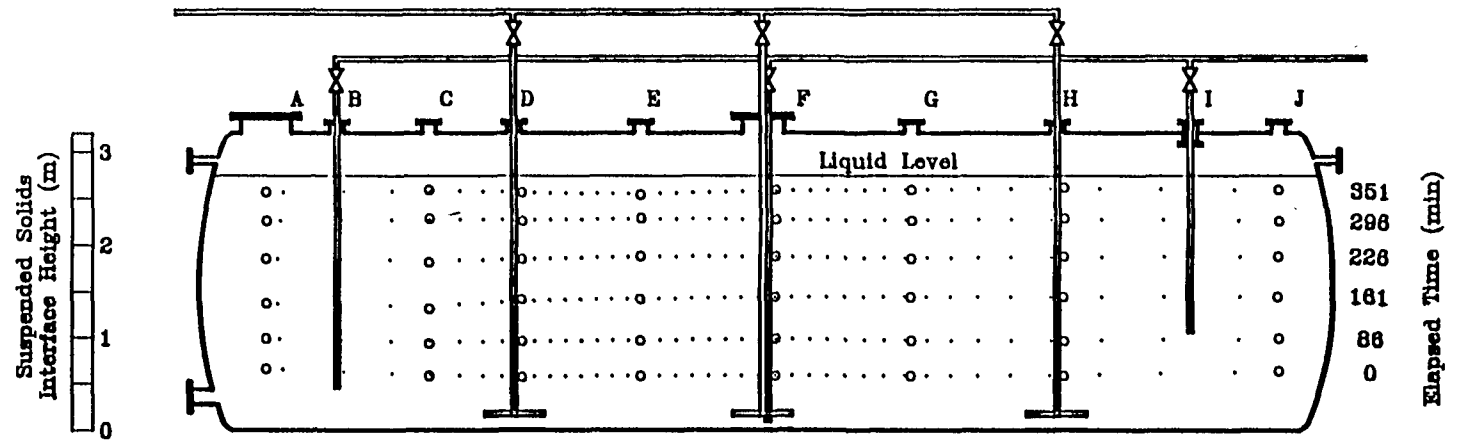


Fig. 5. Height of suspended solids during a mixing experiment.

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