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Sludge Mobilization with Submerged Nozzles in Horizontal Cylindrical Tanks

T. D. Hylton
R. L. Cummins
E. L. Youngblood
J. J. Perona

MANAGED BY
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

UCN-13673 (36 6-95)

ORNL/TM-13036

Chemical Technology Division

SLUDGE MOBILIZATION WITH SUBMERGED NOZZLES IN HORIZONTAL CYLINDRICAL TANKS

T. D. Hylton
R. L. Cummins
E. L. Youngblood*
J. J. Perona*

*Formerly a member of the Chemical Technology Division, ORNL.

Date Published: October 1995

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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ACRONYMS AND NOMENCLATURE

Acronyms

DOE	U.S. Department of Energy
ECL	effective cleaning length
ECR	effective cleaning radius
LEDs	light-emitting diodes
LLLW	liquid low-level waste
MVSTs	Melton Valley Storage Tanks
MVST-CIP	Melton Valley Storage Tank - Capacity Increase Project
ORNL	Oak Ridge National Laboratory
PNL	Pacific Northwest Laboratory
TEMPEST	time-dependent, energy, momentum, pressure, equation solution in three dimensions

Nomenclature

A	area of impact
C_1, C_2	constants
D	nozzle diameter
F	force of the jet striking the sludge
g_c	gravitational constant
r	radial distance from jet axis
V_o	initial discharge velocity
V_x	velocity at point x
x	distance from nozzle
α	proportionality constant
ρ	fluid density
τ_o	yield stress

ABSTRACT

The Melton Valley Storage Tanks (MVSTs) and the evaporator service tanks at the Oak Ridge National Laboratory (ORNL) are used for the collection and storage of liquid low-level waste (LLLW). Wastes collected in these tanks are typically acidic when generated and are neutralized with sodium hydroxide to protect the tanks from corrosion; however, the high pH of the solution causes the formation of insoluble compounds that precipitate. These precipitates formed a sludge layer approximately 0.6 to 1.2 m (2 to 4 ft) deep in the bottom of the tanks. The sludge in the MVSTs and the evaporator service tanks will eventually need to be removed from the tanks and treated for final disposal or transferred to another storage facility. The primary options for removing the sludge include single-point sluicing, use of a floating pump, robotic sluicing, and submerged-nozzle sluicing.

The objectives of this study were to (1) evaluate the feasibility of submerged-nozzle sluicing in horizontal cylindrical tanks and (2) obtain experimental data to validate the TEMPEST (time-dependent, energy, momentum, pressure, equation solution in three dimensions) computer code. Mobilization studies were performed in two model horizontal cylindrical tanks with surrogate sludges. The first model tank had a capacity of 0.87 m^3 (230 gal) and was ~1/6-dimensional scale of the MVSTs. The second model tank had a nominal capacity of 95 m^3 (25,000 gal) and was ~2/3-dimensional scale of the MVSTs. Kaolin clay was used as a surrogate sludge in both of these tanks, and a chemical sludge that

was formulated to represent the constituents of the sludge in the MVSTs was also used as a surrogate sludge in the 0.87-m^3 tank.

The tests performed in the 0.87-m^3 tank with kaolin and the chemical surrogate indicated that the two materials behaved similarly with respect to mobilization and that they could be modeled by comparing the effective cleaning length (ECL) with the product of the nozzle diameter and the jet velocity (DV_o).

Mobilization experiments were conducted in the 95-m^3 tank to obtain scaleup data. Bidirectional discharge nozzles were installed at three locations along the length of the tank. Suction legs were also installed at three locations in the tank. This arrangement provided versatility in conducting mixing and mobilization experiments. The depths of the suction legs were varied to determine whether their location had any effect on mixing.

The mobilization data obtained from the 95-m^3 tank were also fit to the previously mentioned ECL–DV_o model. It was determined that the model could be used to predict the mobilization effort within the range of DV_o values tested. Up to 81% of the kaolin clay was mobilized and mixed; however, the mobilization was limited by use of an existing pump with a capacity of 12.6 L/s (200 gal/min). It is believed that a higher nozzle velocity would mobilize more of the sludge.

A comparison of the positions of the discharge nozzles along the length of the tank indicated that the nozzle position did not affect the quantity of kaolin mobilized. This finding was not surprising because the ECL of the nozzles was shorter than the distance between the nozzle and the end of the tank. A difference would be expected if the ECL was longer than the distance between the nozzle and the end of the tank.

Experimental data indicate that the depth of the suction lines did not affect the quantity of sludge mobilized, but evidence showed that the contents mixed faster when the suction leg was either in the supernatant or near the sludge-supernatant interface. The mixing time was significantly slower when the suction leg was deep in the sludge.

Although kaolin clay was selected to represent the sludge in the tanks because it exhibited some of the same properties as the sludge in MVST W-28, it cannot be considered an ideal simulant. Whether kaolin clay is a reasonable material to represent the sludge in the MVSTs or the evaporator service tanks is unknown. The resistance to mobilization (i.e., the shear strength) should be determined for both kaolin and the actual sludges in the LLLW tanks as one method for determining whether kaolin is a reasonable surrogate.

The most likely place to install submerged nozzles in the existing MVSTs and the evaporator service tanks is at a manhole entry that is located approximately 13.7 m (45 ft) from the long end of the tank. Assuming that kaolin is a reasonable surrogate, a high jet velocity will be required to successfully mobilize the sludge in the long end of the tank. Assuming also that the submerged nozzle will be constructed from 2-in. pipe, the required volumetric flow rate would be 39 L/s (620 gal/min). Additional mobilization studies should be performed to demonstrate that the sludge can be mobilized in the long end of the tank. These mobilization tests should preferably be conducted on a simulant that shows a similar resistance to mobilization as the sludges in the MVSTs and evaporator service tanks. The study should also investigate rotating the nozzle and should determine whether obstacles in the tank (such as air spargers) affect the mobilization of the sludge.

1. INTRODUCTION

The Melton Valley Storage Tanks (MVSTs) and the evaporator service tanks at the Oak Ridge National Laboratory (ORNL) are used for the collection and storage of liquid low-level waste (LLLW). There are eight MVSTs and five evaporator service tanks. Each tank has a nominal capacity of 190 m^3 (50,000 gal). These tanks, which are constructed from stainless steel, are approximately 18 m (60 ft) long and 3.7 m (12 ft) in diameter. Wastes collected in these tanks are typically acidic when generated and are neutralized with sodium hydroxide to protect the tanks from corrosion; however, the high pH of the solution causes the metal compounds to precipitate. These precipitates formed a sludge layer approximately 0.6 to 1.2 m (2 to 4 ft) deep in the bottom of the tanks.[1] To help ease the problems associated with LLLW storage capacity, six new tanks are scheduled to be installed at ORNL by the end of 1998 by the MVST Capacity Increase Project (MVST-CIP). Each of these tanks will have a nominal capacity of 380 m^3 (100,000 gal). Although the wastes that are to be stored in these tanks are not expected to generate a sludge layer, the designers are including features to facilitate sludge mobilization.

The sludge in the MVSTs and the evaporator service tanks will eventually need to be removed from the tanks and treated for final disposal or transferred to another storage facility. The primary options for removing the sludge include single-point sluicing, use of a floating pump, robotic sluicing, and submerged-nozzle sluicing. Communications with personnel from other U.S. Department of Energy (DOE) sites, such as Savannah River, West Valley, and Hanford, indicate that these sites have used submerged nozzles (mixing pumps) for mobilizing sludge in vertical cylindrical tanks; however, the technique has not been used in horizontal cylindrical tanks like those at ORNL.

Since it is difficult to perform sludge mobilization tests at full scale or with the actual waste, it is desirable to model the behavior of the submerged nozzle for purposes of scaleup and to account for differences in properties of waste sludges. Pacific Northwest Laboratory (PNL) originally developed the TEMPEST (time-dependent, energy, momentum, pressure, equation solution in three dimensions) computer code and used it extensively to simulate problems in complex geometries. PNL recently extended the capabilities of the computer code to handle the flow of generalized Newtonian (pseudoplastic and yield-pseudoplastic) fluids. PNL has used the TEMPEST code extensively in recent years to support tank mixing studies and application to waste storage tanks at the DOE Hanford site.[2] Since the ORNL tanks are horizontal cylinders and the Hanford tanks are vertical cylinders, the TEMPEST code was not usable without modification. ORNL contracted with PNL to modify the TEMPEST code to simulate sludge mixing and mobilization in horizontal tanks.

The difference between mobilization and mixing should be emphasized. The term "mobilization" refers to suspending the settled sludge in the supernatant, while "mixing" refers to generating a uniform composition of solids and supernatant in the tank. It is possible to obtain full mobilization without fully mixing the contents.

The objectives of this study were to (1) evaluate the feasibility of submerged-nozzle sluicing in horizontal cylindrical tanks and (2) obtain experimental data to verify the modified TEMPEST code. Mobilization studies were performed in two model horizontal cylindrical tanks with surrogate sludges. The first model tank had a capacity of 0.87 m^3

(230 gal) and was ~1/6-linear scale of the MVSTs. The second model tank had a nominal capacity of 95 m^3 (25,000 gal) and was ~2/3-dimensional scale of the MVSTs. Photographs of these tanks are shown in Figs. 1 and 2. Kaolin clay was used as a surrogate sludge in both of these tanks, and a chemical sludge that was formulated to represent the constituents of the sludge in the MVSTs was also used as a surrogate sludge in the 0.87-m^3 (230-gal) tank.

2. BACKGROUND INFORMATION

Millions of gallons of radioactive waste are stored in underground tanks at DOE installations (e.g., Hanford, Savannah River, West Valley, and ORNL). Concentration and neutralization of the waste have caused solids to precipitate and form a sludge layer in the bottom of many of the tanks.

Several methods have been developed for mixing and mobilization of sludge in the tanks for purposes such as the recovery of uranium and fission products and for tank cleanup. Until the 1970s, the primary method of sludge removal from underground tanks was by sluicing with a medium-pressure liquid nozzle located in the airspace above the sludge. The method developed and used at Hanford has been described by Rasmussen.[3] A similar method, described by Weeren, was used for removal of the sludge from some gunite tanks at ORNL from 1982 to 1984.[4]

Between 1966 and 1969, high-velocity submerged-water nozzles that included a pair of 1/4-in.-diam nozzles operating at 3000 psi were used to remove sludge from tanks at Savannah River.[5] This system required the addition of about five volumes of water for each

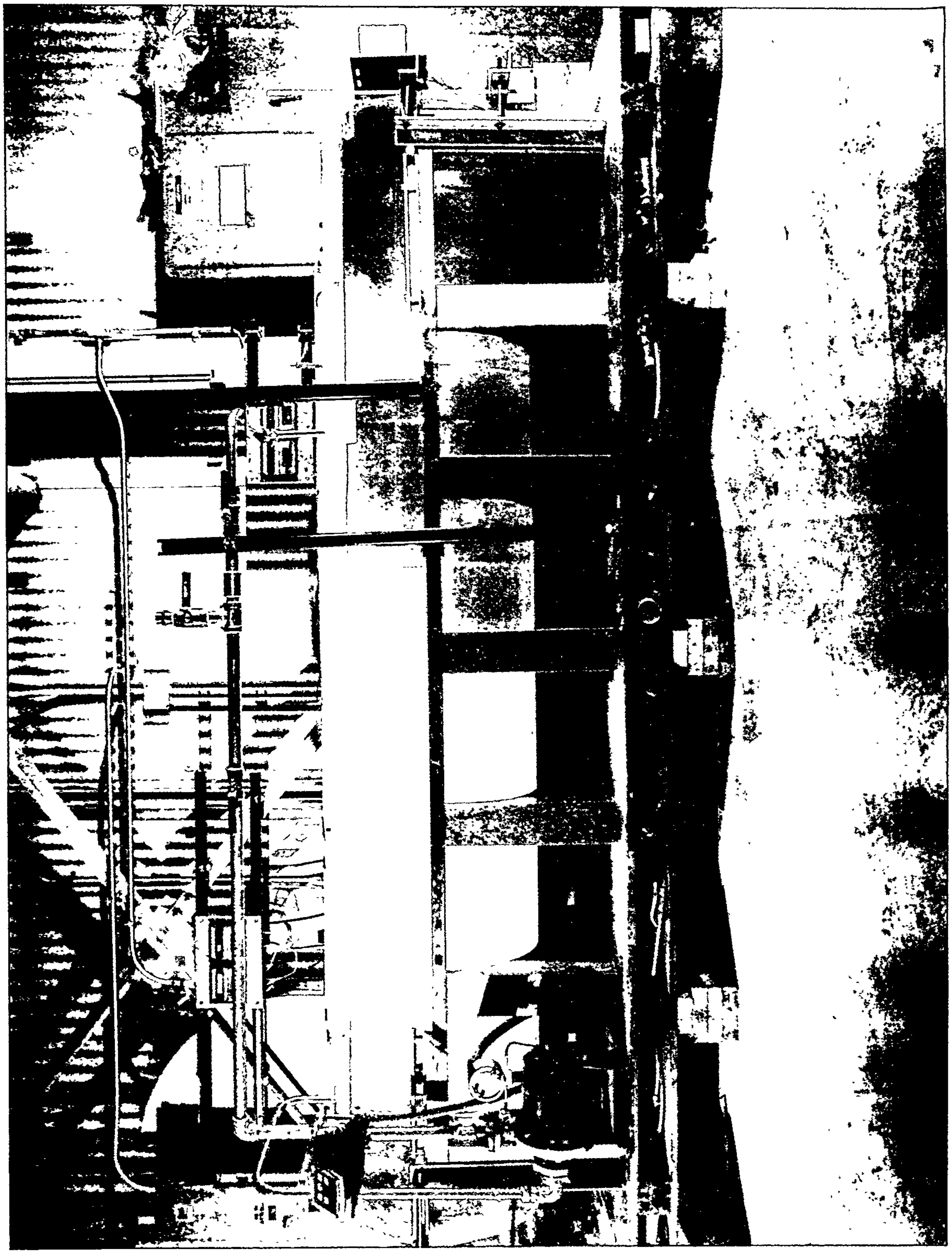

Fig. 1. Photograph of the 0.87-m^3 tank.

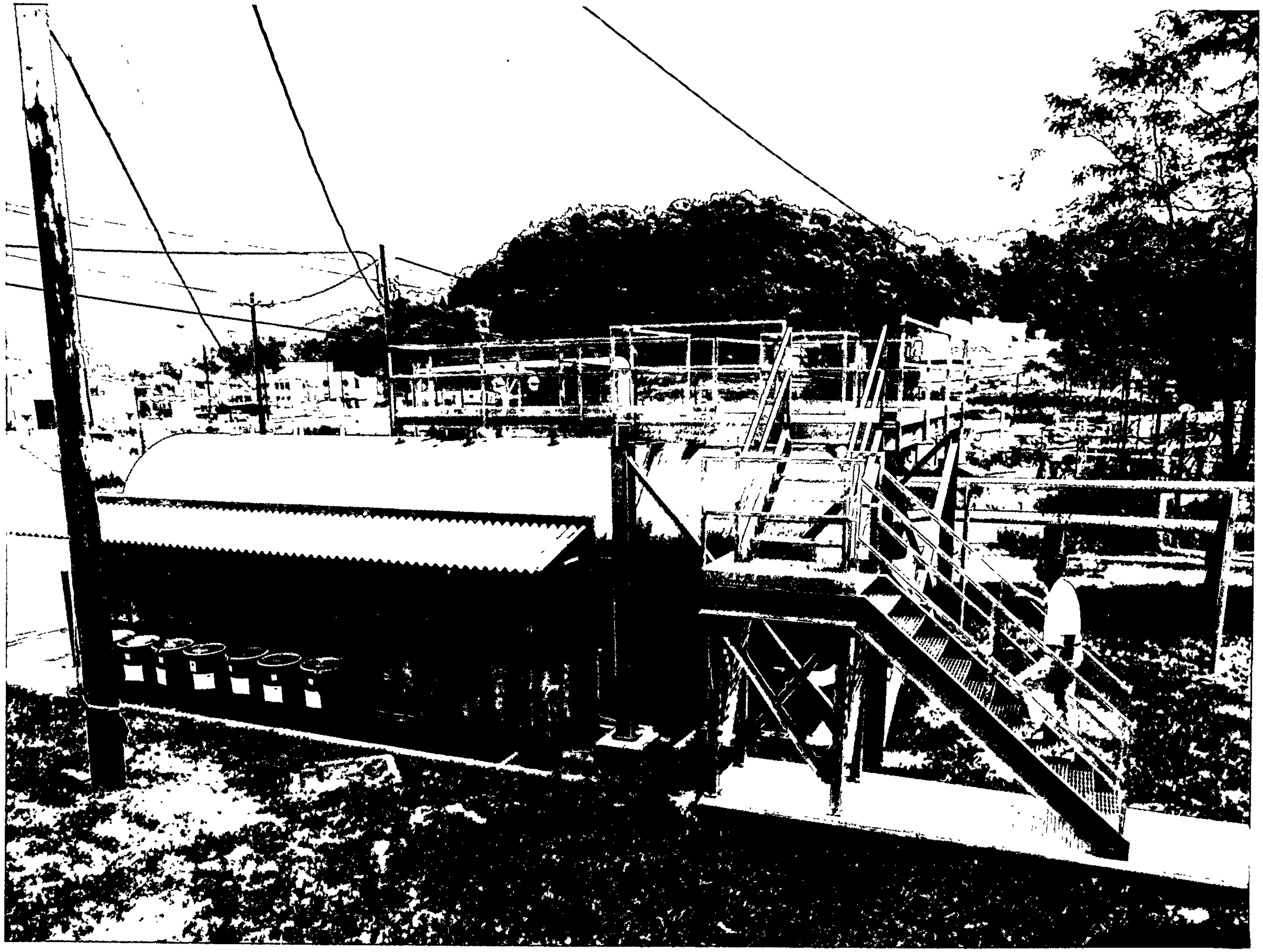

Fig. 2. Photograph of the 95-m^3 tank.

volume of sludge removed. To avoid the addition of large amounts of water to the waste, Savannah River developed a low-pressure submerged-nozzle system that made use of nozzle pumps and the existing supernatant in the tanks. Since that time, considerable work has been done at Savannah River, Hanford, and West Valley to develop nozzle pumps for sludge mobilization and to study sludge mobilization in vertical-wall tanks. Sludge mobilization studies with submerged nozzles or nozzle pumps in horizontal tanks have been previously performed. Previous mobilization studies with sand and fly ash in a 0.87-m^3 model of the MVSTs were reported by Shor and Cummins.[6] Mixing tests of liquids in horizontal cylindrical tanks were performed as a part of this study, and the results are reported separately by Perona et al.[7]

The nozzle pumps that are typically used for sludge mobilization are long-shaft centrifugal pumps mounted on top of the tank with the shaft extending just above the sludge layer. Liquid is drawn into the bottom of the pump and discharged through two to four horizontal nozzles located in the pump casing. As the sludge is mobilized, the pump is lowered deeper into the tank. In vertical-wall tanks the pump is slowly rotated to mobilize the sludge within a certain radius of the pump.[5] Several pumps may be required to mobilize the sludge in a large tank. Results similar to those obtained with the use of a nozzle pump may be obtained by locating the pump outside the tank and extending pipelines to the nozzles at the bottom of the tank. This method was used with a kaolin simulant to represent the action of nozzle pumps for scale-model testing of mobilization of sludge in the West Valley storage tanks.[8] This method is useful in simulating the action of nozzle pumps and may be a less expensive method for use in horizontal tanks and smaller vertical tanks. The limitation would be the suction head for the pump.

Since it is difficult to perform sludge mobilization tests at full scale or with the actual waste, it is desirable to model the behavior of the submerged nozzle for scaleup and to account for differences in properties of the waste. Mathematical equations have been developed by Savannah River and Hanford that balance the force of the liquid jet against that required to shear or erode the sludge.[9-12] These equations generally do not consider variables such as mixing time, concentration gradients, settling, or variations in geometry (such as horizontal tanks).

2.1 THEORY

Four flow regions have been described for turbulent flow of Newtonian fluids through jets.[13] 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 and is 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 it is the region where the major portion of the sludge mobilization occurs. An equation for the velocity profile along the x-axis in the established-flow region of a jet has been developed by Albertson et al.[14] 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,
r = radial distance from jet axis.

The angle at which the jet expands affects constants C_1 and C_2, but Eq. (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 the surface of the sludge at a right angle, 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,
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.[15-17] For a Bingham plastic material, the force required to begin movement is considered the product of the yield stress (τ_o) and the 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.[9] This term was then substituted into Eq. (1) to give the following equation for calculating the distance at which the sludge will be mobilized [i.e., the effective cleaning radius (ECR)]:

$$\text{Effective cleaning radius} = K\,D\,V_0\left(\frac{\rho}{2\,\tau_o\,g_c}\right)^{1/2}, \qquad \textbf{(3)}$$

where

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

Equations (3) and (4) indicate that the ECR is essentially proportional to the product of the nozzle diameter and the initial jet velocity for a system in which the density of the fluid and the yield stress of the sludge are constant:

$$\text{Effective cleaning radius} = \alpha\,D\,V_o. \qquad \textbf{(5)}$$

The value of α is dependent on the type of material to be mobilized. This proportionality relationship has been confirmed to some extent in experimental studies with varying nozzle sizes and jet velocities in vertical tanks.[10] In one test, a 1/4-in.-diam jet operated at 650 ft/s and 3000 psi gave essentially the same ECR as a 1.5-in.-diam nozzle operated at 100 ft/s and 100 psi. These two nozzles had the same DV_o product.[5] Figure 3 shows a typical plot of

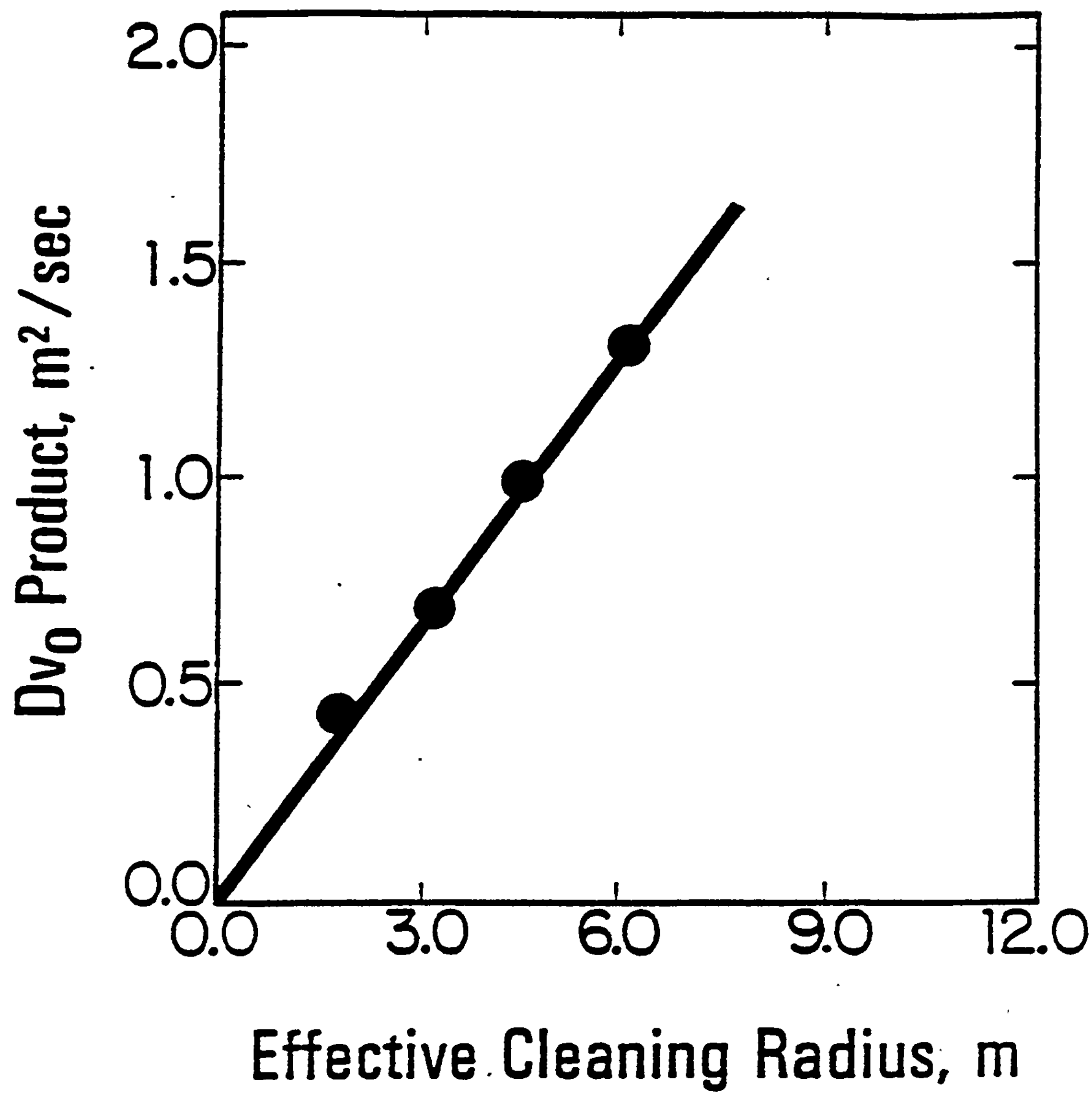

Fig. 3. Typical plot of ECR versus DV_o for jet pumps tested at Savannah River. *Source:* B. V. Churnetski, "Prediction of Centrifugal Pump-Cleaning Ability in Waste Sludge," DP-MS-81-68, presented at the 1981 American Nuclear Society Winter Meeting at San Francisco, Calif., November 29, 1981–December 4, 1981. Graph is reproduced without any modifications.

ECR versus DV_o for jet pumps tested at Savannah River.[10] The previously presented 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. Studies by Hamm indicate that the ECR continues to increase with time although the sludge removal rate may become very slow.[11] The effect of the impact of jet forces on tank components has been studied by Bamberger et al.[18] No information has been found for the effect of geometry on the jet velocity profile in horizontal tanks.

Heath reports of the development of a shear vane device to measure the amount of force required to initiate movement of sludges. This force, defined as the shear strength of the sludge, was determined in situ since changes in properties could result from removal of a sample for measurement. It was determined that a Bingham plastic slurry typically had a shear strength higher than its yield stress.[19]

2.2 TEMPEST SIMULATIONS

In an attempt to better model the effects of geometry, sludge properties, and other variables, the TEMPEST computer program was modified by PNL, as a part of this project, to simulate mixing of fluids and to simulate sludge mobilization and mixing in horizontal cylindrical tanks. The TEMPEST computer program numerically solves a base set of governing transport equations for continuity, momentum, and species transport.[20] TEMPEST has been used extensively for several years to simulate three-dimensional time-dependent thermofluid problems and has been used in recent years to support tank mixing studies.

PNL has published three technical reports for the work performed with the TEMPEST computer code for ORNL. The first report addressed the following objectives.[2]

- Investigate requirements for stable numerical solutions of submerged-liquid jet mixing in a non-Newtonian fluid whose rheology is described by a concentration-dependent power law model approximating W-28 sludge.
- Simulate mobilization and homogenization of sludge layers of Newtonian and non-Newtonian fluids in a half-filled tank that was 1/6-scale of the MVSTs.
- Investigate definition and application of mixing-time criteria based on time-history concentration curves.
- Compute the mixing time of water in tanks that were 1/6-scale and 2/3-scale model MVST tanks.
- Investigate and recommend a simulant for the W-28 sludge to be used in experimental studies in the 1/6-scale and 2/3-scale tanks at ORNL.

The work discussed in PNL's second report was a continuation of the work addressed in the first report. The specific tasks that are examined in the second report include the following.[21]

- Make a preliminary investigation to determine two plausible jet diameters for sludge mobilization.
- Determine mixing times for a tank filled with supernatant only, with a centrally located suction line. Two opposed jets are located in the middle of the tank at least two diameters above the floor. Chemical addition is near the horizontal center at the top of the tank. The recirculation rate is 12.6 L/s (200 gal/min).

- Conduct a procedure identical to the previous one, except suction inlets are located at equal heights at the two tank ends.
- Determine the minimum velocity to mobilize MVST W-28 sludge for each of two jet diameters. Two recirculation inlet locations were considered: one at the tank center under the jets and the other at unequal heights at the tank ends.

The objective of the work described in the third PNL report[22] was to simulate the behavior of kaolin clay sludge in a 95-m^3 (25,000-gal) horizontal tank to obtain model predictions that could be compared with data experimentally obtained by ORNL. The results of the ORNL experimental data are covered in this report. The TEMPEST computer model examined two different jet/suction configurations. When the TEMPEST predictions were compared with the experimental data, it was concluded that the TEMPEST predictions of kaolin sludge mobilization were not totally successful. The experimental data, which are discussed later in this report, indicated that ~65 to 80% of the kaolin was mobilized at a total flow rate of 12.6 L/s (200 gal/min), whereas the TEMPEST model predicted that all the kaolin would be mobilized. PNL has recommended performing additional model development work to improve the TEMPEST capability for sludge mobilization predictions.[22] The recommendations included the following:

- reviewing recent 1/25-scale kaolin mobilization experiments conducted at PNL to determine the important parameters that have been identified,
- implementing logic in TEMPEST to track an approximate interface between a strength-containing sludge region and an adjacent fluid region,
- implementing an interface mass-transport model, and

- numerically test the model improvement to demonstrate that it can be used to correctly predict partial mobilization of a sludge layer.

2.3 USE OF KAOLIN AS A SIMULANT

Previous work has been done using kaolin as a simulant for radioactive sludge at Savannah River.[10,15] Selby's results indicate that the concentration (weight percent solids) of kaolin sludge produced by settling continues to increase for up to 2 months due to water exclusion. Water exclusion is accompanied by a corresponding increase in viscosity. In settling tests, the solids concentration and viscosity varied with the depth of the sludge beneath the surface. Variation of viscosity with depth may explain why long beaches (which contained a higher solids content) were more difficult to mobilize than kaolin that has settled for 2 weeks. While chemically simulated waste did not show a similar variation of viscosity with depth, long beaches were expected to form because of the effect of the jet riding over the surface of the sludge. Small-scale tests with kaolin indicated that the ECR was influenced to some extent by the height of the pump (or nozzle) above the tank bottom.

Kaolin was also used as the simulant in scale-model testing of equipment for removal of the sludge from a high-level radioactive waste tank at West Valley.[8] An approximately 30 wt % kaolin clay sludge was formulated to approximately match the shear strength of the actual sludge in the waste tank.

As part of the TEMPEST simulation work, an investigation was made by PNL to find a simulant with rheological properties similar to those of the sludge in the MVSTs.[2] The properties of the sludge in MVST W-28 were used in the simulant development studies. Properties of the simulant were to be used for computer modeling of tests done in the 0.87- and 95-m^3 tanks at ORNL. Factors considered in selecting the simulant were rheology of the sludge (initial and diluted) and settling rate. Simulants having compositions similar to the actual waste were not considered because of the difficulty and expense of using chemicals in large-scale tests. With this constraint the simulants tested were limited to kaolin and mixtures of kaolin and bentonite. Mixtures of kaolin and bentonite were found to settle too slowly for use in large-scale tests. Kaolin sludges generally had lower viscosities than the W-28 sludge and were deemed not to be ideal simulants. However, the kaolin sludges also exhibited some favorable properties. PNL concluded that kaolin was acceptable for use in the mobilization tests for verification of the TEMPEST computer model, but that the results should not be used for designing the actual mobilization system for the MVSTs.[2]

2.4 DETERMINATION OF JET EFFECTIVENESS

The effectiveness of a submerged nozzle is determined by the distance cleared in the tank. If the jet velocity from a submerged nozzle 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. An example of a beach profile is shown in Fig. 4. Since there is not a distinct wall of sludge, 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. He equated this distance to the ECR.[5] Since the mobilized sludge remained

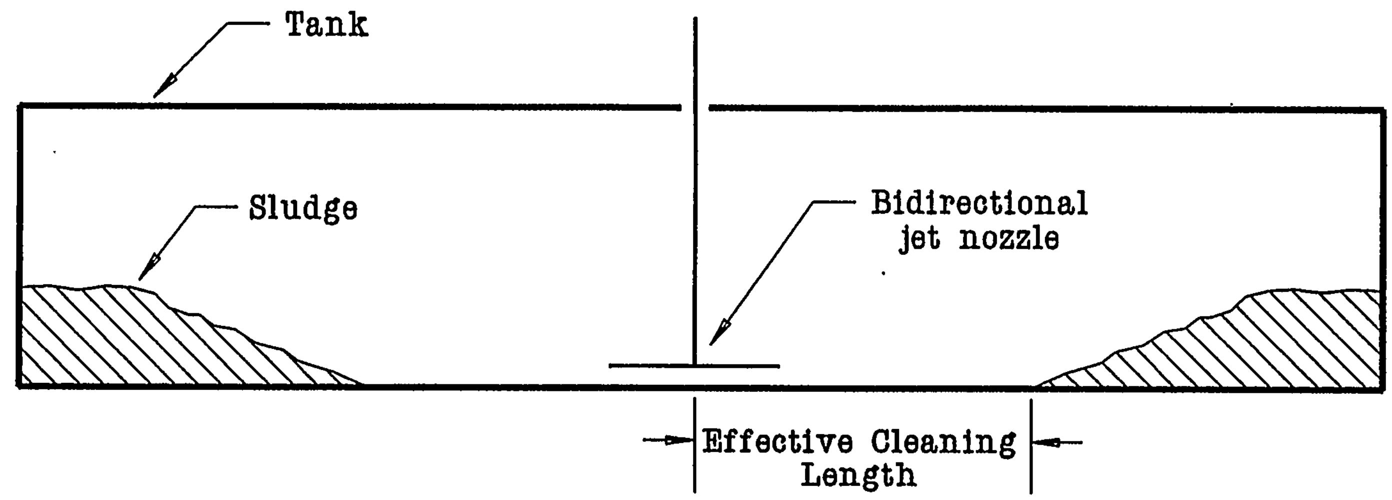

Fig. 4. Diagram of a typical beach profile.

in the tank for the tests conducted for this report, it was not practical to use the 1/8-in. depth of sludge as the criterion for determining the ECR. In addition, since the submerged nozzles were fixed in position (i.e., they did not rotate) for the tests described in this report, it is more reasonable to define a similar quantity known as the effective cleaning length (ECL). This definition is shown schematically in Fig. 4.

At the end of each run, slurry samples were collected approximately 2.5 cm from the bottom at each port location. Samples that showed suspended solids concentrations similar to that in the recirculating slurry were considered within the ECL. Samples that showed significantly higher concentrations were identified as areas outside the ECL.

3. DESCRIPTION OF EQUIPMENT AND MATERIALS

The work with submerged nozzles for sludge mobilization was divided into two phases. The first phase consisted of sludge mobilization experiments in a 0.87-m^3 (230-gal) tank that was ~1/6-dimensional scale model of the MVSTs, and the second phase evaluated sludge mobilization in a 95-m^3 tank that was ~2/3-dimensional scale of the MVSTs. The equipment and materials used with each of these tanks are described below.

3.1 EXPERIMENTS IN THE 0.87-m^3 TANK

The dimensions of the 0.87-m^3 tank are 0.6 m (2 ft) diam by 3 m (10 ft) long. The tank was constructed from Plexiglas so that the mobilization activity could be monitored visually. Although the MVSTs have parabolic ends, the 0.87-m^3 model tank had flat ends. The experimental setup was a simple recirculation loop; a typical experimental setup is shown in Fig. 5. The positions of the discharge nozzle and suction leg were varied so that different LLLW tanks could be simulated. For example, the MVSTs would likely use a submerged nozzle at a distance ~1/4 tank length from the end of the tank and a suction leg on the opposite end of the tank. The MVST-CIP tanks were evaluated by placing the discharge nozzle at the center of the tank, with the suction at either the end or the center of the tank. Dimensioned drawings of a submerged nozzle in the center of the tank and 1/4 tank length from the end of the tank are shown in Appendix B.

A canned motor pump (Crane model GA-1K-1S) was used to provide flow rates up to ~2.3 L/s (36 gal/min). For flow rates greater than 2.3 L/s, a centrifugal pump (Durco Mark II T-line) was used. The flow rate was measured with an electromagnetic flowmeter (EMCO MAGFLO™ model 3000). The discharge nozzle was either a unidirectional or a bidirectional nozzle, and the inside diameter of all the discharge nozzles was 0.022 m (0.87 in.).

Two different simulants were used to represent the sludge in the MVSTs. The first simulant was kaolin clay, which PNL recommended as a simulant.[2] A mixture of 45 kg (100 lb) of kaolin clay, which was procured from Feldspar Corp., Florida, and ~760 L (200 gal) of 1 wt % sodium chloride in water as the supernatant was added to the tank. The purpose of the sodium chloride was to aid in the settling of the kaolin particles after a mixing test was completed. This mixture provided an approximate sludge depth of 0.1 m (4 in.).

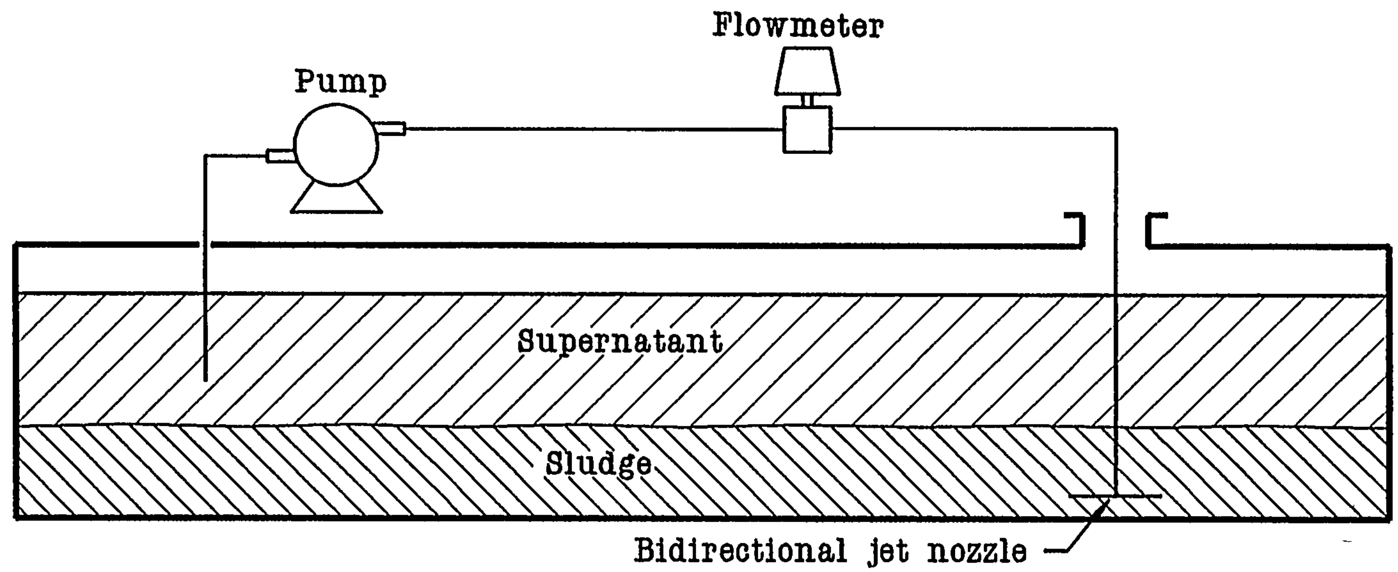

Fig. 5. Typical piping configuration in the 0.87-m^3 tank.

The second simulant was a chemical mixture based on the samples collected from the MVSTs in the 1989-1990 sampling campaign.[1] This simulant was originally used in a slurry transport study to determine the expected rheological properties of the MVST slurry.[23] The supernatant included compounds of sodium nitrate, potassium nitrate, sodium carbonate, sodium chloride, and sodium hydroxide. The total nitrate concentration in the supernatant was approximately 4 *M*. The sludge portion consisted of calcium carbonate, calcium hydroxide, magnesium hydroxide, silicic acid, aluminum hydroxide, and iron hydroxide. The actual chemical formulation and recipe for preparing the simulant are recorded in the transport study report.[23] The sludge depth in the tank was approximately 0.2 m (8 in.).

3.2 EXPERIMENTS IN THE 95-m^3 TANK

3.2.1 Design

The diameter of the 95-m^3 tank is 3.2 m (10.4 ft), and the length of the tank (excluding end caps) is 11.7 m (38.5 ft). A Gardner-Denver® Tee triplex plunger pump was used to provide flow rates up to approximately 12.6 L/s (200 gal/min). The flow rate was measured with an electromagnetic flowmeter (EMCO MAGFLO™ model 3000).

A solids monitoring system (BTG™ model SMS-3000 with sensor RDP-10/5) was installed for continuous in-line measurement and real-time monitoring of the suspended solids concentration in the recirculation line. The solids monitoring system uses a patented 4-Beam™ alternating-light principle. Two infrared light-emitting diodes (LEDs) and two photodetectors are molded into each side of the sensor. The electronic transmitter alternately turns the LEDs on and off, while continuously measuring the amplitude of light transmitted through the process media to the detectors.[24,25] When the solids monitor showed that the concentration of suspended solids was steady for >30 min, the run was considered complete. This condition would indicate that the jets had mobilized all the sludge that was going to be mobilized under the given conditions and that the composition of the contents was uniformly or near-uniformly mixed.

Three bidirectional discharge nozzles and three suction legs were installed in the 95-m^3 tank to provide versatility in modeling different tank configurations (e.g., MVSTs, MVST-CIP). Only one discharge line and one suction line were used for any run; however, multiple suction and discharge locations were used when attempting to mobilize as much sludge as possible to evenly distribute the sludge across the tank. The discharge piping was constructed from 2-in. Schedule 80 pipe, and the suction piping was 3-in. Schedule 40 pipe. The suction legs were nominally located (1) ~1/8 tank length from the end of the tank, (2) at the center of the tank, and (3) ~7/8 tank length from the end of the tank. A schematic diagram of the piping configuration is shown in Fig. 6. A dimensioned drawing of the 95-m^3 tank is shown in Appendix B.

The discharge nozzles were installed as a tee connection on the end of the discharge lines. They were fabricated from 1.25-in. Schedule 40 pipe. The inside diameter of each nozzle was 0.035 m (1.38 in.). The nozzle diameter was selected to provide a jet velocity of approximately 6.1 m/s (20 ft/s) at each nozzle with the available pumping capacity. Each nozzle was approximately 10 pipe diameters long and was located approximately 0.15 m (6 in.) from the bottom of the tank. The discharge nozzles were located (1) ~1/4 tank length

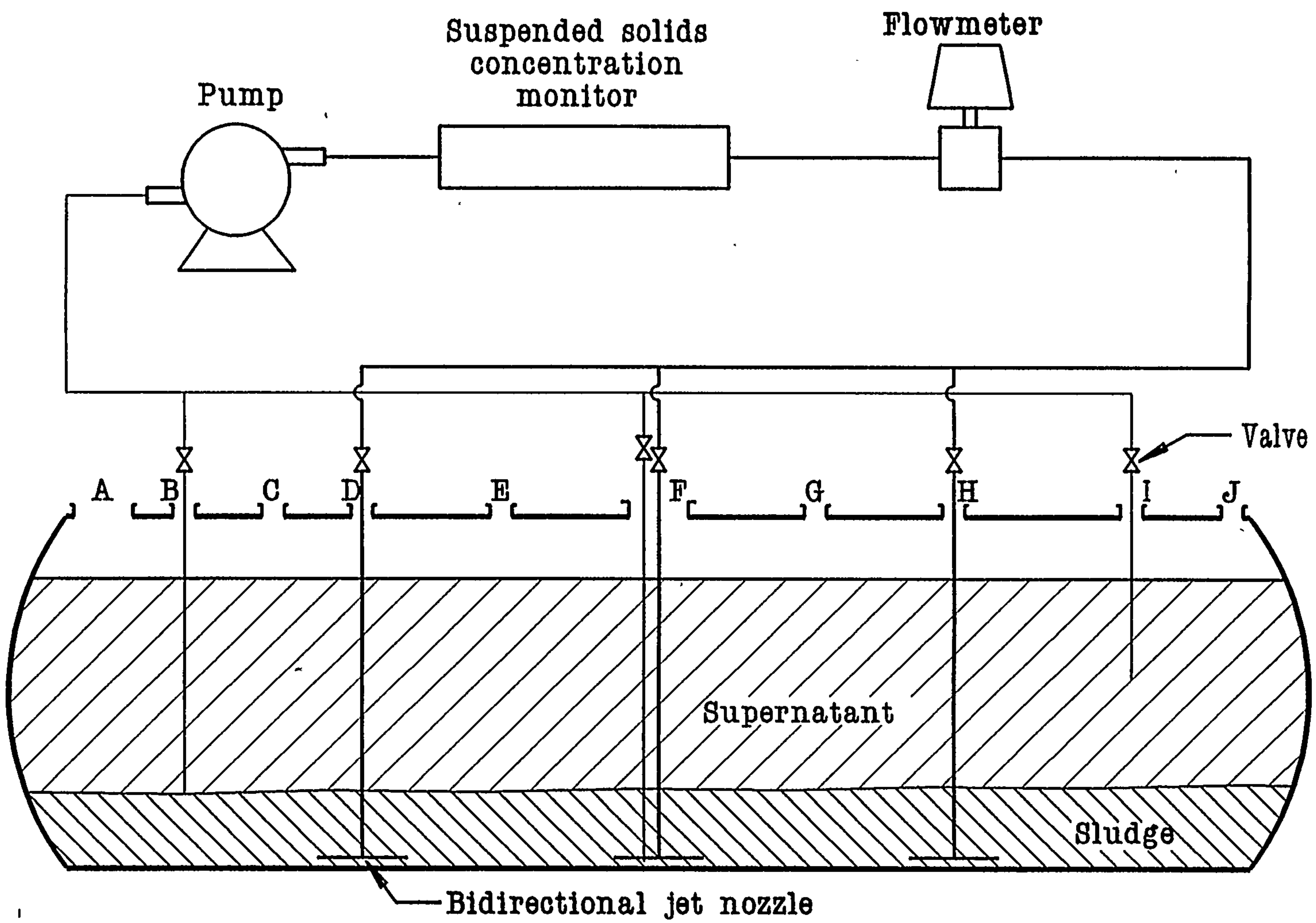

Fig. 6. Piping configuration for the 95-m³ tank.

from the end of the tank, (2) at the center of the tank, and (3) ~3/4 tank length from the end of the tank.

A chemical simulant of the sludge in the MVSTs was not a practical choice for use as a surrogate sludge because of the hazards of dealing with large quantities of the chemicals and the ultimate disposal problems that would be encountered. Based on the recommendation from PNL, kaolin clay was selected as a simulant.

It has been reported that the rheology of kaolin does not stabilize until it has been sufficiently sheared.[15] Therefore, the kaolin was prepared as a slurry in a mixing tank and sheared by agitation prior to adding the mixture to the 95-m^3 tank. The kaolin was prepared in two batches. In the first batch, 2270 kg (5000 lb) of kaolin was added to approximately 9500 L (2500 gal) of 0.1 wt % sodium chloride in water solution. The mixture was sheared for ~96 h and then transferred to the 95-m^3 tank. A second batch of kaolin slurry was prepared that consisted of 1820 kg (4000 lb) of kaolin and approximately 9500 L (2500 gal) of 0.1 wt % sodium chloride in water solution. The second batch was sheared ~120 h and then transferred to the 95-m^3 tank with the first batch. The depth of the kaolin sludge was approximately 0.5 m (20 in.) after settling, and the total depth of supernatant and sludge was 2.67 m (105 in.).

3.2.2 Detection of Sludge-Level Interface

The sludge-level interface was detected and measured in the tank with a portable sludge-level detector (Markland Model 10 Sludge Gun®). The unit consists of the gun and a bob on the end of a cable. When the trigger on the gun is depressed, high-intensity bursts of infrared light are transmitted by an LED across a groove in the bottom of the bob. A photocell detector is on the other side of the groove in the bob. When the groove contains air or clear liquid, the sludge gun gives zero response. When the groove encounters suspended solids, some light is absorbed and the gun gives an audio signal that solid particles have entered the groove.

The height of the sludge interface is established from depth markers on the cable.[26] The minimum detectable suspended solids concentration was determined to be ~3 g/L by a bench-scale test using kaolin as the suspended solid.

3.2.3 Sampling System for In-tank Samples

The suspended solids concentrations at various depths in the tank were determined by sampling. The sampling apparatus consisted of a vacuum pump, a vacuum flask, a 3/8-in.-diam tube that would reach the bottom of the tank, and flexible connectors. To obtain a sample, the tube was lowered into the tank to the desired depth, the vacuum pump was turned on, and an aliquot was collected in the vacuum flask. The first sample was treated as a line flush/conditioner and discarded. A second sample was collected to represent the tank's contents while the sample tube was held at the desired depth. The slurry samples were dried, and the concentrations of suspended solids were determined by the weight loss of water. The procedure for analyzing suspended solids samples is described in Appendix A. These samples were used to determine the quantity of sludge mobilized and to determine the ECL.

3.2.4 Sampling from the Recirculation Line

The suspended solids concentration in the recirculation line during the run was monitored by the solids monitoring instrument, and samples were collected and analyzed to determine the actual concentration of suspended solids. These samples were obtained from a 1/2-in.-diam tube inserted in the center of the recirculation line near the solids monitor detector. The tube was inserted such that the cross-sectional area of the tube was facing the flow. Samples obtained from the recirculation line were analyzed for suspended solids. These samples were collected during the run to track the progress and for comparison with the data obtained by the solids monitor. The final concentration of suspended solids in the recirculation line was used to determine the quantity of kaolin mobilized when the slurry phase was at a uniform or near-uniform concentration.

4. EXPERIMENTAL TESTING AND RESULTS

4.1 EXPERIMENTAL TESTING IN THE 0.87-m^3 TANK

Five runs were made in the 0.87-m^3 tank using submerged nozzles to mobilize kaolin clay sludge. The experimental conditions and results for the kaolin mobilization runs are shown in Table 1. In addition, five mobilization runs were performed with a chemical simulant using submerged jets. The experimental conditions and results for the sludge mobilization runs performed with the chemical mixture are shown in Table 2.

Table 1. Test conditions and results for the kaolin mobilization runs in the 0.87-m^3 tank

Run number	Jet type[a]	Discharge location	Suction location	Jet velocity[b] (m/s)	DV_o product[c] (m^2/s)	ECL[d] (m)	Jet Reynolds number	Length of run (min)	Percent mobilized
1	B	~1/4 tank length from end of tank	Opposite end of tank from jet location	3.0	0.065	NA[e]	65,000	30	85
2	B	~1/4 tank length from end of tank	Opposite end of tank from jet location	1.5	0.033	NA[e]	33,000	30	55
3	B	~1/4 tank length from end of tank	Opposite end of tank from jet location	0.73	0.016	NA[e]	16,000	30	38
4	U	~1/4 tank length from end of tank	Opposite end of tank from jet location	5.9	0.131	1.3	131,000	15	85
5	B	Center	Center	2.6	0.058	≥1.5	58,000	30	99

[a]B = bidirectional, U = unidirectional. All nozzles had an inside diameter of 0.022 m (0.87 in.).
[b]Multiply values by 3.281 to convert unit from m/s to ft/s.
[c]Multiply values by 10.764 to convert unit from m^2/s to ft^2/s.
[d]ECL = effective cleaning length. Multiply values by 3.281 to convert unit from m to ft.
[e]NA = not applicable.

Table 2. Test conditions and results for the chemical surrogate mobilization runs in the 0.87-m^3 tank

Run number	Jet type[a]	Discharge location	Suction location	Jet velocity[b] (m/s)	DV_o product[c] (m^2/s)	ECL[d] (m)	Jet Reynolds number	Length of run (min)	Percent mobilized
1	B	Center	Center	2.5	0.055	0.6	55,000	30	68
2	B	Center	Center	2.5	0.055	0.6	55,000	45	63
3	B	Center	Center	3.4	0.076	0.9	76,000	60	83
4	B	Center	Center	3.4	0.076	0.9	76,000	150	80
5	B	~1/4 tank length from end of tank	Center	3.8	0.084	1.4	84,000	120	88

[a]B = bidirectional, U = unidirectional. All nozzles had an inside diameter of 0.022 m (0.87 in.).
[b]Multiply values by 3.281 to convert unit from m/s to ft/s.
[c]Multiply values by 10.764 to convert unit from m^2/s to ft^2/s.
[d]ECL = effective cleaning length. Multiply values by 3.281 to convert unit from m to ft.

The ECL was determined by measuring the depth of sludge along the centerline of the tank after allowing the suspended solids to resettle. The shallow areas were interpreted to be the mobilized area, and the deeper areas were interpreted to be the unmobilized area. This technique began after the fourth run with kaolin.

4.2 EXPERIMENTAL TESTING IN THE 95-m^3 TANK

The test plan for the mixing and mobilization experiments in the 95-m^3 tank called for testing various piping configurations (e.g., center discharge and center suction) at various flow rates to simulate configurations for the MVSTs and the MVST-CIP tanks. Twelve mobilization runs were performed with kaolin. A list of the conditions for the various runs is shown in Table 3. To ensure that the properties of the kaolin were uniform for each run, the test plan allowed the kaolin to settle for approximately 7 days after each mobilization test. If the kaolin level was significantly uneven in the tank, all of the discharge nozzles were to be used individually and/or combined to fully mobilize the sludge. The kaolin would resettle for approximately 7 days prior to the next specific nozzle configuration run. Each of the mobilization runs is described in more detail in the sections that follow.

4.2.1 Run K-0

This run was performed to determine the maximum amount of the clay that could be mobilized using all three submerged nozzles and all three suction nozzles individually and combined in various configurations. Samples were taken from two locations at three depths

Table 3. Test conditions and results for the kaolin mobilization runs in the 95-m^3 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

[a]Amount of time that the solids settled prior to this run.
[b]All discharge nozzles were bidirectional and constructed from 1.25-in. Schedule 40 pipe. See Fig. 6 for location of ports.
[c]All suction legs were constructed from 3-in. Schedule 40 pipe. See Fig. 6 for visual location of ports.
[d]Multiply values by 3.281 to convert unit from m/s to ft/s. Multiply values by 10.76 to convert unit from m^2/s to ft^2/s.
[e]ECL = 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. Multiply values by 3.281 to convert unit from m to ft.
[f]This run used all the discharge nozzles and suction legs to mobilize the maximum quantity of sludge.
[g]ND = not determined; NA = not applicable.
[h]Estimated value based on the concentration of samples taken from inside the tank.

inside the tank at the end of the run and from the recirculation line at the end of the run. These samples were analyzed for suspended solids, and the results are shown in Table 4. The uniformity of the suspended solids concentration results at the various depths is an indication that the solids concentration was nearly uniform in the tank except for the portion of the sludge layer that was not mobilized. Refer to Fig. 6 for a visual indication of the port locations.

Table 4. Sample results from run K-0[a]

Sample location	Depth from bottom of tank (m)	(ft)	Suspended Solids (g/L)
Port E	0.6	2	31.6
	1.5	5	31.7
	2.4	8	31.7
Port G	0.6	2	31.6
	1.5	5	31.6
	2.4	8	31.6
Recirculation line	NA[b]	NA[b]	31.2

[a]This run used all three discharge nozzles and all three suction legs.
[b]NA = not applicable.

Complete mobilization of the 4090 kg (9000 lb) of kaolin in the 90,500 L (23,900 gal) of liquid would give a suspended solids concentration of 45.2 g/L. The final suspended solids concentration achieved in the run was 31.6 g/L, which indicated that 70% of the kaolin was mobilized. However, mobilization was limited by the use of an existing pump with a capacity that was somewhat less than the capacity predicted to be required to achieve full mobilization. Since all the nozzle locations were used at the maximum pumping capacity, 70% was considered the maximum mobilization achievable with the existing nozzle size, piping configuration, flow capacity, and kaolin packing. It is expected that full mobilization could be achieved by modifying the system to provide increased pumping capacity or possibly by using higher jet velocities with the existing pump.

4.2.2 Run K-1

This run was performed to model a proposed nozzle configuration for the MVST-CIP tanks. The discharge and suction nozzles were located in the center of the tank (port F). Progress of the run was measured by monitoring the output from the solids monitor and collecting samples from the recirculation line. Samples were also collected from inside the tank. The results for the in-tank samples, which are shown in Table 5, indicate that the concentration of suspended solids was uniform in the slurry phase at the end of the run.

The sample results from the recirculation line, which are shown in Fig. 7, indicate that steady state was achieved in 660 min. The final concentration of suspended solids, 29.9 g/L, indicates that 66.1% of the kaolin was mobilized and mixed. The solids monitor was calibrated to report the concentration between 0 and 100 g/L; therefore, the comparison is shown only for concentrations $\leq$100 g/L.

After the solids resettled in the tank, the sludge gun was used in an attempt to profile the depth of kaolin across the tank to determine the ECL. The theory was that the depth of solids would be more shallow in the mobilized areas than in the nonmobilized areas. The results indicated that the depth of solids was consistent across the tank; therefore, the ECL could not be determined for this run.

Table 5. Sample results from run K-1[a]

Elapsed time (min)	Port location[b]	Suspended solids (g/L) by depth from the bottom of the tank				
		0.5 m	1.5 m	1.8 m	2.1 m	2.4 m
120	D	159	0.0			0.0
	E	143	0.0			0.0
230	D	82.6	0.0			
	E		21.5			
	G	82.1	5.0			0.0
370	D	55.8	50.8			0.0
	E	54.6	48.8			0.0
	G	53.7	49.7	47.6	0.2	0.0
480	D			35.5	23.1	0.0
	G		38.6	36.2	23.8	
650	A	29.9	30.2			30.0
	D	29.9	29.8			29.8
	E	30.1	29.9			29.5
	F	30.0	29.9			29.3
	G	30.1	29.9			29.7

[a]The jet velocity for this run was 6.5 m/s (21.5 ft/s), and each nozzle had a DV_o product of 0.23 m^2/s (2.5 ft^2/s).

[b]See Fig. 6 for visual indication of port locations.

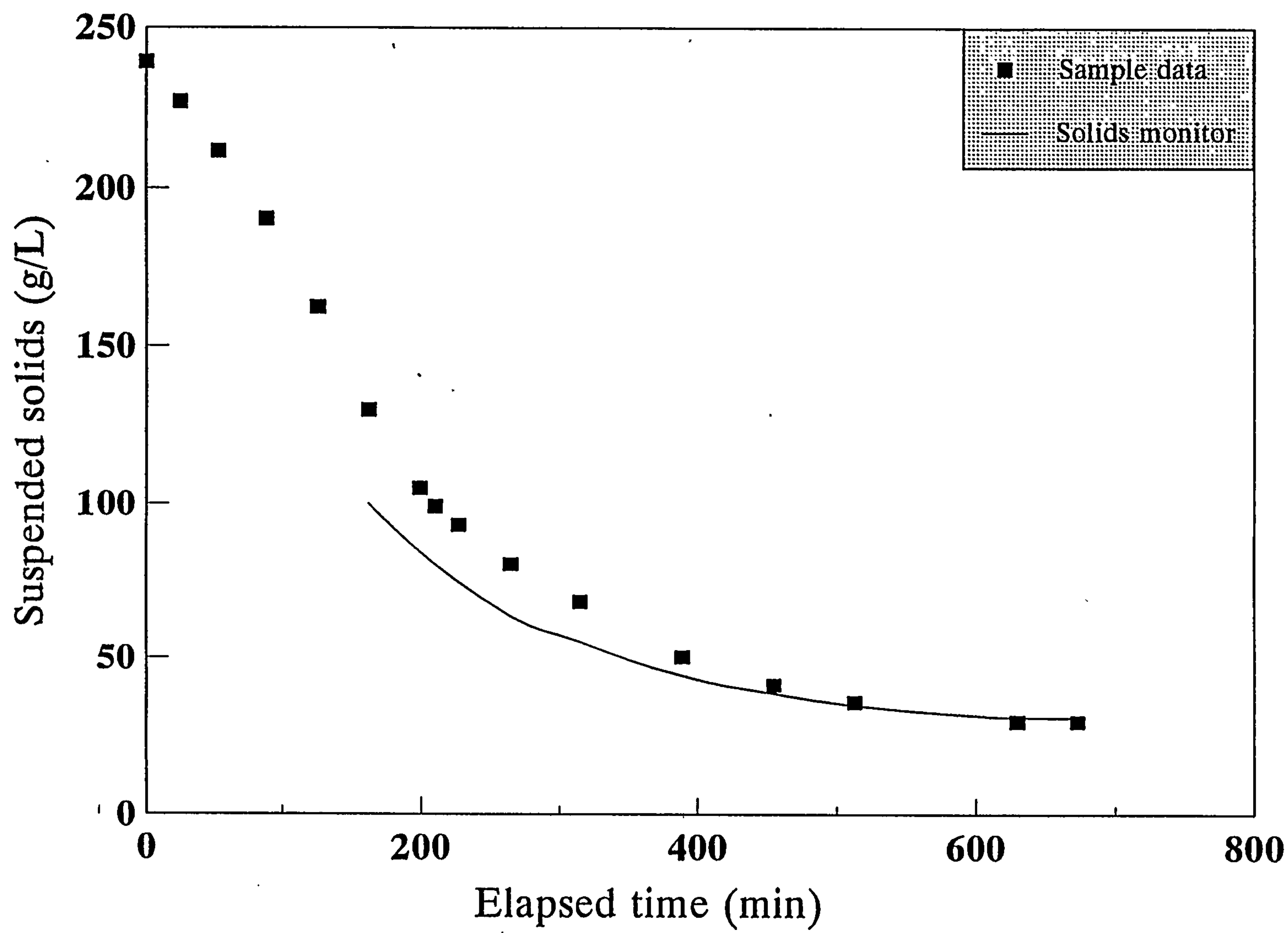

Fig. 7. Concentration of suspended solids in the recirculation line versus mixing time for run K-1.

A video camera was lowered into the tank at several port locations to inspect the sludge layer for valleys and rifts that may have resulted from the formation of a sludge bank during the mobilization activity. The sludge layer appeared to be level with very small ripples. Based on the results of the camera inspection and the sludge gun measurements, it was decided that a full mobilization between runs to relevel the sludge was not required. However, measurements with the sludge gun indicated that the sludge level was still settling ~13 mm (0.5 in.) per day after 7 days; therefore, the test plan was modified to extend the settling time to ~12 to 14 days between runs.

4.2.3 Run K-2

Run K-2 simulated a potential nozzle configuration for mobilizing the sludge in the MVSTs and evaporator service tanks. The discharge nozzle was located ~1/4 tank length from the end of the tank (port H), and the suction nozzle was located ~1/8 tank length from the opposite end of the tank (port B) for this run. Refer to Fig. 6 for a visual indication of the port locations. Samples were collected from the recirculation line and from inside the tank during the run.

The results obtained from samples collected from the recirculation line during the run are compared with the data obtained from the solids monitor in Fig. 8. The results show that the slurry phase reached uniformity in approximately 155 min. The variance between the solids monitor and the sample results is most likely due to a calibration shift.

The results from the in-tank samples are shown in Table 6. The first set of samples was collected to verify the result obtained from the solids monitor that the concentration of

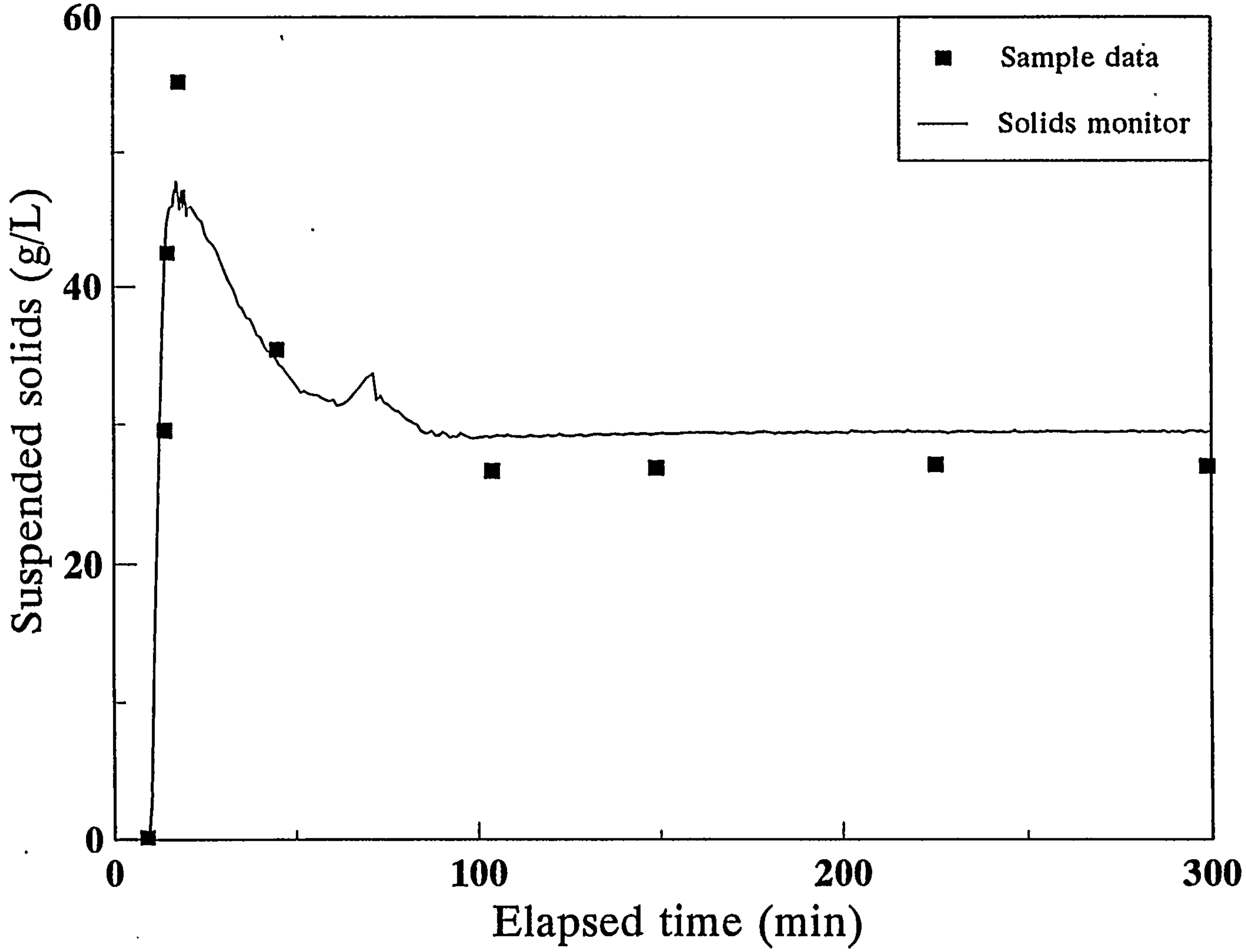

Fig. 8. Concentration of suspended solids in the recirculation line versus mixing time for run K-2.

Table 6. Sample results from run K-2

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank		
		0.56 m	1.5 m	2.4 m
150	A	72.4[b]	26.9	27.0
	E	27.1	27.0	26.6
	F	27.2	27.0	26.9
	G	27.1	27.1	26.9
	J	27.6	27.2	27.1
300	A	27.5	27.3	27.4
	E	27.2	27.1	27.2
	F	27.3	27.0	27.1
	G	27.2	27.3	27.0
	J	27.5	27.4	27.2

[a]See Fig. 6 for visual indication of port locations.
[b]This concentration was confirmed by measuring the density of the sample. This result indicates that the sludge phase was present at this location at the time the sample was collected.

suspended solids was nearly uniform. The results from the first in-tank samples indicated that the tank contents were near-homogeneous except for one sample. The second set of in-tank samples verified that the slurry phase had reached a uniform concentration at the end of the run.

The final concentration of suspended solids in the slurry phase was ~27.4 g/L, which indicates that 60.5% of the kaolin was mobilized. The ECL could not be determined by measuring the depth of settled solids after the run.

This run proceeded more quickly than run K-1 as it required ~155 min to obtain a nearly uniform concentration of slurry. Possible reasons for the faster mixing time include (1) the position of the suction leg with respect to the sludge layer and (2) the position of the discharge nozzle with respect to the end caps of the tank. The suction leg in run K-1 was located deep in the sludge layer near the bottom of the tank, whereas, in run K-2, it was located near the surface of the sludge layer. Since the suction leg was deep in the sludge layer in run K-1, less opportunity existed for the supernatant to mix with the solids than in run K-2. Because the density of the mobilized solids phase was much higher than that of the supernatant, the two phases tended to remain separate until the density became more uniform by additional mixing. It is also believed that the curvature of the end caps may have influenced the mixing action by reflecting some of the jet action into the liquid.

4.2.4 Run K-3

The nozzle configuration for run K-3 was similar to that used for run K-2. The major difference between the two runs was the depth of the suction leg. The discharge nozzle was located ~1/4 tank length from the end of the tank (port D), and the suction leg was located ~1/8 tank length from the opposite end of the tank (port I). The solids monitor was used to monitor the progress of the run, and samples were collected from the recirculation line and from inside the tank during the run.

Results from the suspended solids analysis of the recirculation line samples are compared with the solids monitor data in Fig. 9. This graph shows that the mixing time required to reach a nearly uniform concentration in the recirculation line was ~185 min,

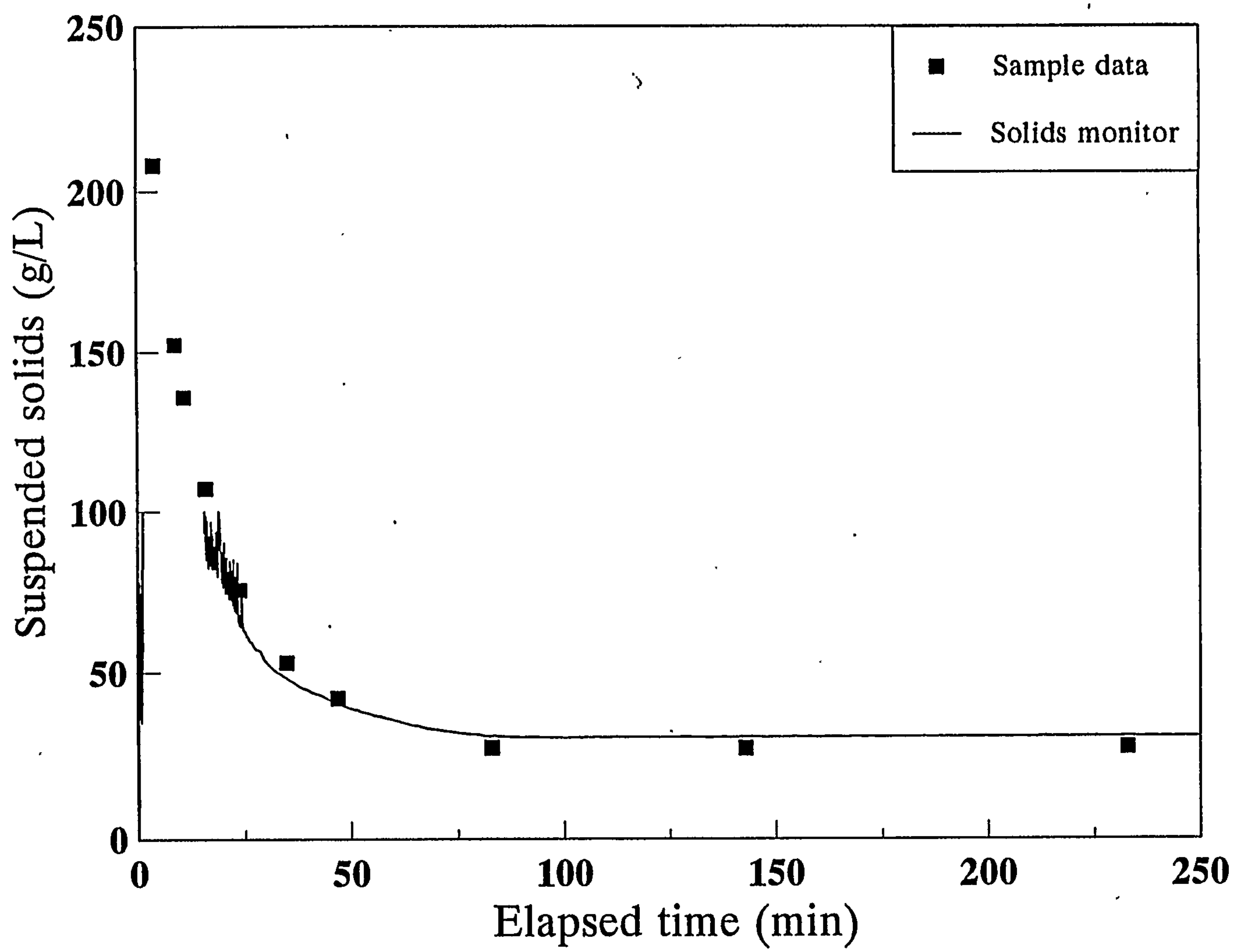

Fig. 9. Concentration of suspended solids in the recirculation line versus mixing time for run K-3.

which compares well to the mixing-time result found in run K-2. This finding indicates that the depth of the suction leg had little effect on the mixing time when the suction leg was in the liquid phase or near the sludge/liquid interface. However, mixing time for this piping arrangement would have likely been longer if the suction leg had been deep in the sludge.

The results for the in-tank samples are shown in Table 7. The first set of samples, which were collected before the contents could become uniform, revealed a definite concentration gradient in the tank; however, the concentration was nearly uniform on the suction end of the tank. The second set of samples was taken after the concentration of suspended solids in the recirculation line had stabilized, and these results indicated that the composition of the slurry phase was nearly uniform. The final concentration of suspended solids was ~27.2 g/L, indicating that 60.3% of the kaolin was mobilized, a value that compares well with the percentage of kaolin mobilized in run K-2.

Since determining the ECL by measuring the depth of sludge after resettling was not an effective method, an alternate method was employed. Additional samples were collected from inside the tank ~0.05 m (2 in.) from the bottom of the tank at the end of the run. If the sludge had been mobilized in the sampling area, the suspended solids concentration would be the same as that in the slurry phase at the end of the run and this area would be considered to be within the ECL. A significantly higher concentration of suspended solids would indicate that a layer of sludge remained in this area and that this area was outside the range of the ECL. Therefore, the ECL could be estimated by sampling at each available port location. It should be recognized that this method would not indicate the depth of the sludge remaining unless samples were collected at several depths near the bottom. It should also

Table 7. Sample results from run K-3

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank			
		0.05 m	0.56 m	1.5 m	2.4 m
80	A		32.9	26.1	17.6
	C		30.9	25.3	21.2
	F		27.2	25.8	24.5
	G		26.0	25.7	23.8
	J		25.9	25.8	26.1
260	A		27.2	27.2	27.2
	E		27.1	27.1	27.8
	F		27.1	27.0	27.0
	G		27.2	27.0	27.1
	J		27.1	27.0	27.1
290	A	ND[b]			
	C	397			
	D	403			
	E	408			
	F	27.4			
	G	27.5			
	H	27.5			
	J	68.0			

[a]See Fig. 6 for diagram of physical locations of the ports.
[b]Not determined because the sludge was too thick to obtain a sample at this location.

be noted that samples collected in the presence of sludge cannot be relied upon to give an accurate concentration of suspended solids, since it is impossible to know whether supernatant is "leaking" into the sludge phase around the sample probe when the sample is obtained. The results from the samples taken at 0.05 m (2 in.), which are shown in Table 7, indicate that the ECL started at the discharge nozzle (port H) and stopped between ports E and F. Using the tank dimension data in Fig. B-3, the ECL can be estimated to be between 3.2 and 4.6 m (10.6 and 15 ft).

4.2.5 Run K-4

The discharge nozzle for this run was located at the center of the tank (port F), and the suction nozzle was located ~1/8 tank length from the end of the tank (port I). This arrangement is also a potential configuration for the MVST-CIP. As in previous runs, samples were collected from the recirculation line and from inside the tank for suspended solids analysis.

Figure 10 shows the results from the recirculation line samples and compares them with the data obtained from the solids monitor. The final concentration of suspended solids in the slurry was ~27.0 g/L, indicating that 59.8% of the kaolin was mobilized. The mixing time, which is determined from the point at which the solids monitor data are uniform, was ~280 min. A comparison indicates that the mixing time for run K-4 was faster than that for run K-1 but slower than runs K-2 and K-3. The mixing time appears to have been improved by locating the suction leg above the sludge layer.

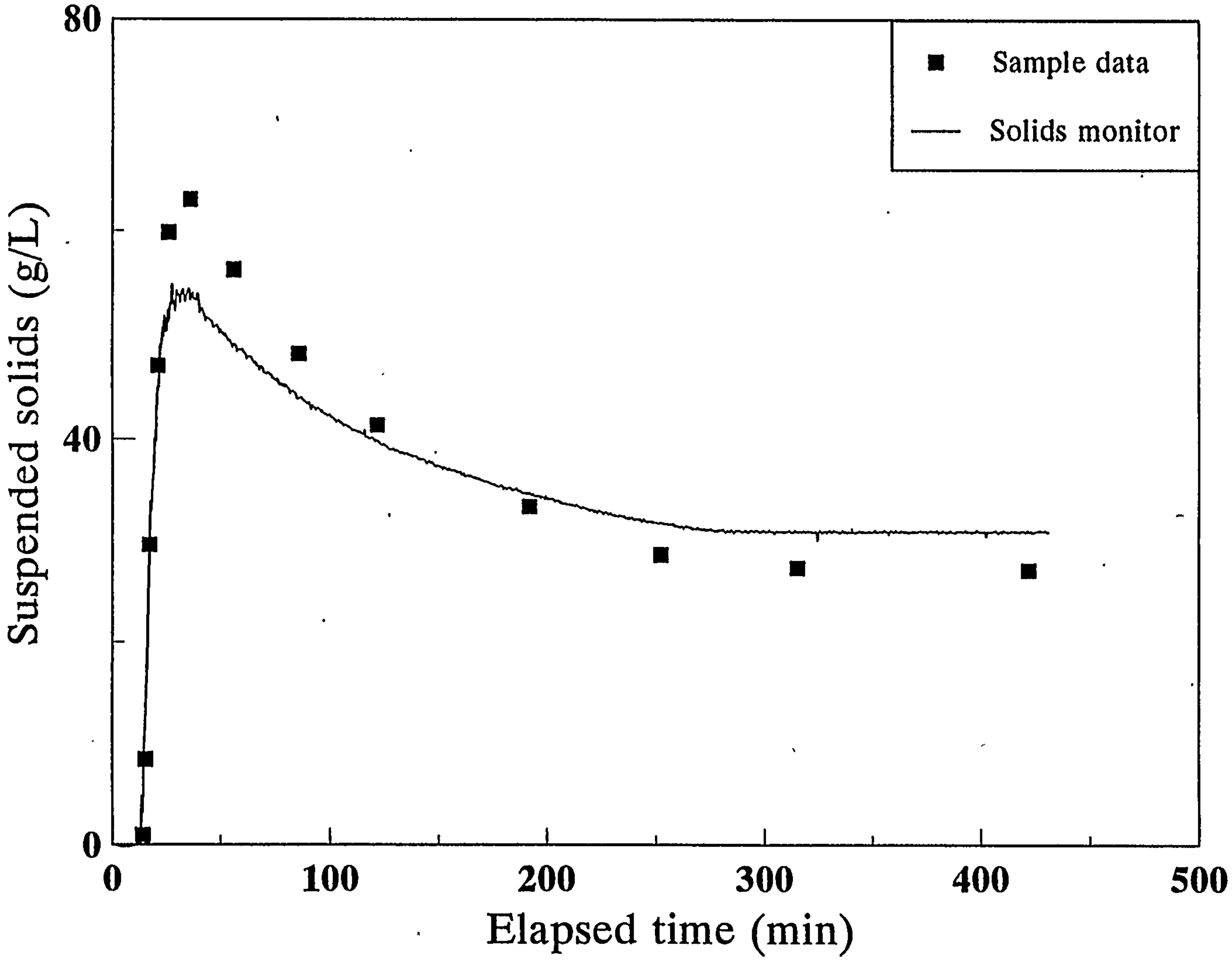

Fig. 10. Concentration of suspended solids in the recirculation line versus mixing time for run K-4.

The results from the in-tank samples are shown in Table 8. The results from the first set of samples show that the suspended solids did not reach the surface after 150 min of mixing. The second set of samples shows that the slurry contents had reached a uniform concentration. The samples collected at 0.05-m depth indicate that the ECL was between 3.2 m (10.6 ft) and 3.7 m (12 ft). In addition to samples collected at the 0.05-m depth, samples were collected at other depths to further define the sludge bank. The results of these samples are also shown in Table 8.

4.2.6 Run K-5

The mixing time required for run K-1 was significantly longer than for runs K-2 through K-4. In order to verify the results, run K-5 was performed with the same piping configuration and flow rate conditions as in run K-1. Samples were collected from the recirculation line and from inside the tank during the run.

Figure 11 shows the suspended solids concentration in the recirculation line versus elapsed time and compares the data with those provided by the solids monitor. The final concentration of suspended solids was 26.5 g/L, which indicated that 58.6% of the kaolin was mobilized. The mixing time for this run was 525 min. A comparison of this data with that obtained from run K-1 shows that run K-5 mixed faster; however, a possible explanation for the shorter mixing time is that less kaolin was mobilized. The results from this run confirmed the earlier finding that a longer period of time was required to mix the contents when the center discharge and center suction configuration was used.

Table 8. Sample results from run K-4

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank						
		0.05 m	0.15 m	0.20 m	0.36 m	0.56 m	1.5 m	2.4 m
150	A					40.6	36.9	0.0
	E					38.8	38.1	0.0
	F					38.3	38.0	0.0
	G					37.6	37.3	0.0
	J					37.3	37.0	0.0
390	A					27.2	28.0	26.9
	E					27.0	27.0	26.5
	F					27.1	27.1	26.6
	G					27.2	27.0	26.4
	J					27.1	27.1	27.1
420	A				158			
	C	62.1	34.2					
	D	27.1						
	E	26.9						
	F	27.0						
	G	27.1						
	H	27.5						
	J		251	56.6				

[a]See Fig. 6 for diagram of physical locations of the ports.

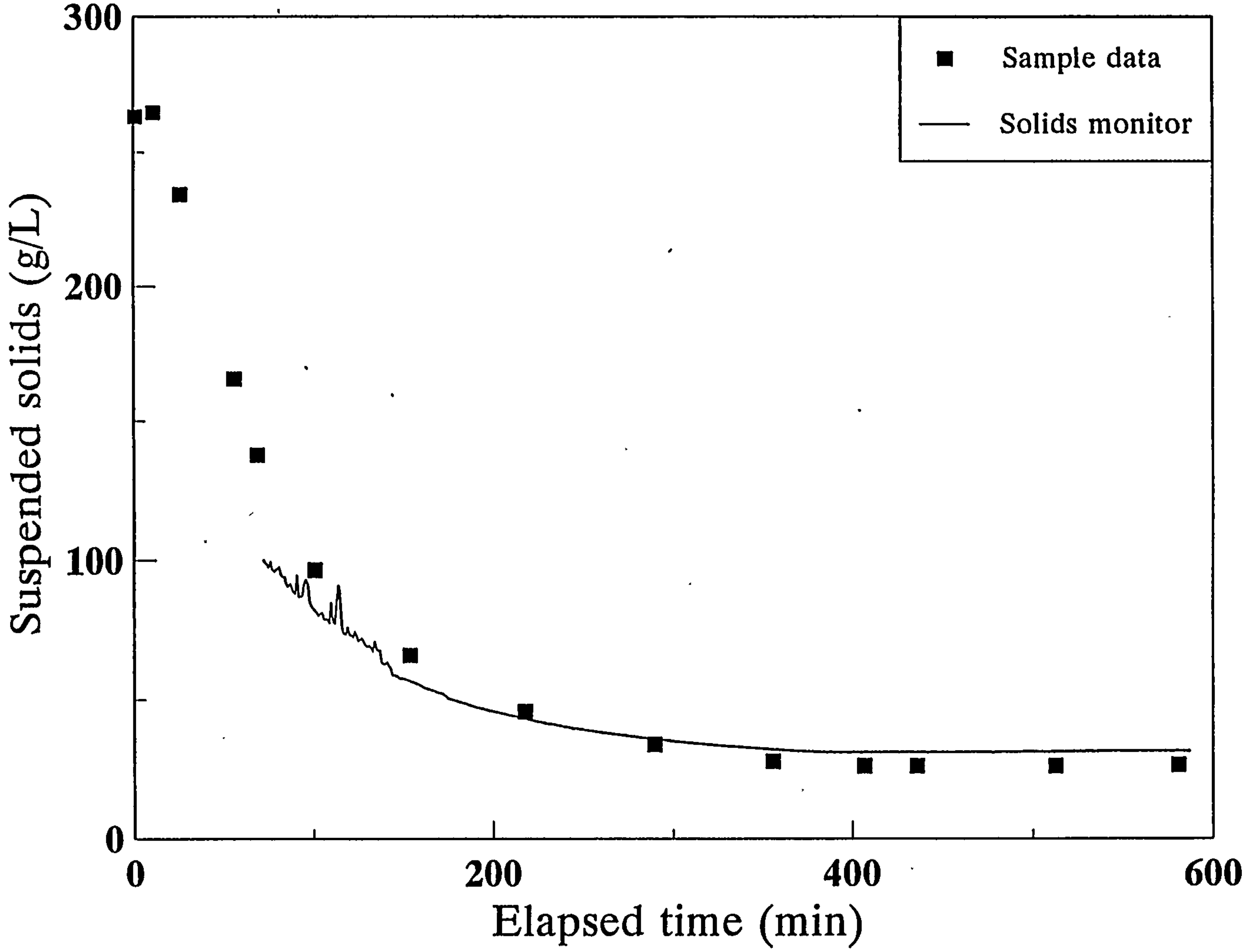

Fig. 11. Concentration of suspended solids in the recirculation line versus mixing time for run K-5.

Results from the in-tank samples are shown in Table 9. The samples collected in the various sets show the progression of the mixing action at the designated ports. The sample results collected at 0.05 m (2 in.) indicated the ECL was between 3.2 m (10.6 ft) and 3.7 m (12.1 ft).

The sludge gun was used to monitor the height of the suspended solids interface during this run. The interface height was measured approximately once per hour until the solid particles began to reach the surface of the liquid. The diagram in Fig. 12 shows the height of the suspended solids interface with respect to position in the tank and as a function of elapsed time. As shown in Fig. 12, the height of the suspended solids interface was approximately the same across the tank at any given time.

4.2.7 Run K-6

This run used the piping arrangement of the discharge nozzle at ~1/4 tank length from the end of the tank (port D) and the suction nozzle at ~1/8 tank length from the end of the tank (port I). This is the same arrangement used in run K-2; however, this run differs from run K-2 in that a flow rate of 6.3 L/s (100 gal/min) was used. The results from this run will be compared with the results from run K-2 to obtain scale-up data based on the relationship between jet velocity and the ECL.

Since the jet velocity in run K-6 was significantly lower than in previous runs, the mixing time was expected to be longer. Therefore, a limit of 12 h of mixing time was set before the run began. If the contents had not reached a uniform concentration within that period of time, the percentage of kaolin mobilized would be estimated from data collected

Table 9. Sample results from run K-5

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank								
		0.05 m	0.10 m	0.25 m	0.31 m	0.41 m	0.56 m	1.5 m	2.1 m	2.4 m
115	A						94.3			
	E						90.8			
	F						89.1			
	G						88.2			
	J						87.0			
325	A						31.4	31.4		0.0
	E						30.9	30.8	26.2	
	F						30.6	30.5	26.2	
	G						30.2	30.1	24.9	
	J						30.1	30.2	29.2	
550	A						26.7	26.6		26.6
	E						26.5	26.4		25.8
	F						26.6	26.5		25.6
	G						27.4	26.6		25.8
	J						26.7	26.7		26.7
575	A				480	29.4				
	C	55.3								
	D	26.6								
	E	26.5								
	F	26.5								
	G	26.6								
	H	33.2								
	I		462	27.8						
	J			43.9						

[a]See Fig. 6 for schematic of tank showing port locations.

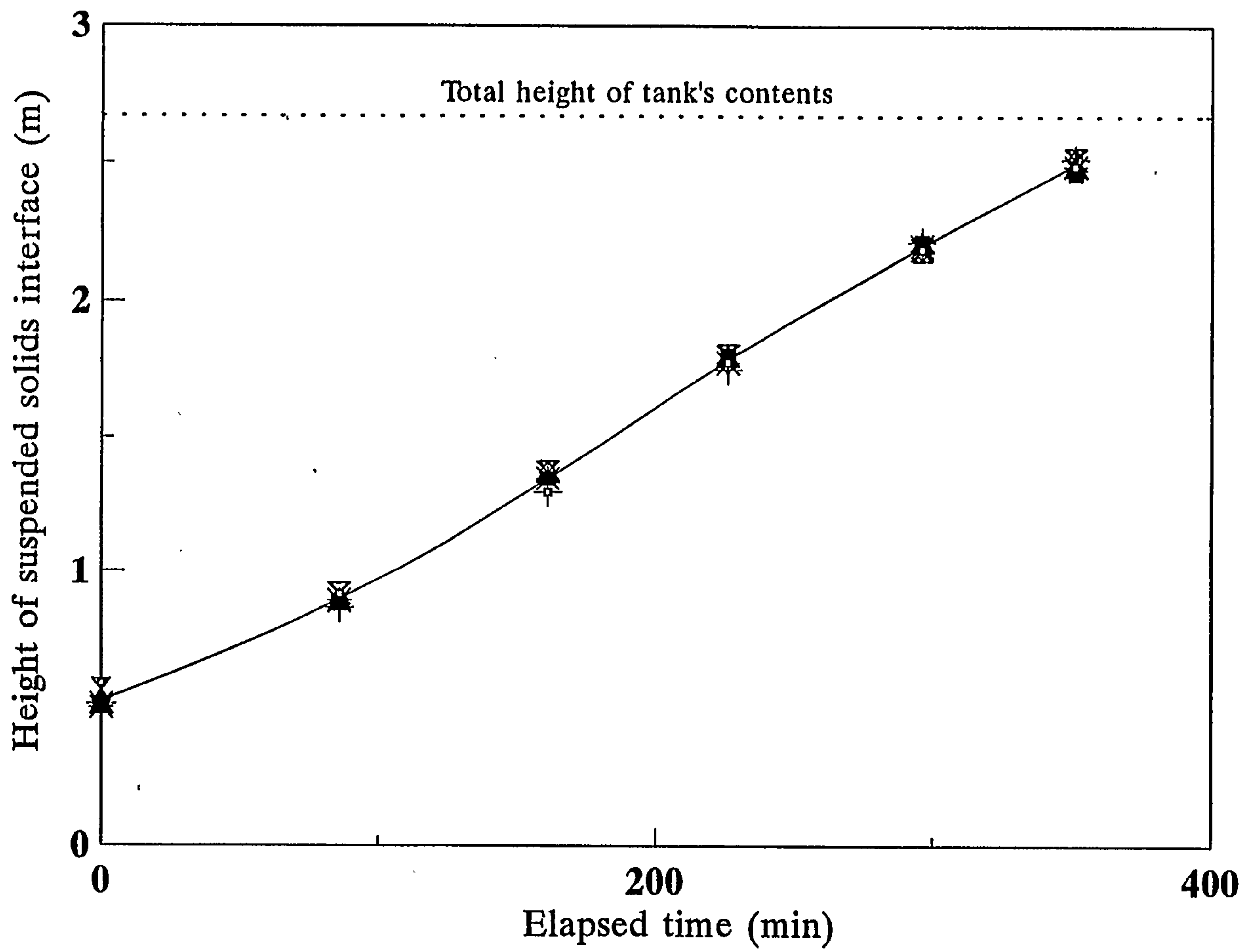

Fig. 12. Height of suspended solids interface (all port locations) versus mixing time for run K-5.

from in-tank samples.

The sample results for the slurry concentration in the recirculation line and the results from the solids monitor are shown in Fig. 13. As shown by the graph, the concentration of suspended solids had not reached uniformity after 12 h of mixing time. Samples were collected from inside the tank, and the run was stopped at this point.

The in-tank sample results are shown in Table 10. The first set of samples shows that the interface height was less than 1.5 m (5 ft) in the tank after 135 min. After 660 min of mixing, a concentration gradient still existed in the tank and the suspended solids had still not reached the surface of the liquid. The third group of samples was collected to determine the ECL and to estimate the sludge depth profile. The results from the samples collected at 0.05 m (2 in.) indicated that the effective jet length was approximately 1.4 m (4.6 ft), based on the concentration results for port D (discharge nozzle) and port E. The concentration at port E was slightly higher than the recirculated slurry concentration, but it was significantly lower than the concentration at port F. Therefore, it is likely that port E is the edge of the ECL.

Since the slurry did not reach a near-uniform concentration, it is difficult to determine the percentage of the kaolin mobilized; however, based on the height of the suspended solids interface at the end of the run and the results from the in-tank samples, it is estimated that 35% of the kaolin was mobilized under the conditions described for this run. Figure 14 shows the results from monitoring the height of the suspended solids interface with the sludge gun with respect to port location and mixing time. These results confirm the conclusion from run K-5 that the suspended solids interface is approximately

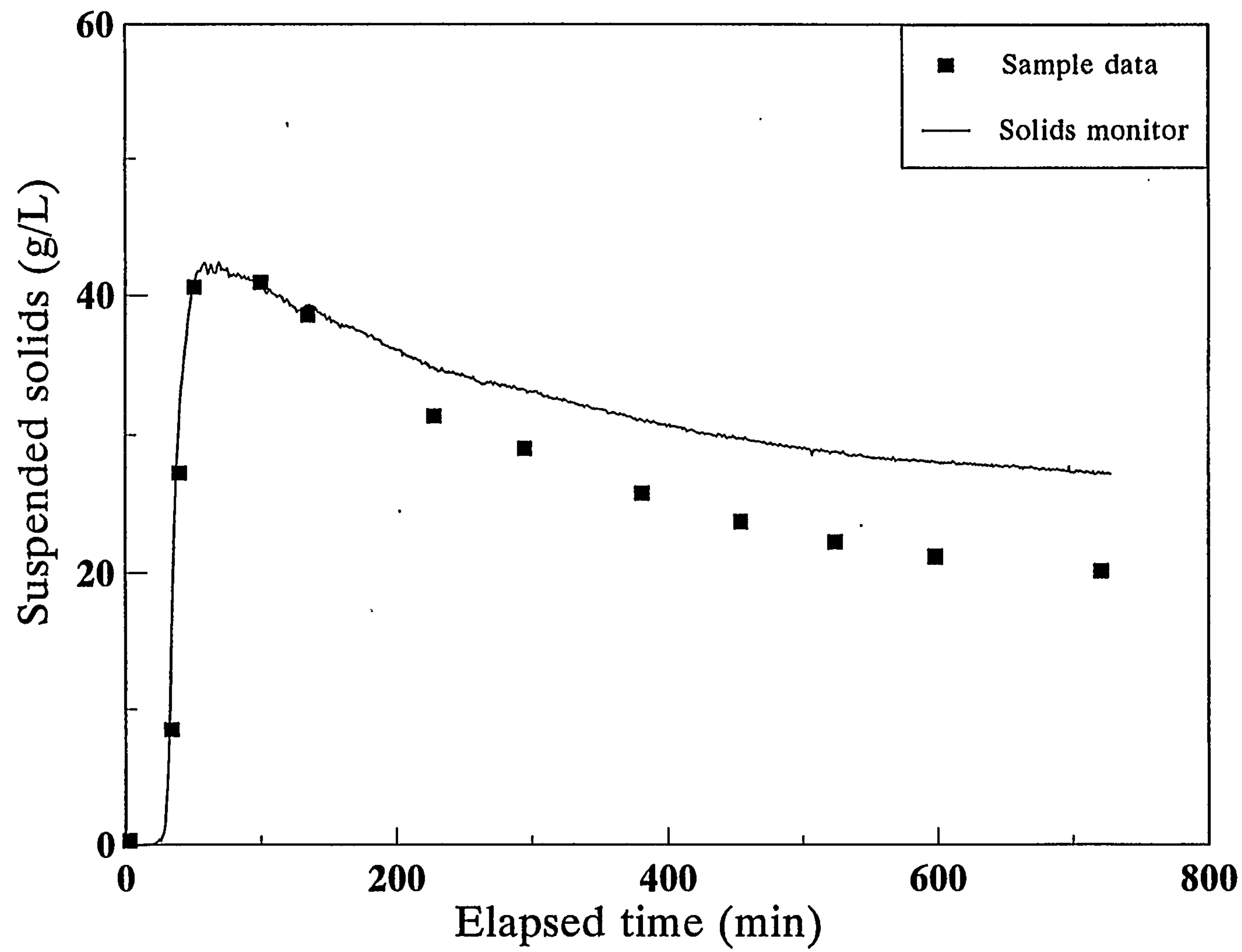

Fig. 13. Concentration of suspended solids in the recirculation line versus mixing time for run K-6.

Table 10. Sample results from run K-6

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank									
		0.05 m	0.23 m	0.36 m	0.41 m	0.46 m	0.56 m	1.2 m	1.5 m	1.8 m	2.1 m
135	A						40.4	37.9	0.0		
	E						39.7	37.7			
	F						39.8	36.6			
	G						40.1	36.6			
	J						39.3	38.2			
675	A[b]						21.1		20.8	20.5	16.8
	E						20.8		20.5		19.1
	F						21.2		20.5	20.5	19.1
	G						21.5		20.4		19.2
	J					22.1	21.3		20.7	20.3	19.3
715	A				84.5	20.9					
	C	20.8									
	D	24.1									
	E	26.6									
	F	373									
	G	338									
	H		340								
	I				21.0						
	J			259							

[a]See Fig. 6 for a diagram to identify the port locations.
[b]The suspended solids concentration at 2.4 m was determined to be 0.0 g/L.

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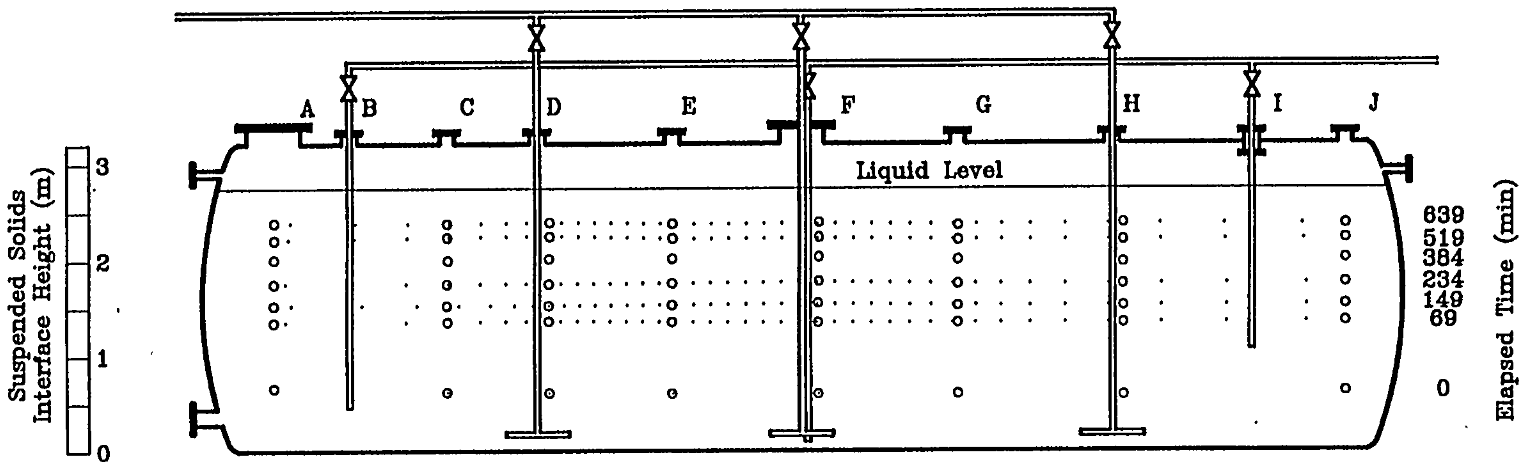

Fig. 14. Height of suspended solids interface with respect to tank position and mixing time for run K-6.

the same depth across the tank at any given time. Figure 15 is a graph of solids interface height versus time for all the ports. This figure shows that the height of the suspended solids interface increased rapidly at the beginning of the run and that the rate then decreased with time. This graph indicates that it would likely take several more hours for the suspended solids to reach the surface of the liquid; furthermore, it is not certain that the suspended solids would ever reach the surface using this nozzle configuration and velocity.

4.2.8 Run K-7

In runs K-1 through K-5, the quantity of kaolin that was mobilized decreased slowly with each run. This finding most likely indicated that the unmobilized kaolin was becoming even more concentrated because of the exclusion of water. As a result, the sludge was becoming more resistant to mobilization, indicating that the sludge properties were not consistent throughout the tank.

Run K-7 was performed to mobilize as much of the kaolin as possible, so that the resettled sludge would have similar properties throughout the tank. A long, 3/4-inch-diam tube was used to assist the submerged nozzles in mobilizing the kaolin by directing a portion of the recirculating flow to the ends and sides of the tank. All the submerged nozzles and suction nozzles were used at various times to maximize the mobilization. Samples were collected from inside the tank and from the recirculation line at the end of the run.

The in-tank sample results, which are shown in Table 11, show that the concentration of the slurry was nearly uniform at the end of the run. The samples collected at shallow depths verified that the sludge in the ends of the tank that had shown resistance to mobilization

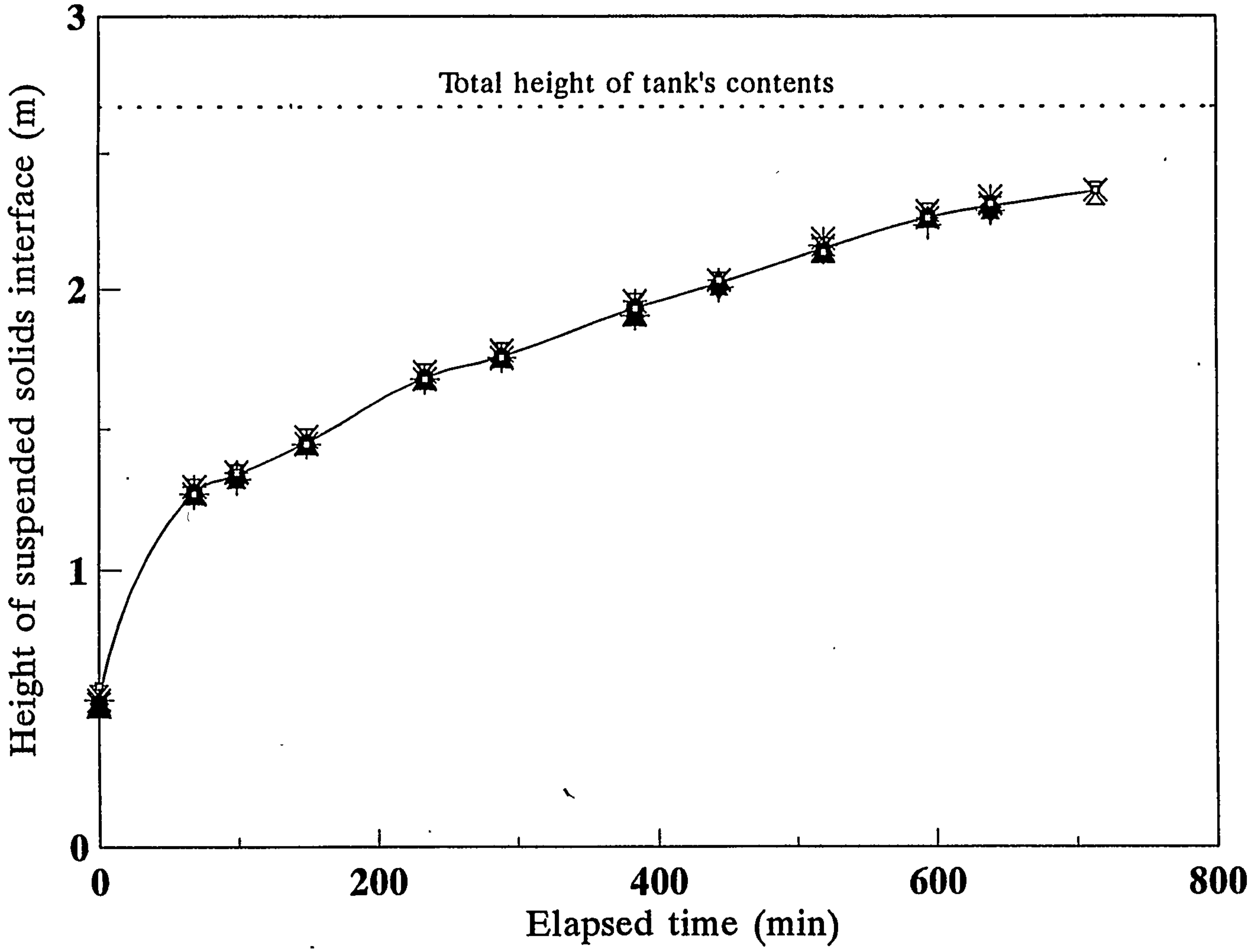

Fig. 15. Height of suspended solids interface (all port locations) versus mixing time for run K-6.

Table 11. Sample results from run K-7[a]

Port location[b]	Suspended solids (g/L) by depth from the bottom of the tank			
	0.05 m	0.56 m	1.2 m	1.8 m
A	41.2	41.3	40.5	41.4
E	41.5	41.4	41.3	41.4
F	41.5	41.4	41.4	41.5
G	41.4	41.3	41.4	41.3
J	41.5	41.5	41.5	41.5

[a]The suspended solids concentration in the recirculation line was 41.2 g/L.
[b]See Fig. 6 for a diagram to identify the port locations.

in prior runs had been successfully mobilized. The final concentration of suspended solids was ~41.4 g/L, which indicates that 91.6% of the kaolin was successfully mobilized.

4.2.9 Run K-8

Following the successful mobilization of the kaolin clay in run K-7, the piping configuration was reset for the center discharge nozzle and center suction, which was the same setup as used in runs K-1 and K-5. After 660 min of mixing time, the suspended solids had not reached the surface. The run was stopped at this point.

Figure 16 shows the relationship of suspended solids concentration in the recirculation line versus elapsed time and compares the solids monitor data with the sample data. The sample results from the in-tank samples are shown in Table 12. The results show the progression of the solids concentration at the designated ports and depths. The uniformity of the sample results of the specific groups is interesting to note for the various

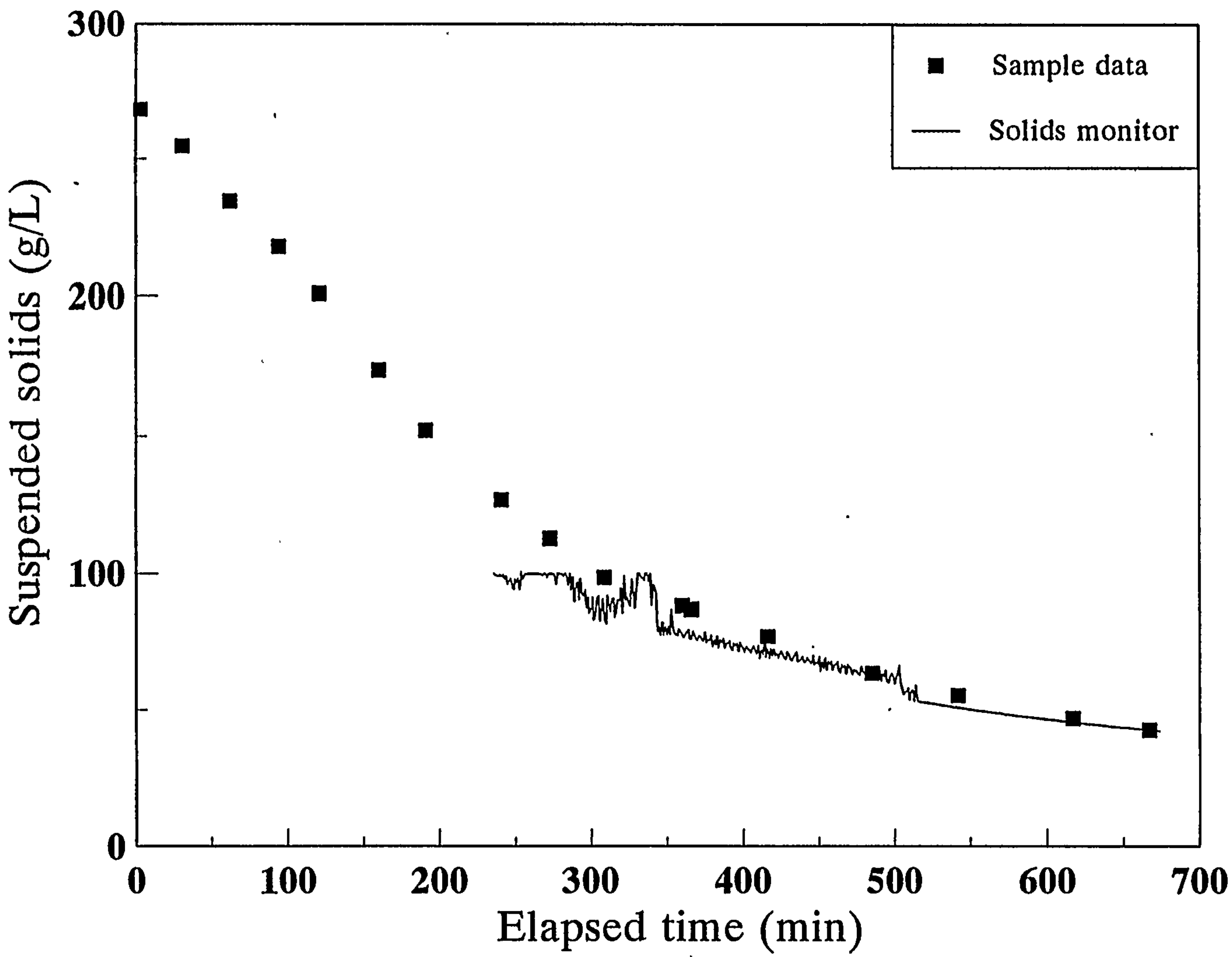

Fig. 16. Concentration of suspended solids in the recirculation line versus mixing time for run K-8.

Table 12. Sample results from run K-8

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank					
		0.025 m	0.56 m	1.2 m	1.5 m	1.8 m	2.4 m
140	A		195				
	E		192				
	F		182				
	G		177				
	J		189				
450	A		72.4	72.6			
	E		71.7	70.4			
	F		71.0	70.3			
	G		70.0	67.8			
	J		70.0	69.2			
640	A		46.4	46.4		46.4	
	E		45.8	45.8		43.7	
	F		45.3	45.4		43.1	
	G		45.0	45.1		43.0	
	J		44.7	44.7		44.8	
665	A	372					
	C	81.8					
	D	43.3					
	E	43.4					
	F	43.5					
	G	43.9					
	H	171					
	I	451					
	J	460					
		Full mobilization run following K-8[b]					
	A	42.3	42.0		42.0		42.1
	E	44.7	44.7		44.7		44.8
	J	42.2	42.1		42.1		42.1

[a]See Figure 6 for a diagram to identify the port locations.
[b]The suspended solids concentration in the recirculation line was 42.1 g/L.

sample groups. Results at the end of the run indicated that ~81% of the kaolin was suspended. For this run and the remaining runs, it was decided that the samples for determining the ECL would be collected at 0.025 m (1 in.) rather than at 0.05 m (2 in.). The results from these samples indicated the ECL was between 2.7 m (9.0 ft) and 3.2 m (10.6 ft).

A plot of all the data points from the various ports is shown in Fig. 17. This graph confirms previous data and the conclusion that the suspended solids interface is approximately the same height at any given time during the mobilization and mixing activity.

At the completion of the run, the kaolin was allowed to settle overnight. A full mobilization run, which included using the long, 3/4-in.-diam. tube for localized sparging, was performed the following day. Samples were taken from inside the tank to verify that the unmobilized sludge from run K-8 was mobilized. The kaolin was then allowed to resettle for approximately 14 days in preparation for the next run.

4.2.10 Run K-9

The discharge nozzle for K-9 was located at port H, and the suction leg was located at port B (see Fig. 6 for visual indication of nozzles in the tank). The sludge was mobilized much more quickly than in Run K-8. These results agree with the previous results obtained for runs K-1 and K-3. The results from the samples collected during the run are discussed in the following paragraphs.

The results of the samples collected from the recirculation line are shown in Fig. 18. These results show that the concentration of the slurry had become uniform after ~130 min

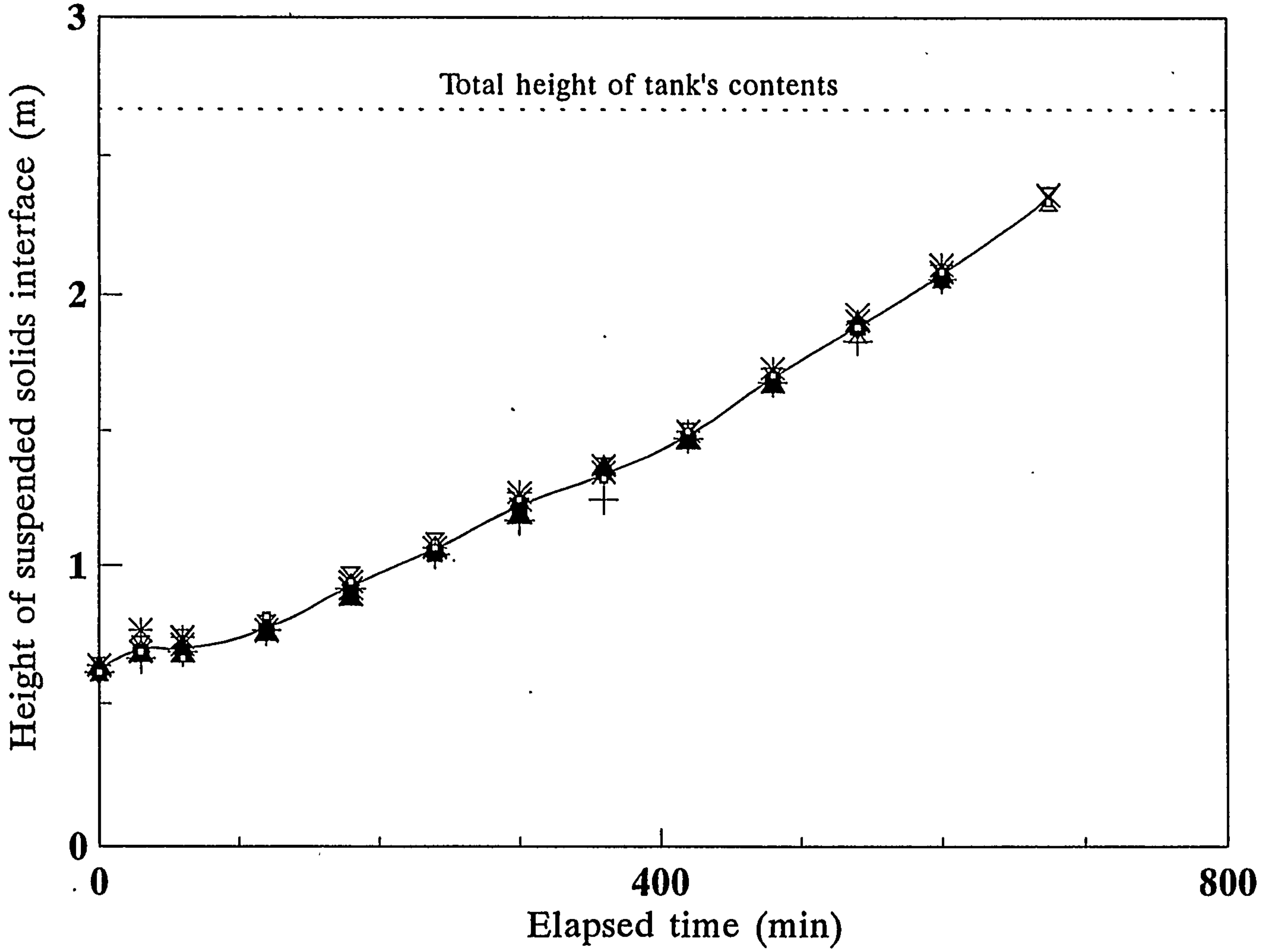

Fig. 17. Height of suspended solids interface (all port locations) versus mixing time for run K-8.

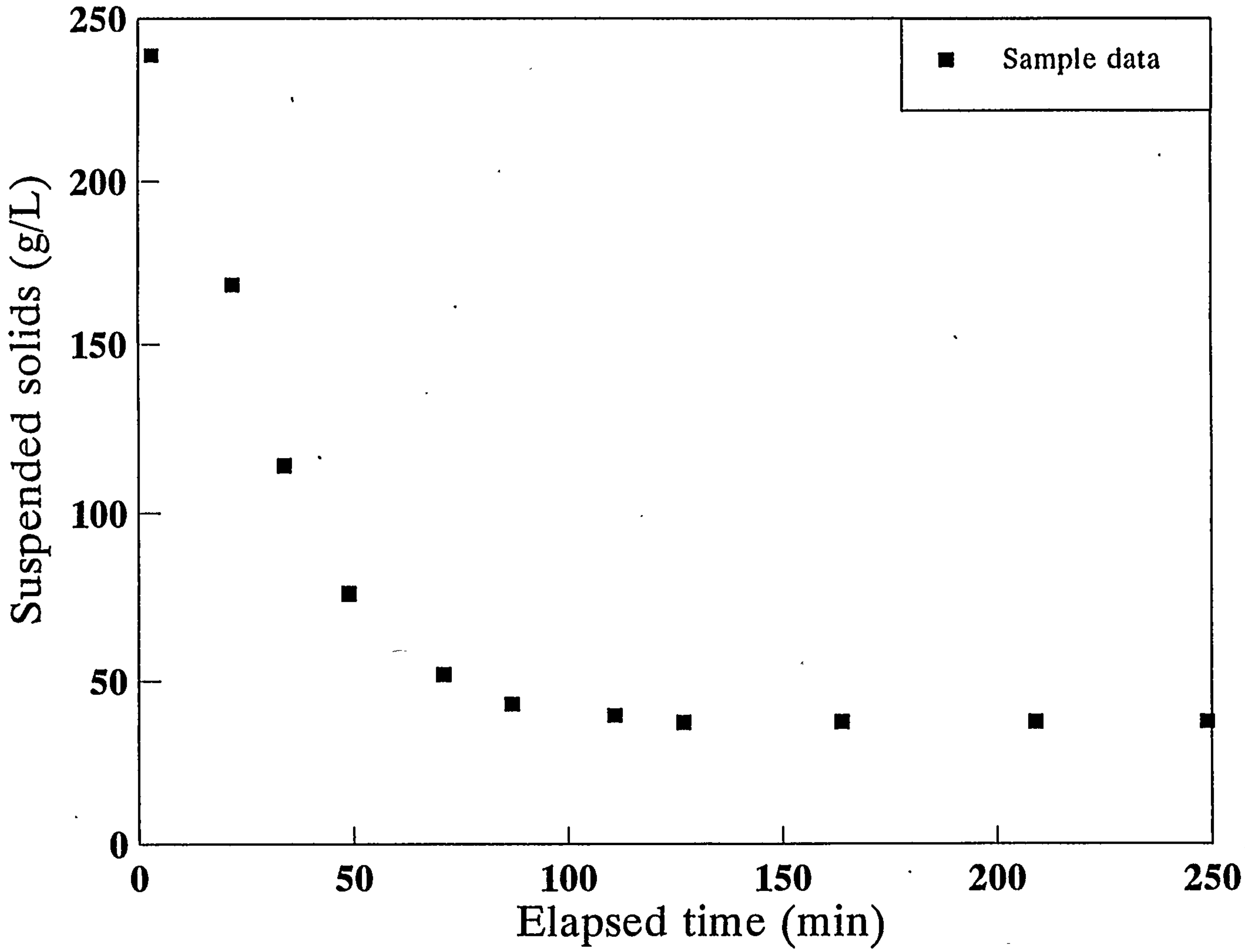

Fig. 18. Concentration of suspended solids in the recirculation line versus mixing time for run K-9.

of mixing. The concentration of suspended solids at the end of the run was 36.6 g/L, which indicates that 81% of the kaolin was successfully mobilized.

The sample results are shown in Table 13 for the samples collected from inside the tank. The sample results show that the ECL was between 3.2 m (10.6 ft) and 4.6 m (15 ft).

Figure 19 is a graph of all the interface height data versus elapsed time. The familiar pattern of the interface height being at approximately the same height at any given time was observed again.

After the run was complete, the kaolin was allowed to settle overnight; then another full mobilization run was performed the next day. During the full mobilization run, the solids monitor probe was blown out of its housing and approximately 700 gal of slurry (estimated suspended solids concentration of 41.5 g/L) was lost from the tank. This loss of kaolin reduced the inventory of kaolin from 4090 kg (9000 lb) to 3980 kg (8760 lb). It appeared that the probe escaped from its housing because the bolts vibrated loose and the clamping pins sheared. The probe was reinserted into the housing and bolted down with locknuts to prevent the probe from escaping again. It is unlikely that the system built for mobilizing the actual sludge in the waste tank will undergo as much vibration as was induced by the pump in our system. However, the design should include devices to dampen vibrations to prevent the potential spill of radioactive fluid.

4.2.11 Run K-10

The piping configuration for run K-10 used the discharge nozzle at port H and the suction leg at port B. This is the same piping configuration used in run K-9, but the flow rate

Table 13. Sample results from run K-9

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank			
		0.025 m	0.56 m	1.5 m	2.4 m
70	A		63.6	47.1	
	E		59.8	46.7	
	F		55.1	45.4	
	G		47.0	44.4	
	J		45.6	40.1	
165	A	332	36.8	36.8	36.8
	C	364			
	D	433			
	E	434	36.7	36.6	36.7
	F	36.8	36.8	36.7	36.6
	G	36.8	36.7	36.7	36.0
	H	127			
	I	36.9			
	J	37.0	36.9	36.8	36.9
Full mobilization run following run K-9[b]					
	A	42.9	42.9	42.6	40.6
	F	41.8	42.1	41.6	41.4

[a]See Fig. 6 for a diagram to identify the port locations.
[b]The concentration of suspended solids in the recirculation line at the end of the run was 42.1 g/L.

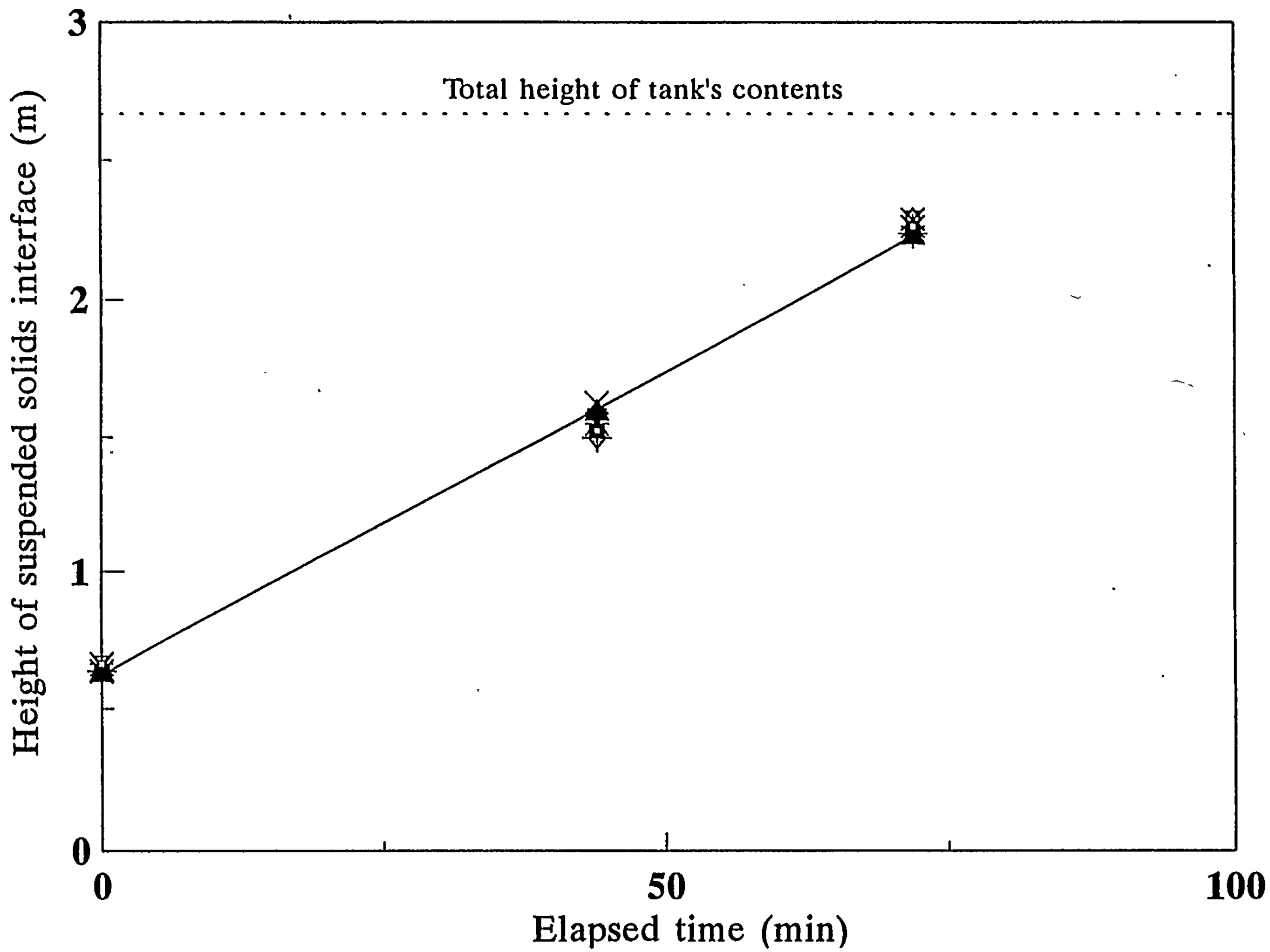

Fig. 19. Height of suspended solids interface (all port locations) versus mixing time for run K-9.

was reduced from 12.6 L/s (200 gal/min) to 6.3 L/s (100 gal/min). The results from samples collected during the run are discussed in the following paragraphs.

A graph of the suspended solids concentration in the recirculation line with respect to time is shown in Fig. 20. As shown in the graph, the suspended solids concentration in the recirculation line decreased from a maximum of 232 g/L to 206 g/L over a period of 660 min, indicating that the solid particles were being suspended into the supernatant very slowly.

Figure 21 plots the height of the suspended solids interface height versus time. The interface height changed only slightly during the run, and the results confirm that the supernatant was mixing very slowly into the sludge.

Since the height of the suspended solids interface did not change much during the run, only one group of samples was collected from inside the tank. The sample results are shown in Table 14. These results also confirm that the solids were not suspended in the supernatant very much. A substantial difference existed in the concentration of suspended solids samples near the discharge nozzle as compared with the samples collected away from the discharge nozzle. The results indicate that the kaolin was mobilized within the range of the ECL. Apparently, the mobilized slurry flowed across the sludge bank to the suction leg at the other end of the tank. The jet velocity was too low to effectively mix the solid particles with the supernatant. The results of the samples collected at a depth of 0.025 m (1 in.) indicate that the ECL was between 1.6 m (5.3 ft) and 2.4 m (7.9 ft). It is estimated that 49% of the kaolin was mobilized.

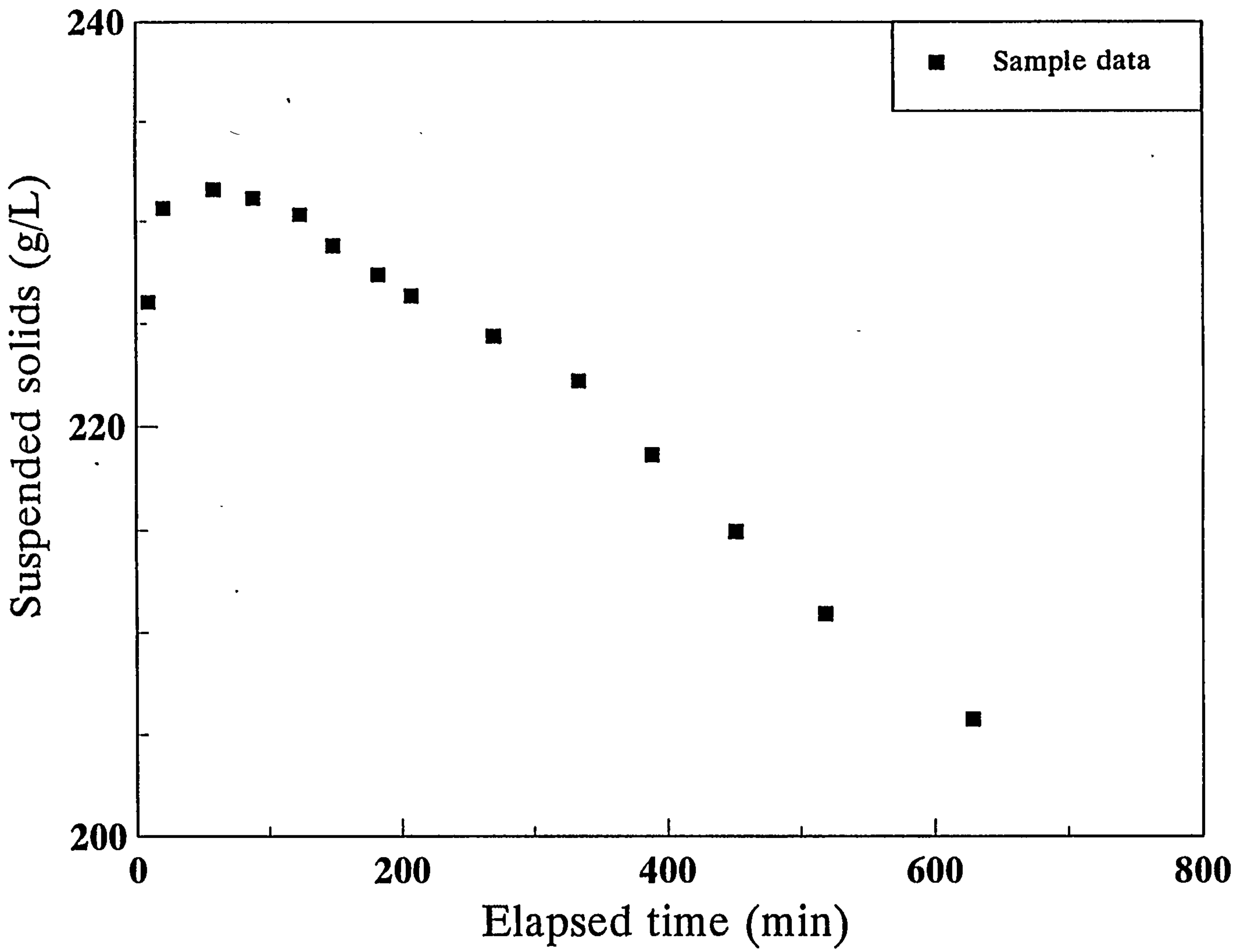

Fig. 20. Concentration of suspended solids in the recirculation line versus mixing time for run K-10.

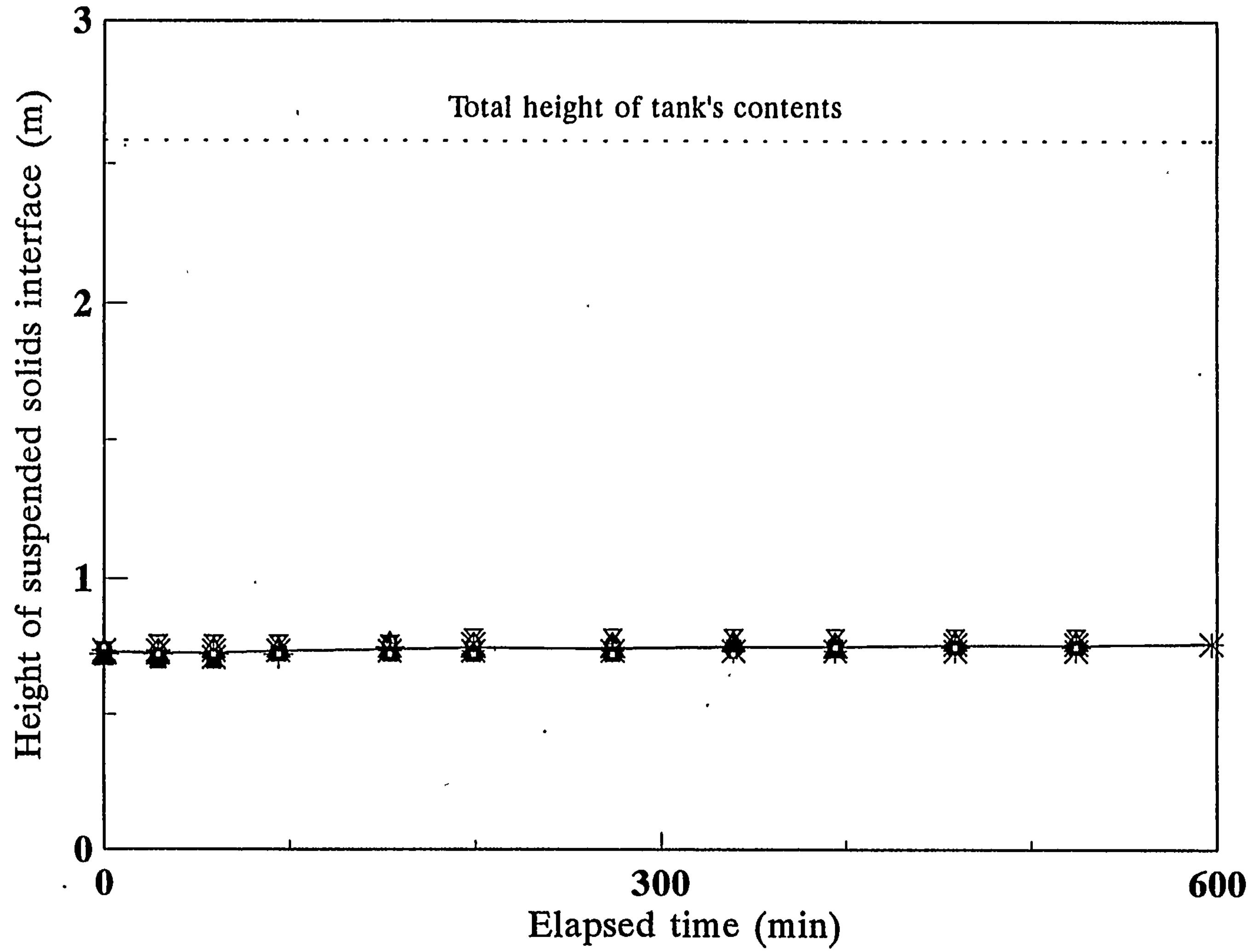

Fig. 21. Height of suspended solids interface (all port locations) versus mixing time for run K-10.

Table 14. Sample results from run K-10

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank		
		0.025 m	0.56 m	2.4 m
620	A	313	201	
	C	300		
	D	334		
	E	341	204	
	F	362	205	
	G	205	188	
	H	232		
	I	202		
	J	230	182	
	Full mobilization run following run K-10[b]			
	A	43.0		39.9
	G	42.0		40.3
	J	41.6		41.5

[a]See Fig. 6 for a diagram to identify the port locations.
[b]The suspended solids concentration in the recirculation line was 41.9 g/L.

A full mobilization run was performed after run K-10. The results are shown in Table 14 for the samples collected from the tank at the end of this run.

4.2.12 Run K-11

For run K-11, the discharge nozzle was located at port H, and the suction leg was located at port B. The jet velocity for this run was 4.9 m/s (16.1 ft/s).

Figure 22 is a graph of the suspended solids concentration in the recirculation line with respect to time and also shows the output from the solids monitor. The curve shows that the suspended solids concentration became nearly uniform at ~300 min. The solids

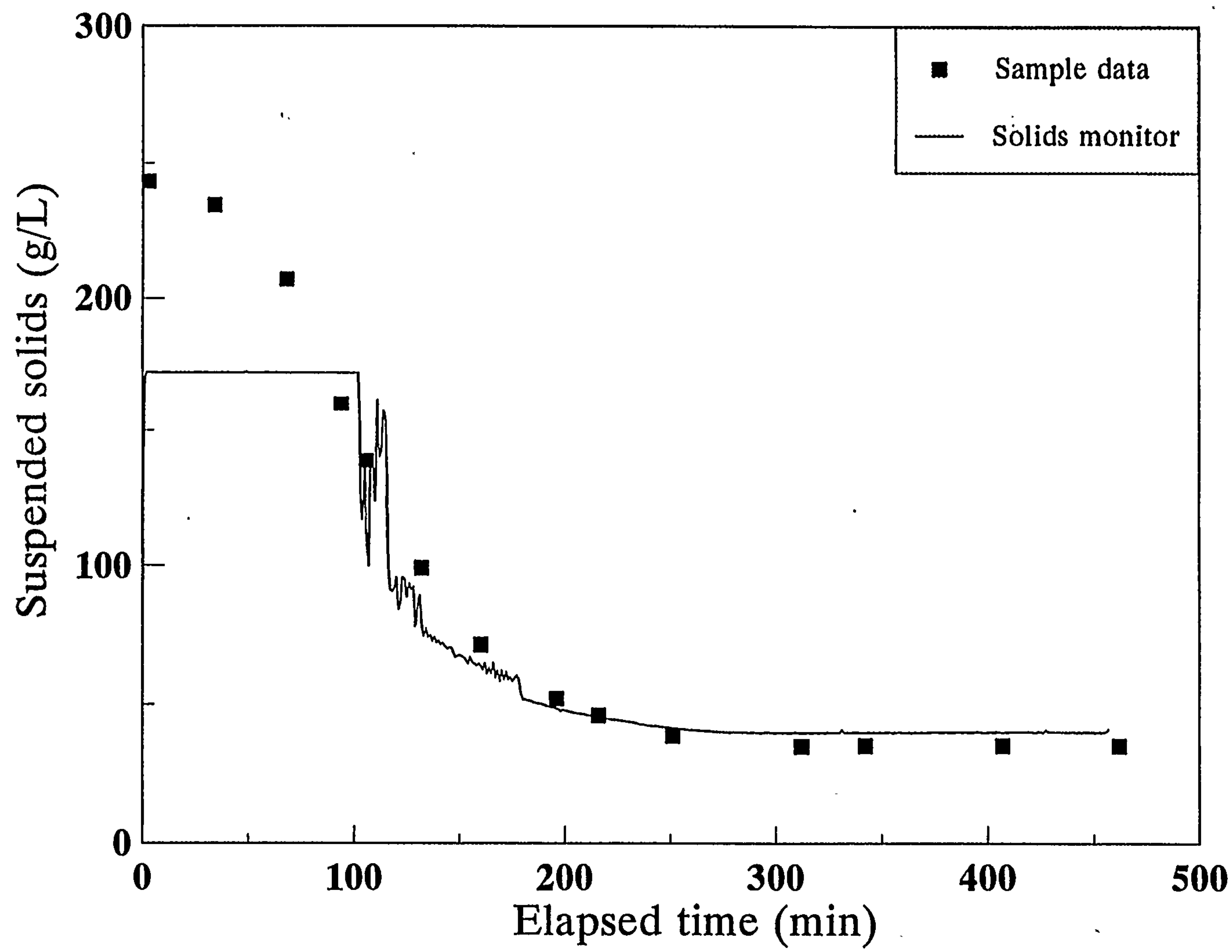

Fig. 22. Concentration of suspended solids in the recirculation line versus mixing time for run K-11.

monitor was recalibrated for the range 0 to 200 g/L prior to this run. The data show that the solids monitor was saturated at ~170 g/L. The probe used in the recirculation line was designed for low concentration of solid particles, and the concentration at the beginning of the run apparently was beyond the range of this probe. The manufacturer of the solids monitor fabricates probes for higher-concentration slurries, and these probes could be used in conjunction with the low-concentration probe for similar applications.

Table 15 shows the results from the in-tank samples collected during run K-11. The results from the samples collected at a depth of 0.025 m (1 in.) indicate that the kaolin was mobilized between port H (discharge nozzle) and port F. The ECL was between 3.2 m (10.6 ft) and 4.6 m (15 ft). The final concentration of ~35.0 g/L indicates that 77% of the kaolin was mobilized.

The results from monitoring the height of the suspended solids interface during run K-11 are shown in Fig. 23.

5. CORRELATION OF RESULTS

The approximate relationship between the ECR and the DV_o product is shown in Eq. (5). For the reasons previously mentioned, the effectiveness of the submerged nozzle was defined as the ECL for the mobilization tests described in this report. An equation analogous to Eq. (5) was assumed for the ECL, and it is shown as Eq. (6). The parameter α, a proportionality factor that is dependent on the sludge properties, is determined from the slope of the plot of ECL versus DV_o:

Table 15. Sample results from run K-11

Elapsed time (min)	Port location[a]	Suspended solids (g/L) by depth from the bottom of the tank				
		0.025 m	0.56 m	1.2 m	1.5 m	2.4 m
175	A		51.6	46.2		
	E		62.6	51.6		
	F		61.1	51.3		
	G		54.0	51.0		
	J		78.6	55.1		
390	A	298	35.1		35.3	34.9
	C	377				
	D	448				
	E	355	34.9		35.0	34.8
	F	35.2	34.9		34.9	34.9
	G	35.3	35.1		35.0	34.8
	H	41.0				
	I	35.0				
	J	35.0	34.8		34.9	34.2

[a]See Fig. 6 for a diagram to identify the port locations.

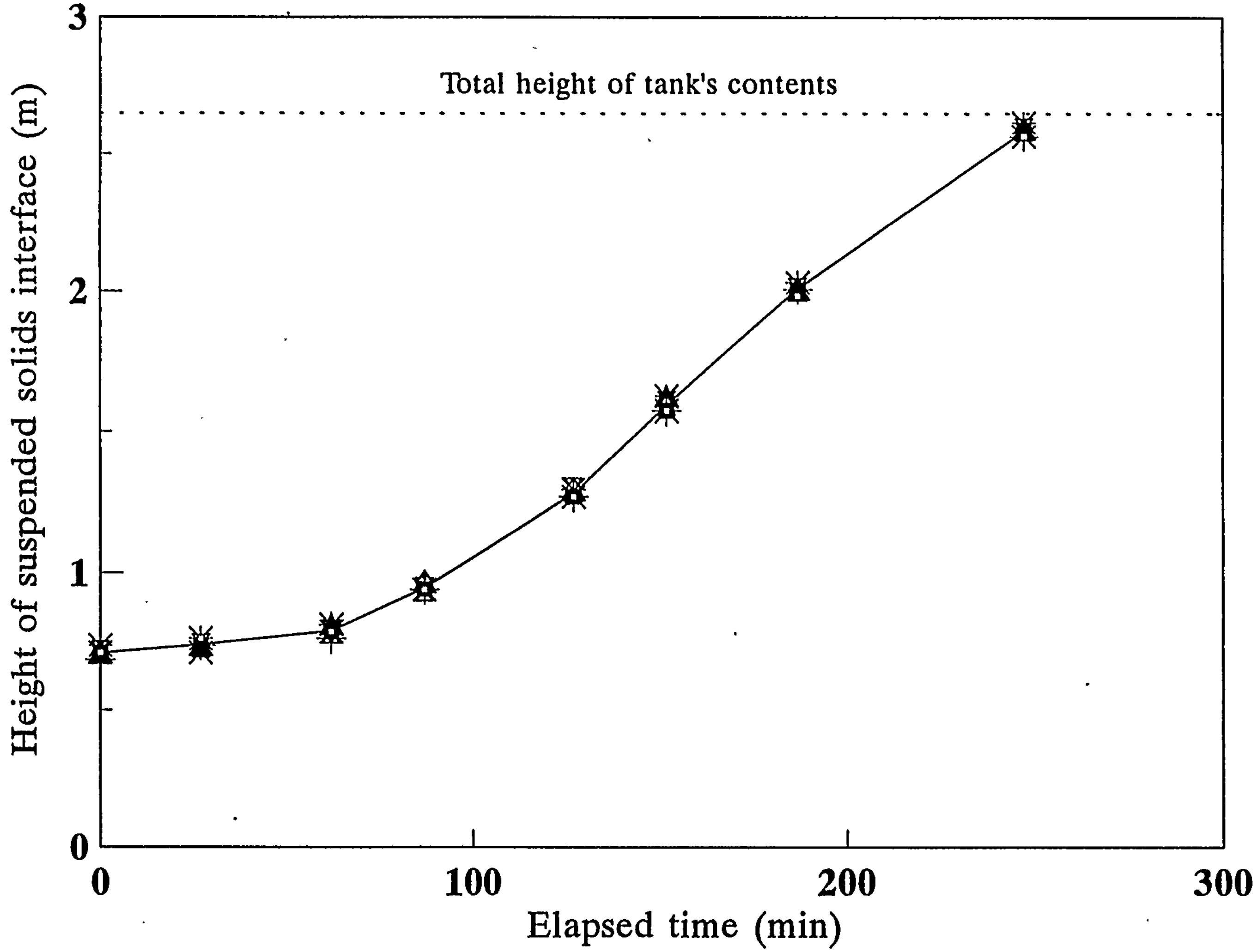

Fig. 23. Height of suspended solids interface (all port locations) versus mixing time for run K-11.

$$\text{Effective cleaning length} = \alpha D V_o \quad (6)$$

The value of α was determined for the ECL data shown in Tables 1 through 3 by performing a linear regression on the ECL and DV_o data. The data for the 95-m^3 tank were analyzed in three groupings: (1) runs K-1 through K-6 (the sludge was not fully mobilized between individual runs); (2) runs K-8 through K-11 (the sludge was fully mobilized after each run); and (3) runs K-1 through K-11 except run K-7. The term "fully mobilized" refers to using multiple submerged nozzles to mobilize as much sludge as possible. The results, as shown in Table 16, indicate that the value of α for the chemical surrogate was similar to the value of α for the kaolin clay; however, it should be noted that the chemical surrogate tests were performed on the low end of the DV_o range. A graph of the ECL versus DV_o for kaolin and the chemical surrogate is shown in Fig. 24.

6. CONCLUSIONS

This project demonstrated the feasibility of using submerged nozzles for mobilizing the sludge in horizontal cylindrical tanks such as the MVSTs and the evaporator storage tanks. The study was conducted with two model tanks: (1) a 0.87-m^3 Plexiglas tank (which was ~1/6-dimensional scale of the MVSTs) and (2) a 95-m^3 tank (~2/3-dimensional scale of the MVSTs). Kaolin clay was used as the primary material to represent the sludge in the MVSTs and other LLLW tanks. In addition, some tests were performed in the 0.87-m^3 tank with a chemical mixture to represent the sludge.

Table 16. Experimental determined values of proportionality factor α

Tank capacity (m^3)	Sludge type	Proportionality factor α
0.87	Kaolin clay	[a]
0.87	Chemical simulant	14.3
95	Kaolin clay (runs K-1 through K-6)	15.8
95	Kaolin clay (runs K-8 through K-11)	12.8
95	Kaolin clay (runs K-1 through K-11 except K-7)	14.0

[a] Not enough data to make a determination.

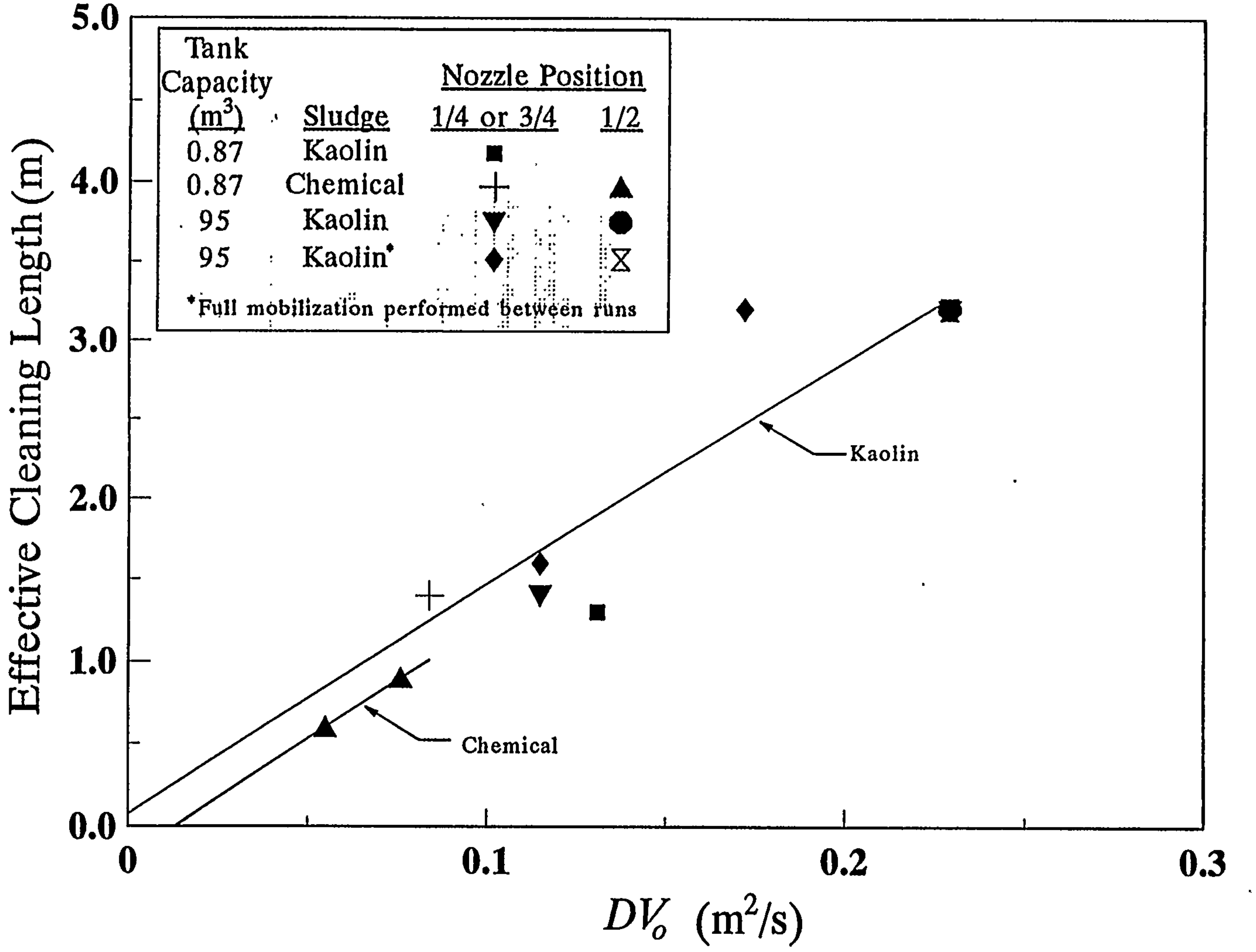

Fig. 24. Effective cleaning length versus DV_o product.

The mobilization of the sludge was strongly affected by the jet velocity (for nozzles of the same diameter) as predicted by the ECL–DV_o model. Although the final suspended solids concentrations measured in the tank indicated that up to 81% of the kaolin was mobilized when specific piping configurations were used, mobilization was limited by use of an existing pump with a capacity that was somewhat less than that predicted to be required to achieve full mobilization. Use of the relationship between DV_o and the ECL appears to be a valid model for designing a jet system; however, the proportionality constant will be dependent on the material to be mobilized.

The results showed that the position of the discharge nozzle did not affect the quantity of sludge mobilized; however, the distance between the end of the tank and the nozzles located at the ~1/4 and ~3/4 tank length positions was approximately the same as the ECL. If the ECL had been longer than that distance, a noticeable difference in the quantity of sludge mobilized may have existed. Some data indicated that the mixing time was faster when the discharge nozzle was located ~1/4 tank length from the end of the tank compared with locating the discharge nozzle in the center of the tank; however, the location (i.e., depth) of the suction leg was most likely the controlling parameter, as discussed below.

Although the location of the suction line did not affect the quantity of sludge mobilized, data indicated that the mixing time was faster if the suction leg was not deep in the sludge layer. Experimental data showed that the mixing time was approximately the same for suction lines located at depths of 0.5 m (20 in.) and 1.1 m (44 in.). The discharge nozzle was located ~1/4 tank length from the end of the tank and the suction leg was located ~1/8 tank length from the opposite end of the tank for these tests.

Kaolin clay sludge has been reported by other researchers to undergo a process known as water exclusion. The term "water exclusion" means that the weight of the particles causes them to pack closer together and squeeze out the water that is trapped between them. The result is a concentrated sludge layer that is viscous and exhibits a larger shear strength. The longer the sludge settles, the more viscous the sludge becomes, an effect that was observed in the 95-m^3 tank. Mobilization tests performed indicated that while the ECL was not affected by the water exclusion behavior, the quantity of sludge mobilized was affected. This indicates that the distance between the nozzle and the edge of the beach did not significantly change, but the profile of the beach changed.

The mobilization tests in the 0.87-m^3 tank with kaolin clay and the chemical surrogate indicated that a submerged nozzle was feasible in mobilizing sludge in horizontal tanks. The results presented in Table 16 indicate that the kaolin clay and the chemical surrogate matched reasonably well in their resistance to mobilization.

The data shown in Fig. 24 indicate that the relationship between DV_o and ECL reasonably follows a linear trend. Some of the data scatter in the figure can be attributed to imprecise determination of the ECL since the distance between the available ports in the tank ranged from 1 to 2 m (3 to 6 ft) as shown in Fig. B-3. Another potential explanation for some of the data scatter is the inconsistency in the shear strength of the material.

The TEMPEST computer model had previously showed reasonable agreement with experimental data in predicting the mixing time for liquids in horizontal cylindrical tanks. The TEMPEST computer simulation was not successful in predicting the mobilization of kaolin clay in the 95-m^3 tank. Additional development for the TEMPEST model is needed before using it to design a mobilization system.

Monitoring of the height of the suspended solids interface during the mixing and mobilization activity revealed that the interface was approximately the same height across the tank at any given time regardless of which discharge nozzle was in use. This behavior is attributed to density stratification. The density of the mixture decreases as the supernatant is mixed with the solids. Although the interface height of suspended solids was approximately the same across the tank, samples collected from inside the tank at various depths indicated that the concentration of suspended solids varied across the tank until the contents had become nearly mixed.

The ends and sides of the tank were more difficult to mobilize because the jet did not directly influence the sludge in those areas. It is believed that mobilization in these areas can be improved by (1) increasing the jet velocity and (2) modifying the jets to be rotational. One option for increasing the jet velocity is to use a smaller-diameter nozzle, but this may cause large pressure-drop problems that would need to be addressed. Another option to increase the jet velocity is to use a larger-capacity pump.

If one assumes that kaolin clay is a reasonable surrogate for the MVST and other LLLW sludges, the ECL data in Fig. 24 and Eq. (6) can be used to determine the jet velocity required for sluicing the sludge from these tanks. A submerged nozzle used in the MVSTs or evaporator service tanks would likely be positioned ~1/4 tank length from the end of the tank in the existing manhole port in the tanks. The distance between the manhole port and the end of the tank is approximately 13.7 m (45 ft). A submerged nozzle would need a DV_o

value of 0.98 m^2/s. If one assumed that the submerged nozzle was fabricated from 2-in. Schedule 80 pipe, then the jet velocity required would be 19.3 m/s (63.3 ft/s), which corresponds to a volumetric flow of 39 L/s (620 gal/min). It should be emphasized that this calculation was done for a unidirectional submerged nozzle. A larger flow rate would be required if a bidirectional nozzle is used.

7. RECOMMENDATIONS

The data obtained from this project should prove valuable in the design of a mobilization system for the MVSTs and other long horizontal tanks containing sludge. However, the data in this report cannot necessarily be used directly in designing such a system because it is not known how the rheological properties of the simulated sludges compare with those of the actual sludges. Few data are available concerning the rheological properties of the sludges in the MVSTs, although there are some viscosity data available for the sludge in tank W-28. Kaolin clay was used as a simulant in these tests because it exhibited some of the same properties as the W-28 sludge, but it cannot be considered an ideal simulant.

Is the mobilization resistance exhibited by kaolin and the chemical simulant used in these tests similar to the mobilization resistance that will be exhibited by the actual sludges in the MVSTs and other LLLW tanks? The answer is unknown at this time. Since the actual sludges have settled in the tanks for many years, the maximum resistance to mobilization (i.e., shear strength) is found in the undisturbed condition; therefore, the measurement should be made in situ. Obtaining samples for analysis in a laboratory will not provide accurate data for the shear strength of the sludge. PNL has developed a shear vane device to measure the shear strength of sludges in situ; however, the device has not been thoroughly tested outside the laboratory. Using the shear vane device to compare the shear strength of the actual MVST sludges with that of the kaolin clay (or any other surrogate) with the shear vane device would help answer the question posed above.

Additional mobilization studies should be performed to demonstrate that the sludge in the long end of the tank can be mobilized successfully. Preferably, these mobilization tests should be conducted on a simulant that shows similar resistance to mobilization as the sludges in the MVSTs. Areas that should be addressed include (1) using higher jet velocities to mobilize the sludge to the end of the tank, (2) using a rotating nozzle to mobilize sludge on both sides of the manhole and to remove sludge that may stick to the sides of the tank, and (3) installing obstacles (e.g., air spargers) in the jet's path to determine the effect.

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APPENDIX A

PROCEDURES

PROCEDURE FOR THE ANALYSIS OF SAMPLES FOR SUSPENDED SOLIDS

Introduction

This procedure describes the method of determining the concentration of suspended solids. The method involves determining the concentration of total solids (i.e., dissolved and suspended) and then subtracting the dissolved solids from the total solids to determine the suspended solids. This procedure assumes that the concentration of dissolved solids in the interstices of the sludge particles is the same as that in the supernatant. This should be a valid assumption for the water/kaolin/sodium chloride components involved. All weights should be recorded in grams (to the nearest 0.1 mg). All volumes should be recorded in milliliters.

Determination of Dissolved Solids

1. Obtain a sample of supernatant from the tank. The tank's contents should have had several days to settle, and no visible solids should be present in the sample. If solids are visible, the sample should settle longer or be filtered. It may be prudent to filter the supernatant samples in some cases.

2. Obtain a clean, dry, cool evaporating dish, and weigh the dish. Record the container identification and weight (A).

3. Pour an aliquot (approximately 20 to 30 g) of supernatant into the evaporating dish and

reweigh. Please note that the sample may begin evaporating, so the sample should be weighed immediately after adding the sample. Record this information (B).

4. Place the sample in an oven (>100°C), and allow the sample to dry for at least 16 h.

5. After the sample has dried the required time, remove the sample from the oven and place it in a desiccator to cool. Allow approximately 1 h for cooling. Remove the sample from the desiccator and reweigh the sample. Please note that the sample may begin adsorbing water, so the sample weight should be determined quickly. Record this information (C).

6. Determine the concentration of dissolved solids from Eq. (A-1). For a supernatant sample, the concentration of total solids is equivalent to the concentration of dissolved solids:

$$\text{Dissolved solids (wt \%)} = \frac{(C - A)}{(B - A)} \times 100 \ . \qquad \text{(A-1)}$$

Determination of Suspended Solids

1. Obtain a clean, dry, cool evaporating dish, and record the container identification. Weigh the container, and record the information (D).

2. Obtain the desired sample to be analyzed for suspended solids. Shake the sample to obtain a homogeneous mixture of suspended solids. The solid particles may begin to settle very quickly after the shaking is stopped, so the next step should be done very quickly.

3. Pour an aliquot of sample (approximately 20 to 30 g) into the evaporating dish. Reweigh the evaporating dish, and record the data (E). Note that the sample may begin losing weight very quickly because of water evaporation; therefore, the weight should be measured very quickly after pouring the sample into the dish.

4. Place the sample in an oven (>100°C), and dry the sample for at least 16 h.

5. After the drying period is complete, remove the sample from the oven and place it in a desiccator to cool. The recommended cooling time is 1 h.

6. After the cooling period is complete, remove the sample from the desiccator. Reweigh the dish, and record the weight (F). Please note that the sample may begin adsorbing water from the atmosphere, which will affect the weight. Therefore, the sample should be weighed very quickly after it is removed from the desiccator.

7. Determine the concentration of solids from the following equations:

$$\text{Total Solids (wt \%)} = \frac{(F - D)}{(E - D)} \times 100 \,. \qquad \text{(A-2)}$$

Since the sample size will vary from sample to sample, the suspended solids cannot be determined by simply subtracting the dissolved solids from the total solids. The following equations must be used. Please note that the "Dissolved Solids (wt %)" term is determined from analysis of the supernatant:

$$\text{Dissolved Solids (g)} = \frac{(E - D) - (F - D)}{\left(\dfrac{100}{\text{Dissolved Solids (wt \%)}} - 1\right)} \,, \qquad \text{(A-3)}$$

$$\text{Suspended Solids (g)} = (F - D) - [\text{Dissolved Solids (g)}] \,, \qquad \text{(A-4)}$$

$$\text{Suspended Solids (wt \%)} = \frac{(F - D - [\text{Dissolved Solids (g)}])}{(E - D)} \times 100 \,. \qquad \text{(A-5)}$$

Equation (A-6) is a simplified equation for converting the weight percent (wt %) unit to grams per liter (g/L):

$$\text{Suspended Solids (g/L)} = [\text{Suspended Solids (wt \%)}] \times \text{Density (g/mL)} \times 10 \,. \qquad \text{(A-6)}$$

The density term that is required in Eq. (A-6) may be determined by the method described in the following section of this appendix.

PROCEDURE FOR MEASURING THE DENSITY OF SLURRY SAMPLES

1. Obtain a clean, dry, cool volumetric flask. Weigh the flask, and record the weight (G). Also record the volume of the flask (H).

2. Obtain the sample that is to be analyzed for density. Shake the contents to mix the solids with the supernatant.

3. Pour the sample into the volumetric flask until the volume of slurry is level with the calibration mark on the neck of the flask. Avoid contacting the slurry with the neck walls above the calibration line.

4. Reweigh the volumetric flask, and record the weight (I). Calculate the density from the following equation:

$$\text{Density}\left(\frac{g}{mL}\right) = \frac{(I - G)}{H} . \tag{A-7}$$

The density of several kaolin slurry samples was measured by this procedure. The density results were plotted as a function of the suspended solids concentration (weight percent), and it was determined that a relationship existed between the two variables. The data were analyzed and statistically fit to simple algebraic equations as shown in Fig. A-1. The equation represented by the solid line in the figure was selected as the best fit. After this

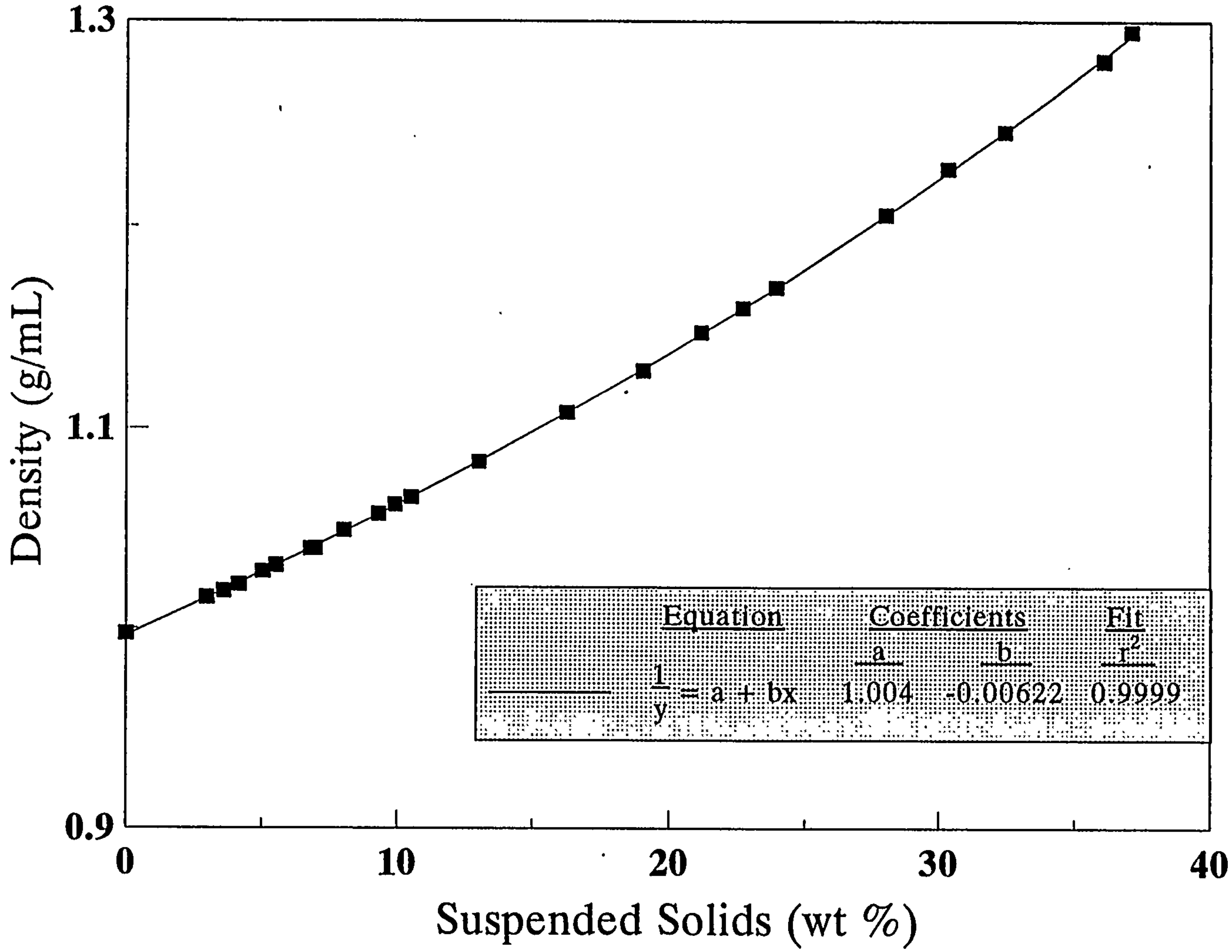


Fig. A-1. Density versus concentration of suspended solids for kaolin/water mixtures.

equation was determined, the density of the kaolin samples was calculated from the equation rather than from direct measurement.

This equation also proved useful for cases where the result from the suspended solids analysis appeared questionable. The density of the sample was measured using the procedure described above. The corresponding concentration of suspended solids was then determined from Fig. A-1. The concentration of suspended solids determined by the density determination method was then compared with the previously determined suspended solids concentration for confirmation.

APPENDIX B

DIMENSIONED DRAWINGS OF TANKS

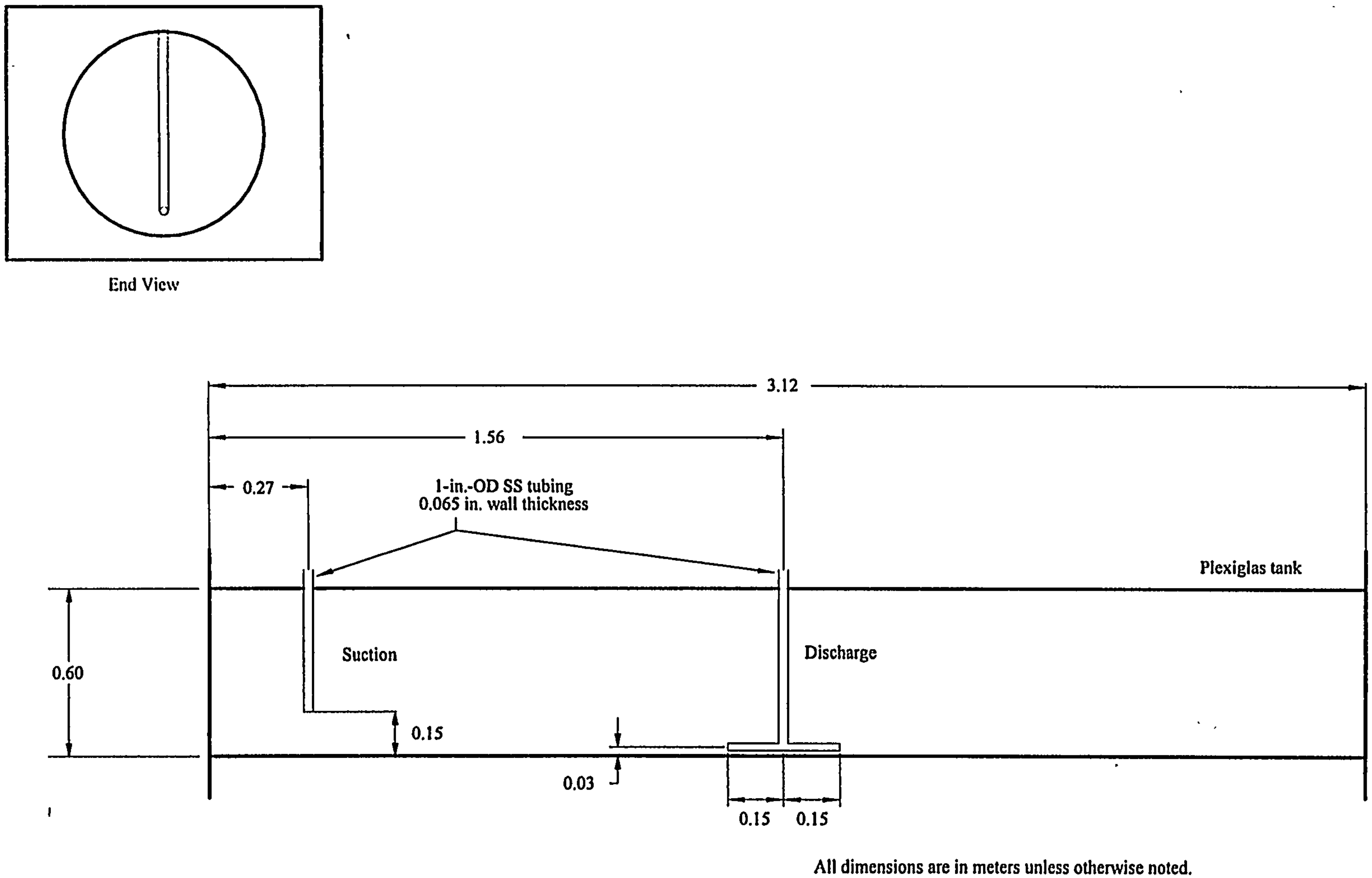
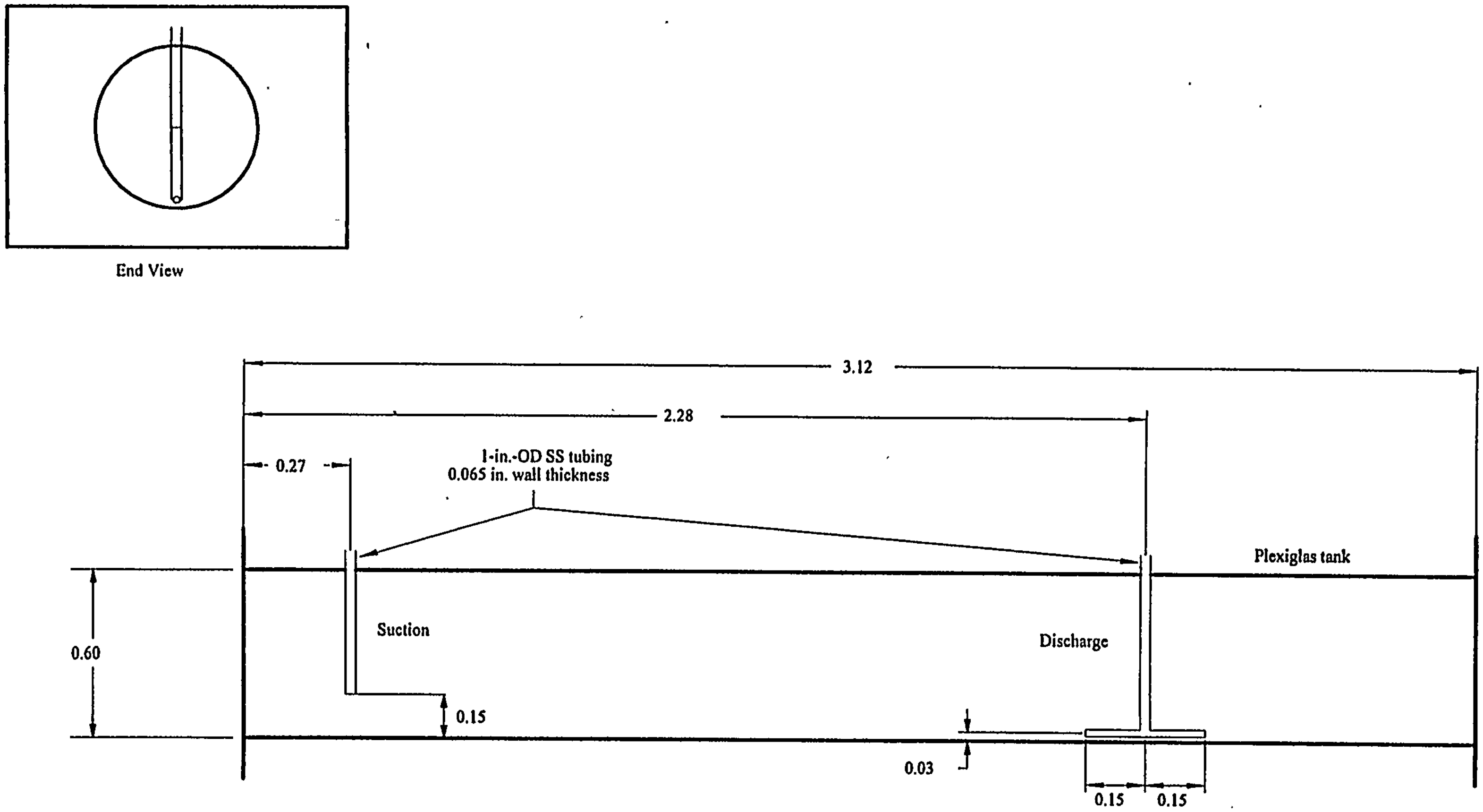


Fig. B-1. Dimensions for the 0.87-m^3 tank with submerged nozzle in the center of the tank.



All dimensions are in meters unless otherwise noted.

Fig. B-2. Dimensions for the 0.87-m^3 tank with submerged nozzle ~1/4 tank length from the end of tank.

ORNL DWG 95A–28R

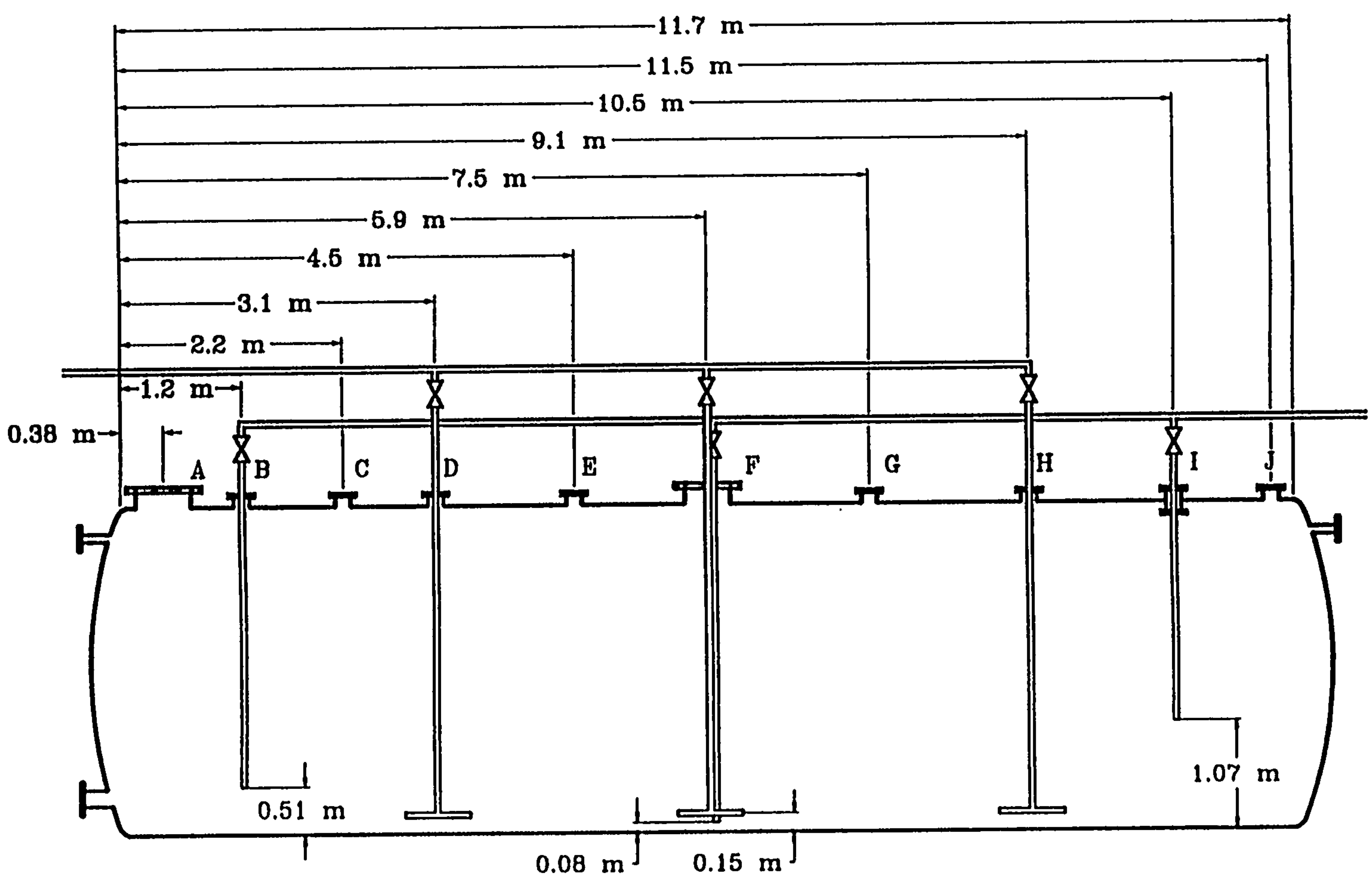


Fig. B-3. Dimensions for the 95-m^3 tank with submerged nozzles and suction lines.

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