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Richland, WA 99354

Summary

Scaled mixing experiments were conducted to address the issue of maintaining mobilized particles in a uniform suspension (the condition of concentration uniformity) using jet pumps to mix the suspension. The tests are based on the general analysis of maintaining uniformity described in *Strategy Plan: A Methodology to Predict the Uniformity of Double-Shell Tank Waste Slurries on Mixing Pump Operation* (Bamberger et al. 1990) and *Test Plan: 1/12-Scale Scoping Experiments to Characterize Double-Shell Tank Slurry Uniformity* (Bamberger and Liljegren 1994). The objectives of these 1/12-scale scoping experiments were to

- Determine which of the dimensionless parameters discussed in Bamberger and Liljegren (1994) affect the maximum concentration that can be suspended during jet mixer pump operation in the full-scale double-shell tanks
- Develop empirical correlations to predict the nozzle velocity required for jet mixer pumps to suspend the contents of full-scale double-shell tanks
- Apply the models to predict the nozzle velocity required to suspend the contents of Tank 241-AZ-101
- Obtain experimental concentration data to compare with the TEMPEST[a] (Trent and Eyler 1989) computational modeling predictions to guide further code development
- Analyze the effects of changing nozzle diameter on exit velocity (U_0) and U_0D_0 (the product of the exit velocity and nozzle diameter) required to suspend the contents of a tank.

The scoping study experimentally evaluated uniformity in a 1/12-scale experiment varying the Reynolds number, Froude number, and gravitational settling parameter space. The initial matrix specified only tests at 100% U_0D_0 and 25% U_0D_0. After initial tests were conducted with small diameter, low viscosity simulant this matrix was revised to allow evaluation of a broader range of U_0D_0. The revised matrix included a full factorial test between 100% and 50% U_0D_0 and two half-factorial tests at 75% and 25% U_0D_0. Adding points at 75% U_0D_0 and 50% U_0D_0 allowed evaluation of curvature. Eliminating points at 25% U_0D_0 decreased the testing time by several weeks.

Test conditions were achieved by varying the simulant viscosity (μ), the mean particle size (d_p), and the jet nozzle exit velocity (U_0). Concentration measurements at sampling locations throughout the tank were used to assess the degree of uniformity achieved during each test. Concentration data was obtained using a real time ultrasonic attenuation probe and discrete batch samples. The undissolved solids concentration at these locations was analyzed to determine whether the tank contents were uniform (< ±10% variation about mean) or nonuniform (> ±10% variation about mean) in concentration. Concentration inhomogeneity was modeled as a function of dimensionless groups.

The two parameters that best describe the maximum solids volume fraction that can be suspended in a double-shell tank were found to be 1) the Froude number (Fr) based on nozzle velocity (U_0) and tank contents level (H) and 2) the dimensionless particle size (d_p/D_0). The dependence on the Reynolds number (Re) does not appear to be statistically significant.

(a) TEMPEST is an acronym for “Transient energy, momentum, and pressure equation solution in three dimensions.”

The empirical correlations were applied to determine the best estimate of nozzle velocity require to suspend the contents of Tank 241-AZ-101 based on 1/12-scale data. The estimated nozzle velocity required using a 6-in.-diameter nozzle was found to be 8.9 m/s. This corresponds to a U_0D_0 of 14.6 ft^2/sec. The standard error in this estimate could be determined using the correlations, but has not been done here.

TEMPEST simulations of particle concentrations showed very good agreement with the experimental data. The particle transport models employed by TEMPEST captured important aspects of the erosion and deposition of solids on the tank floor as well as size-dependent settling.

The empirical correlations were applied to estimate the nozzle velocity required to suspend material in 101-AZ using mixer pumps with 4- or 8-in.-diameter nozzles. These estimates are highly uncertain because no data was collected to determine the effect of nozzle diameter.

Nomenclature

C	concentration
d_p	mean particle diameter
D_0	nozzle diameter
DST	double-shell tank
E	erodibility
Fr	Froude number
Gs	gravitational settling parameter
H	fluid depth
K	consistency index
m_d	solids deposition flux
m_e	mass flux of solids away from sludge
n	behavior coefficient
PNNL	Pacific Northwest National Laboratory
Q	mixer pump volumetric flow rate
R	mixer pump oscillation rate
Re	Reynolds number
s	density ratio (ρ_s/ρ)
T	temperature
t	time
U_s	particle settling velocity
U_0	nozzle exit velocity
WHC	Westinghouse Hanford Company

Greek Letters

Δ	uncertainty
θ	nozzle angular location
μ	viscosity
μ_b	bulk viscosity anticipated when fully mixed
ν	kinematic viscosity
Φ_p	volume fraction of solids
Φ_s	volume fraction, species mass fraction
ρ	bulk density
ρ_f	supernatant density
ρ_s	solids density
τ_d	critical shear stress for deposition
τ_e	critical shear stress for erosion
τ_f	shear stress exerted on sludge by fluid
τ_s	shear stress

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1.0 Introduction

Million-gallon double-shell tanks (DSTs) at Hanford are used to store transuranic, high-level, and low-level radioactive wastes. These wastes generally consist of a large volume of salt-laden solution covering a smaller volume of settled sludge primarily containing metal hydroxides. These wastes will be retrieved and processed into immobile waste forms suitable for permanent disposal. Retrieval is an important step in implementing these disposal scenarios. Retrieval technologies applicable to the various double-shell tank wastes were defined, developed, and demonstrated at Pacific Northwest National Laboratory (PNNL) in conjunction with Westinghouse Hanford Company (WHC). The current retrieval concept is to use submerged dual-nozzle pumps to mobilize the settled solids by creating jets of fluid that are directed at the tank solids. The pumps oscillate, creating arcs of high-velocity fluid jets that sweep the floor of the tank. After the solids are mobilized, the pumps will continue to operate at a reduced flow rate sufficient to maintain the particles in a uniform suspension (concentration uniformity).

Several types of waste and a number of tank configurations exist at Hanford. The mixer pump systems and operating conditions required to mobilize sludge and maintain slurry uniformity will be a function of the waste type and tank configuration. While it would be possible to specify the mixer pump system for each tank using scaled testing, it is more efficient to develop analytical models that relate slurry uniformity to tank and mixer pump configurations, operating conditions, and sludge properties. These models can then be used over a range of conditions to specify mixer pumps. It is the goal of this research to develop models that will be adequate over the expected range of slurry properties and tank configurations. The most efficient method to determine appropriate pump sizes and predict the flow rates required during the retrieval process to mobilize sludge and maintain slurry uniformity is to develop generalized relations describing the behavior of these waste slurries.

The experiments described address the issue of maintaining mobilized particles in a uniform suspension; the companion problem of mobilizing the settled solids is addressed separately (Powell et al. 1995a, b). The tests to be conducted during this scoping study are based on the general analysis of maintaining uniformity described in *Strategy Plan: A Methodology to Predict the Uniformity of Double-Shell Tank Waste Slurries on Mixing Pump Operation* (Bamberger et al. 1990).

1.1 Objectives

The general uniformity objectives are to define mixing pump configurations and operating limits that will ensure an adequately uniform feed waste stream during waste retrieval from the double-shell tanks. The objectives specific to this 1/12-scale study are to

1. Determine which dimensionless parameters discussed in Bamberger and Liljegren (1994) affect the maximum concentration that can be suspended during jet mixer pump operation in the full-scale double-shell tanks.
2. Develop empirical correlations to predict the nozzle velocity required for jet mixer pumps to suspend the contents of full-scale double-shell tanks.
3. Apply the models to predict the nozzle velocity required to suspend the contents of Tank AZ-101.

4. Obtain experimental concentration data to compare with the TEMPEST[(a)] (Trent and Eyler 1989) computational modeling predictions to guide further code development.

5. Analyze the effects of changing nozzle diameter on U_0 (nozzle exit velocity) and U_0D_0 (the product of the jet exit velocity and nozzle diameter) required to suspend the contents of a tank.

1.2 Scope

The experiments were designed to evaluate uniformity in a 1/12-scale experiment at the positions on the Reynolds number, Froude number, and gravitational settling parameter space shown in Figure 1.1. (The points are defined in Section 4, Table 4.1.) The initial test matrix was based on a full-factorial experiment conducted between 100% and 25% U_0D_0 (the product of the jet exit velocity and nozzle diameter). Early results showed that solids could not be suspended fully over the entire range of tests.

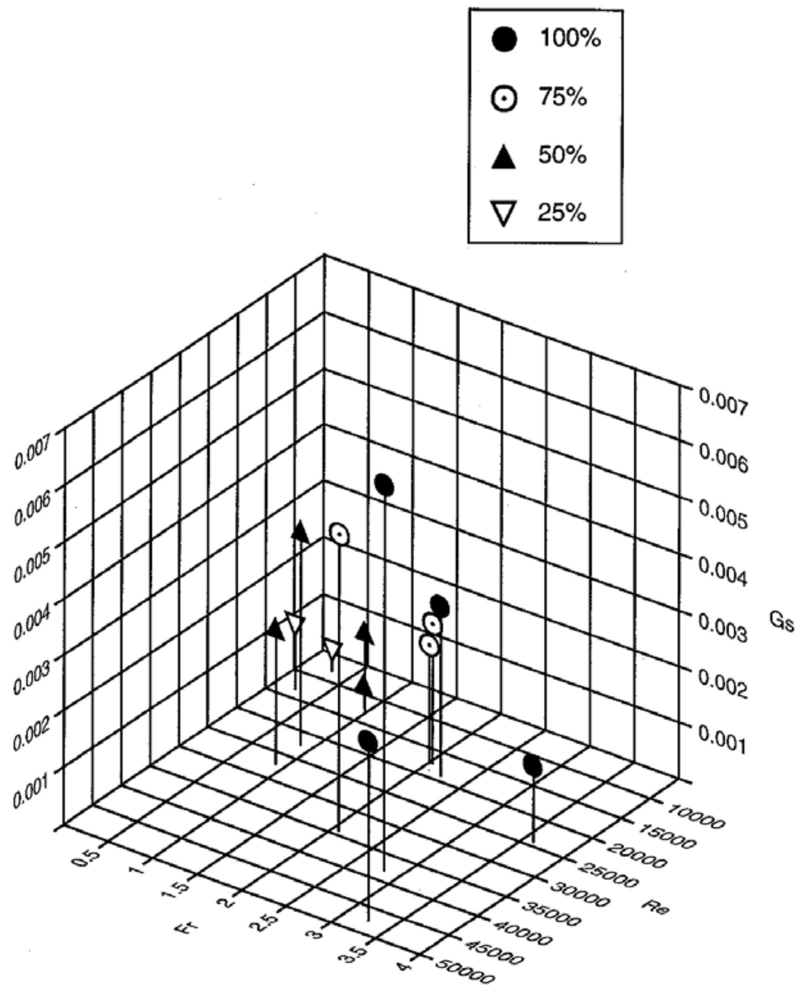

Figure 1.1. Experiment Dimensionless Parameter Space

(a) TEMPEST is an acronym for “transient energy, momentum, and pressure equation solution in three dimensions.”

The test matrix was modified to study the maximum concentration that could be suspended at a particular U_0D_0. The values of U_0D_0 were expanded to provide a larger test matrix. The revised test matrix included a full-factorial test between 100% and 50% U_0D_0 and two half-factorial tests between 100% and 75% and 100% and 25% U_0D_0. The test conditions were achieved by varying the simulant viscosity (μ), the mean particle diameter (d_p), and the jet nozzle exit velocity (U_0). The data acquired during these tests was used to complete objectives 1, 2, and 4. Models developed during completion of objective 2 are used to complete objectives 3 and 5.

Concentration measurements at sampling locations throughout the tank were taken to assess the degree of uniformity achieved during each test. The undissolved solids concentration at these locations was analyzed for two features. One was to determine whether the tank contents are uniform (≤±10% variation about mean) or nonuniform (>±10% variation about mean) in concentration. In most cases, solids settled in the tests. Data were also analyzed to determine the average concentration of solids suspended in the tank at a particular U_0D_0. The maximum concentration that could be sustained by mixer pumps was modeled as a linear function of the dimensionless groups. The measured degree of inhomogeneity during the tests was used for comparison with computational predictions.

1.3 Limitations

The test plan (Bamberger and Liljegren 1994) described experiments that are part of a broader strategy for developing methods to predict the uniformity of waste tank contents during waste retrieval. The Strategy Plan (Bamberger et al. 1990) described the procedure to continue analyses of uniformity via computational modeling and larger scaled experiments after completion of these 1/12-scale experiments. The understanding gained from these scoping experiments is subject to the following limitations.

- The experiments were performed in a specific Reynolds number, Froude number, and gravitational settling parameter region.[a] Prediction of the behavior outside that region will require extrapolation, which may introduce inaccuracies.
- The models developed are useful for predicting concentration uniformity from operating jet mixer pumps in tanks with geometries similar to double-shell tanks. The degree to which the models may be applied to predict the uniformity in geometrically dissimilar tanks is not known.
- The experiments were conducted in a tank without scaled tank components; therefore, effects of tank components, such as air lift circulators, upon uniformity was not determined.

(a) The region chosen for these experiments was limited by fluid rheology and the need for experiments to be conducted in a turbulent Reynolds number regime. The selected range is deemed satisfactory for conducting the scoping experiments at 1/12 scale.

2.0 Conclusions and Recommendations

2.1 Conclusions

These conclusions are ordered to correspond to the five objectives listed in Section 1.2.

1. The two parameters that best describe the maximum solids volume fraction that can be suspended in a DST were found to be 1) the Froude number (Fr) based on nozzle velocity (U_0) and tank contents level (H) and 2) the dimensionless particle size (d_p/D_0). The dependence on the Reynolds number (Re) does not appear to be statistically significant.

2. The following two empirical correlations were found to predict the maximum concentration, Φ_p, that can be achieved in a DST during steady-state mixer pump operation. Error bands in the exponents are provided to indicate the standard error in the predictive value of the correlation.

$$\Phi_p = 10^{(-5.415\pm1.801)}\, Re_0^{\ 0.021\pm0.320}\, Fr_0^{\ 1.478\pm0.360}\, (d_p/D_0)^{-1.03\pm0.41} \tag{2.1}$$

$$\Phi_p = 10^{(-5.34\pm1.37)}\, Fr_0^{1.49\pm0.29}\, (d_p/D_0)^{-1.03\pm0.39} \tag{2.2}$$

Correlations were not developed to predict the following two features:

1. The degree of inhomogeneity. In general, those contents that were suspended appeared homogeneously distributed.

2. The stratification by size. The experiments indicated that when insufficient power is supplied to the tank larger particles settled preferentially.

Data were not examined in detail to verify certain features that are critical to the accuracy of the correlation. For example, the individual data points have not been examined to determine whether any cases should be eliminated because they had not achieved steady-state. Thus, the correlations should be considered preliminary.

Both empirical correlations were applied to determine the best estimate of nozzle velocity required to suspend the contents of AZ-101 based on 1/12-scale data. The estimated nozzle velocity required using a 6-in.-diameter nozzle was found to be 8.9 m/s. This corresponds to a U_0D_0 of 14.6 ft^2/sec. The standard error in this estimate could be determined using the correlations, but that has not been done.

TEMPEST simulations of particle concentrations showed very good agreement with the experimental data. The particle transport models employed by TEMPEST captured important aspects of the erosion and deposition of solids on the tank floor as well as size-dependent settling. TEMPEST-predicted concentrations continued to decay slightly at the experimentally determined equilibrium time. This may be caused by the selected number of particle size bins and certain limitations of the erosion deposition floor model.

The empirical correlations were applied to estimate the nozzle velocity required to suspend material in AZ-101 using mixer pumps with 4- or 8-in.-diameter nozzles. These estimates are highly uncertain because no data were collected to determine the effect of nozzle diameter.

The following best estimates are recommended based on 1/12-scale data using a scaled 6-in.-diameter nozzle. None of these recommendations reflect the uncertainty in the correlation for a 6-in.-diameter nozzle.

- For D_0 = 4 in., the required nozzle velocity falls between 8.4 and 10.2 m/s.
- For D_0 = 8 in., the required nozzle velocity falls between 8.1 and 8.9 m/s.
- For D_0 = 6 in., the best estimate of the nozzle velocity is 8.9 m/s.

2.2 Recommendations

The results from this report represent preliminary evaluations of the data collected in the 1/12-scale experiments. The uncertainty in the recommendation can be reduced through two activities that should be performed sequentially.

- The data for individual experiments should be reviewed in detail for a number of features. The most important is to determine whether individual data points do not represent steady-state results because the solids had not completed settling. If some tests are found to be invalid, this could affect both the form of the best fit correlation and the coefficients in the correlation.
- To reduce the error in the extrapolation to other nozzle diameters, at least one experiment should be performed using a nozzle diameter other than a scaled 6-in.-diameter.

It is also recommended that the data should be analyzed to obtain correlations to predict the following two features:

- The spatial inhomogeneity in the concentration of the suspended solids. This inhomogeneity appears to be small but is of interest to engineers sizing mixer pumps.
- The spatial inhomogeneity in the solids size. The results suggest that larger solids settle to the bottom of the tank. In general, this means that heavier solids are settling and presents the possibility that if nozzle velocities are insufficient, the heavier metals in tanks will concentrate in the lower regions of the tank. This could be a concern from the standpoint of criticality or from the standpoint of supplying excess metal to glass melters at a later point in processing.

The following recommendations are related to TEMPEST code development:

- Develop a sloped floor model that simulates sludge buildup near outer walls.
- Develop empirical correlations to accurately predict erosion and deposition model constants from particle physical properties and rheological data.
- Develop a size-dependent erosion model to accurately represent the particle size stratification observed in the settled layers.

3.0 Simulant Development

Four simulants were required to conduct the scoping experiments. Specifications for the physical properties of the simulants are defined in Section 3.1, and simulant recipes for the 1/12-scale experiments are listed in Section 3.2.

3.1 Specifications

Specific Reynolds numbers, Froude numbers, and gravitational settling parameters are needed to achieve the desired experimental conditions. The Froude number is set by controlling the jet nozzle exit velocity. Simulant physical properties are chosen to obtain the required Reynolds number and gravitational settling parameter; kinematic viscosity is varied to set Reynolds number; particle diameter is varied to set the gravitational settling parameter. The simulant physical properties must meet the following criteria:

- At the target nozzle exit velocity (U_0), the bulk density (ρ) and effective viscosity (μ) of each individual simulant must allow target Reynolds numbers to be achieved within ±20%.
- At the target nozzle exit velocity (U_0), the bulk density (ρ) and particle diameter (d_p) of each individual simulant must allow the target gravitational settling parameter to be achieved within ±50%.
- When identical viscosities (μ) are specified for two simulants, the difference between the two viscosities should not be more than ±10%, thereby ensuring that the effect of varying the Reynolds number between a high and low value can be determined.
- When identical mean particle diameters (d_p) are specified for two simulants, the mean particle diameters in the two simulants should match within ±3 µm for the smaller-diameter simulant and ±5 µm for the larger-diameter simulant.

The magnitudes of the simulant physical properties were selected to allow the values of the Reynolds number and gravitational settling parameter to be achieved. Acceptable ranges for the measured values of these properties at 20°C (68°F), as specified in the test plan (Bamberger and Liljegren 1994), are provided in Table 3.1. These ranges pertain to the target specifications and not the accuracy with which the properties must be measured. The actual properties obtained after simulant mixing are listed in Table 3.2. Values underlined are outside the initial specification range.

Table 3.1. Target Simulant Properties

Simulant	Absolute Viscosity μ (cP)	Particle Diameter d_p (µm)	Bulk Density ρ (kg/m^3)	Density Ratio ($s=\rho_s/\rho$)	Concentration (wt%)	Kinematic Viscosity ν (m^2/s)	Nominal Particle Settling Velocity[(a)] u_S (µm/s)
S1	<2[(b)]	5±3	1,250±10%	2±25%	18%±5%	<1.6±10%	8.5
S2	<2	20±5	1,250±10%	2±25%	18%±5%	<1.6±10%	136
S3	3.4 ± 5%	5±3	1,250±10%	2±25%	18%±5%	2.7±10%	5
S4	3.4 ± 5%	20±5	1,250±10%	2±25%	18%±5%	2.7±10%	80

(a) Calculated value based on particle diameter.
(b) This absolute viscosity is anticipated to approach that of water at ambient temperature (~1 cP). The maximum permissible viscosity for simulants S1 and S2 is 2 cP.

Table 3.2. Initial Simulant Properties

Simulant	Absolute Viscosity μ (cP)	Particle Diameter d_p (μm)	Bulk Density ρ (kg/m³)	Density Ratio[(a)] (s = ρ_s/ρ)	Concentration (wt%)	Kinematic Viscosity ν (m²/s)	Nominal Particle Settling Velocity[(b)] U_S (μm/s)
S1	1.55	5.45	1,112 Lower bound 1,125	2.381	17.2	1.41	16
S2	1.75	17.76	1,119 Lower bound 1,125	2.366	17.6	1.46	150
S3	3.53	5.76	1,216	2.177	18.1	2.91	7.3
S4	3.10–3.20[(c)] Lower bound 3.23	18.19	1,139	2.324	16.6 Lower bound 17.1	2.73[(d)]	82

(a) Calculated based on density of SiO_2 of 2,635 to 2,660 kg/m³ (CRC 1975).
(b) Calculated value based on particle diameter.
(c) This absolute viscosity range was measured at equilibrium at 100% and 50% U_0D_0. The initially mixed value may not be representative.
(d) These data were measured at equilibrium at 100% U_0D_0. The initially mixed value may not be representative.

3.2 Simulant Recipes

From the target properties listed in the test plan, the simulant recipes were developed based on the solids selected for the tests. Simulants were manufactured using Minusil-10 and Minusil-40.[(a)] The revised simulant target properties are listed in Table 3.3. The simulants were developed based on the properties shown in the table and were mixed to provide the desired concentration of suspended solids and viscosities. For the low-viscosity simulant the recipe was 18 wt% solids in water; for the high-viscosity simulant the recipe was 18 wt% solids in a 22 wt% sugar water solution. Laboratory tests were conducted to determine the optimum wt% sugar solution. Data to support selection of 22 wt% sugar solution are shown in Table 3.4.

Table 3.3. Revised Simulant Target Properties

Simulant	Absolute Viscosity μ (cP)	Particle Diameter[(a)] d_p (μm)	Bulk Density ρ (kg/m³)	Density Ratio (s=ρ_s/ρ)	Concentration (wt%)	Kinematic Viscosity ν (m²/s)	Nominal Particle Settling Velocity[(b)] U_S (μm/s)
S1	1.53	6.30	1,110	2.38	18	1.38	8.5
S2	1.51	27.41	1,120	2.37	18	1.35	136.0
S3	3.08	6.30	1,210	2.19	18	2.55	5.0
S4	~3.50	27.41	1,210	2.19	18	~3.00	80.0

(a) Particle diameter is the volume mean as determined by Brinkman particle size analyzer.
(b) Settling velocity was not measured. Values are the same as calculated in Table 3.1.

(a) U. S. Silica company.

Table 3.4. Laboratory Data to Support Simulant Recipe Selection

Solvent	Minusil Size	Solids (wt%)	Density (kg/m^3)	Viscosity (cSt)
Water	10	2	1,010	0.99
Water	10	5	1,020	1.09
Water	10	18	1,110	1.38
Water	10	30	1,200	1.67
Water	10	40	1,310	2.35
Water	40	2	1,000	0.93
Water	40	5	1,030	1.09
Water	40	10	1,060	1.19
Water	40	18	1,120	1.35
Water	40	30	1,210	----
Water	40	40	1,410	2.16
20% sugar water	10	18	1,100	2.08
25% sugar water	10	18	1,220	3.04
22% sugar water	10	18	1,210	2.55
22% sugar water	40	18	1,210	2.55

Each simulant was used to conduct two experiments. Experiments using the same simulants were conducted consecutively. For each particle size, initial tests were conducted with the low viscosity simulant. After completion of these tests, the simulant viscosity was increased via addition of sugar.

4.0 Experiments

Operating conditions for the tests, the experimental system, the experimental procedure developed to conduct these tests, and the data acquisition modes and instrumentation are described in this section.

4.1 Operating Conditions

Operating conditions for these experiments were chosen to produce the desired nondimensional Reynolds and Froude numbers and gravitational settling parameters required to model uniformity at 1/12 scale. The nondimensional numbers were chosen based on the simulant physical properties defined in Table 3.1 and mixer pump operating conditions of fluid depth (H), jet nozzle exit velocity (U_0), and mixing pump oscillation rate (R). Mixer pump operation is defined by the pump oscillation rate, which is not varied during these experiments, and mixer pump volumetric flow rate. The nozzle diameter is geometrically sized to 1/12 scale, thereby defining the nozzle exit velocity based on the volumetric flow rate that supplies the two opposed nozzles. The operating conditions, target Reynolds numbers, Froude numbers, and gravitational settling parameters for these tests are listed in Table 4.1. The actual values of the dimensionless parameters varied slightly due to variations in simulant physical properties.

4.2 1/12-Scale Test System

These experiments were conducted in a 1/12-scale system for testing double-shell tank retrieval technologies installed in the 336 Building on the Hanford Site. The system included a 1/12-scale model of a Hanford double-shell tank, simulated 1/12-scale mixer pumps, simulant preparation equipment, and instrumentation. The system flow diagram is shown in Figure 4.1.

Table 4.1. Target Operating Conditions for the Tests

Test Number	Simulant[a]	Nozzle Exit Velocity (m/s ±5%)	Mixer Pump Flow Rate[b] (m^3/s ±5%)	Reynolds Number	Froude Number	Gravitational Settling Parameter[c]	Settling Time (hr)	Nozzle Oscillation Rate (rpm)
S1 100%	1	5.2	1.3×10^{-3}	4.1×10^{4}	3.58	1.9×10^{-3}	24.9	0.346
S1 50%	1	2.6	6.5×10^{-4}	2.0×10^{4}	0.88	1.6×10^{-2}	24.9	0.346
S1 25%	1	1.3	3.3×10^{-4}	1.0×10^{4}	0.22	1.2×10^{-1}	24.9	0.346
S2 100%	2	5.2	1.3×10^{-3}	4.1×10^{4}	3.58	3.0×10^{-2}	1.6	0.346
S2 75%	2	3.8	9.8×10^{-4}	3.1×10^{4}	1.99	7.7×10^{-2}	1.6	0.346
S2 50%	3	2.6	3.3×10^{-4}	1.0×10^{4}	0.22	2.08	1.6	0.346
S3 100%	3	5.2	1.3×10^{-3}	2.4×10^{4}	3.58	1.1×10^{-3}	42.3	0.346
S3 75%	3	3.8	9.8×10^{-4}	1.8×10^{4}	1.99	2.9×10^{-3}	42.3	0.346
S3 50%	3	2.6	3.3×10^{-4}	6.0×10^{3}	0.22	7.8×10^{-2}	42.3	0.346
S4 100%	4	5.2	1.3×10^{-3}	2.4×10^{4}	3.58	1.7×10^{-2}	2.6	0.346
S4 75%	4	3.8	9.8×10^{-4}	1.8×10^{4}	1.99	4.6×10^{-2}	2.6	0.346
S4 50%	4	2.6	6.5×10^{-4}	1.2×10^{4}	0.88	1.6×10^{-1}	2.6	0.346
S4 25%	4	1.3	3.3×10^{-4}	6.0×10^{4}	0.22	1.1	2.6	0.346

(a) Simulant properties are defined in Table 3.1.
(b) Flow rate to mixer pump required to operate two nozzles.
(c) The gravitational settling parameter is the ratio of the rate at which the gravitational field draws particles to the lower regions of the tank to the power supplied by the jet to suspend particulate.

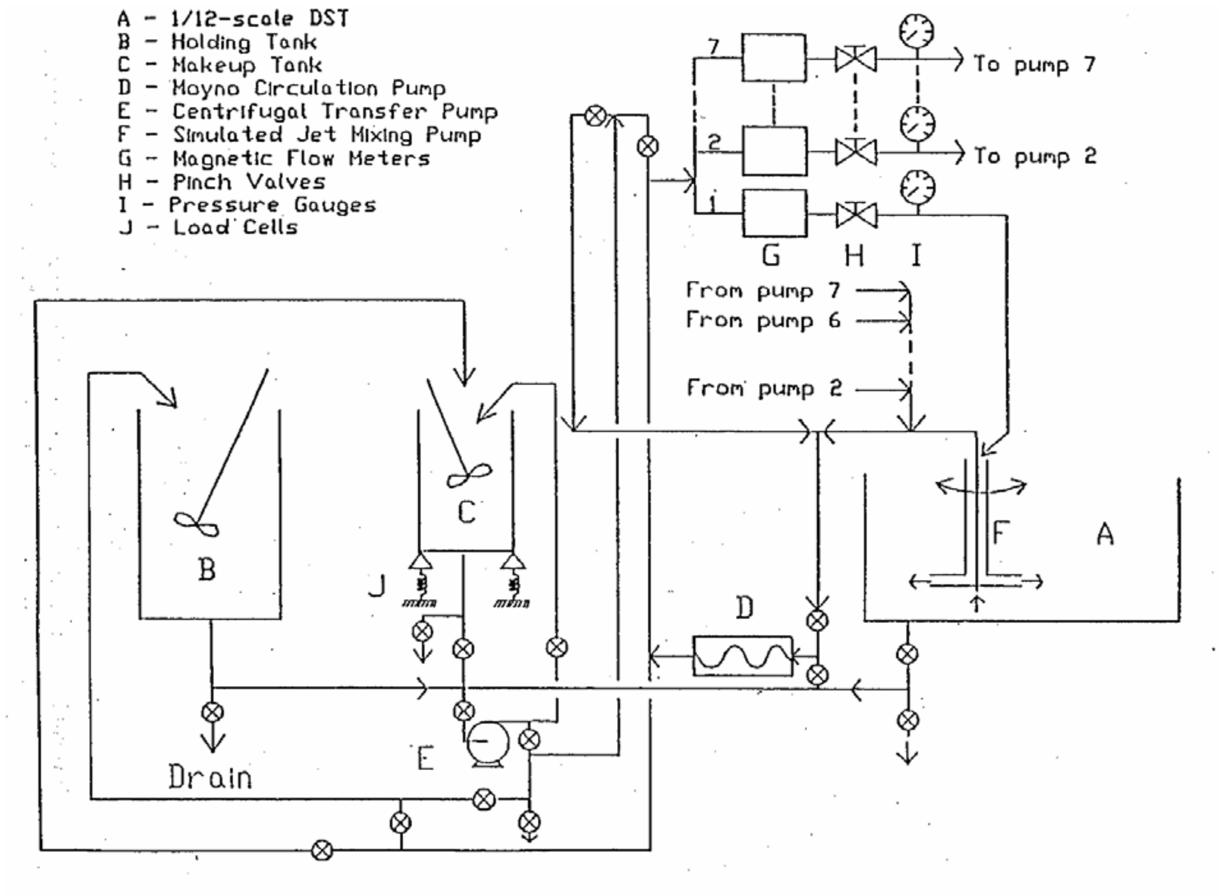

Figure 4.1. Flow Diagram for 1/12-Scale System

4.2.1 One-Twelfth-Scale DST Model

Dimensions of the 1/12-scale tank are listed in Table 4.2. The tank models the major internal dimensions of a Hanford 3785-m^3 (1-million-gallon) DST. The tank knuckle, which is the corner radius connecting the tank wall and floor, was not modeled during the 1/12-scale tests. The absence of the knuckle was not anticipated to affect these experiments because of its small size and limited influence on flow patterns. If larger-scale experiments are pursued, the knuckle can be modeled in the 1/4-scale tank. The tank is made of 304L stainless steel and can be configured to represent actual locations of the tank penetrations and internal components.[a] No tank internal components were modeled during these scoping experiments.

(a) Tank internal components include steam coils, air lift circulators, radiation dry wells, thermocouple trees, and other hardware.

Table 4.2. 1/12-Scale Model Configuration

Tank Geometry	Prototype (m)	(ft)	Model (m)	(in.)
Diameter	23.00	75.00	1.900	75.00
Knuckle radius	0.30	1.00	Not modeled	
Fluid depth	9.10	30.00	0.760	30.00
Mixer Pump Dimensions				
Nozzle diameter	0.15	0.50	0.013	0.50
Tank wall to pump vertical centerline	11.40	37.50	0.950	37.50
Tank bottom to nozzle centerline	0.46	1.50	0.038	1.50
Pump centerline to nozzle discharge	0.44	17.50	0.037	1.50
Tank floor to pump intake	0.15	0.50	0.013	0.50
Discharge angle from vertical	90° +3	0°	90° +3	0°
Jet Properties	m/s	ft/sec	m/s	ft/sec
100% U_0 jet velocity	5.46	58.80	5.28	17.04
Nozzle exit parameter	m^2/s	ft^2/sec	m^2/s	ft^2/sec
100% U_0D_0 condition	2.73	29.40	0.066	0.71
75% U_0D_0 condition	2.73	22.10	0.050	0.53
50% U_0D_0 condition	2.73	14.70	0.033	0.36
25% U_0D_0 condition	2.73	7.35	0.017	0.18
Pump oscillation (rpm)	0.1		0.346	
Pump angle of oscillation	180.0°		180.0°	

4.2.2 Simulated Jet Mixer Pump

The 1/12-scale mixer pump design shown in Figure 4.2 models operation of the proposed full-scale jet mixer pump. A Moyno® progressive cavity pump draws simulant up the inside tube of the pump model and through the pump.[a] The simulant then discharges through the mixing pump annulus from two diametrically-opposed nozzles. The 1/12-scale nozzle, with diameter D_0, is designed to simulate the nozzle in the prototype pump. During these 1/12-scale experiments, one mixing pump located at the tank center oscillates through a 180° arc at 0.346 rpm. Scaled mixing pump dimensions, location, and operating conditions are summarized in Table 4.2.

(a) Robins & Myers, Inc., Springfield, Ohio.

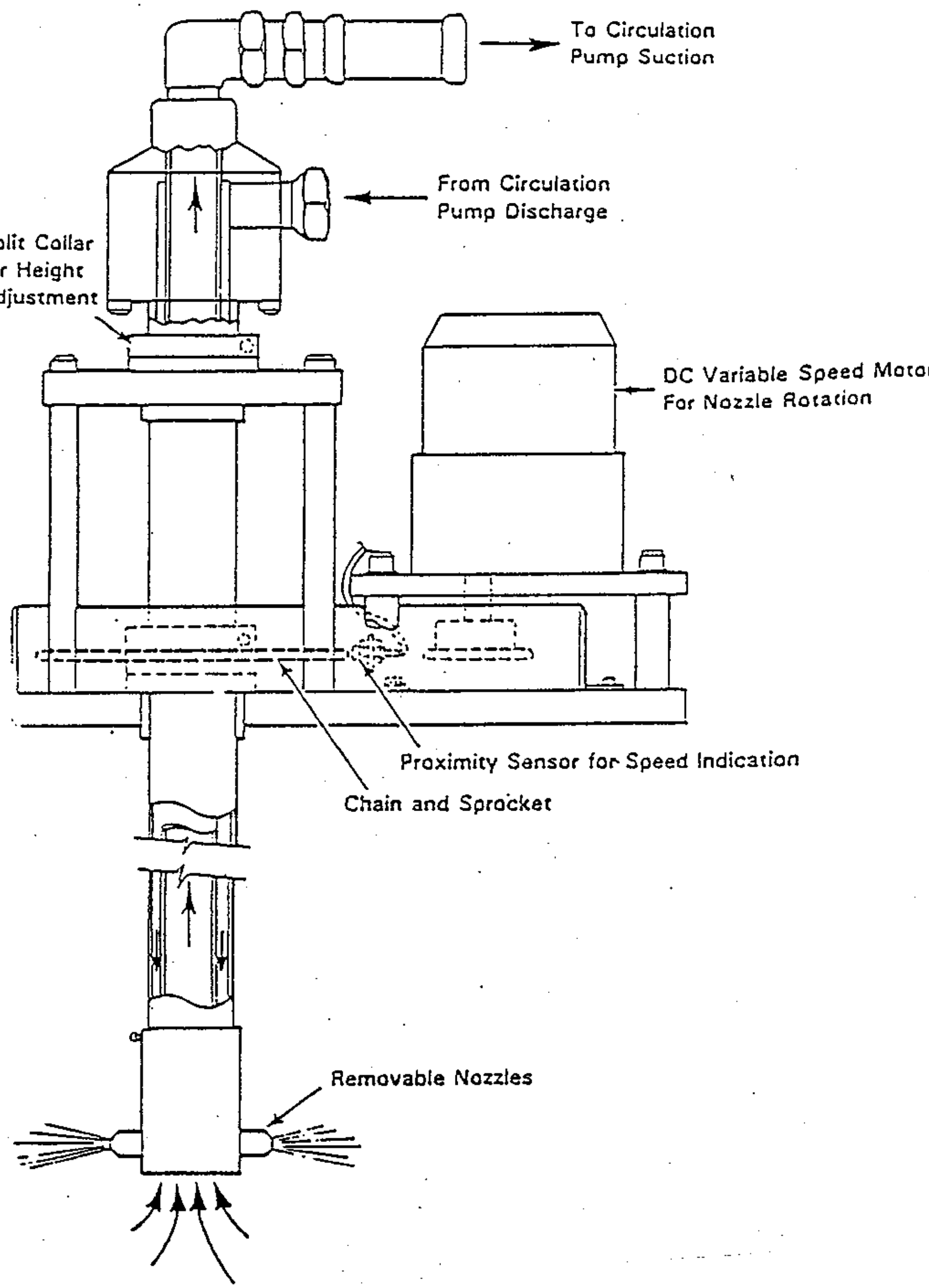

Figure 4.2. 1/12-Scale Slurry Mixer Pump Configuration

4.2.3 Ancillary Equipment

Simulant preparation equipment includes make-up and holding tanks and a transfer pump. The make-up tank is a 0.681 m^3 (180 gal) carbon steel tank [0.762-m (30-in.) diameter by 1.5-m (5-ft) high] equipped with an agitator. Three load cells, one under each support leg, are accurate to ±0.5 kg (±1.1 lbm). The tank is used for slurry preparation and transfer. The holding tank is a 2.135 m^3 (564 gal) carbon steel tank [1.22-m (4-ft) diameter by 1.8-m (6-ft) high]. The holding-tank piping is routed to allow transfer of slurry to or from the make-up tank or the 1/12-scale tank, or to drain.

The transfer pump is used for transferring slurry to or from any of the tanks, circulating slurry within the tanks, draining the tanks, and flushing the piping. The transfer pump is a centrifugal pump driven by a 1490-W (2-hp), single-phase, 230-V motor with a mechanical shaft seal. The pump has a capacity of 0.00317 m^3/s (50 gpm) at 15 m (50 ft) of head.

4.3 Test Procedure

Each 1/12-scale test involved three basic steps: 1) preparing the simulant (described in Section 3), 2) obtaining the desired operating conditions inside the tank (listed in Table 4.1), and 3) conducting the test. Before the start of each test, instrumentation was checked and initial conditions verified and recorded.

4.3.1 Test Period Definition

Each test is composed of several operating periods governed by the concentration distribution throughout the 1/12-scale tank.

- Period 1: completely mixed tank with uniform concentration profile throughout, obtained by high flow rate ≥100% U_0D_0
- Period 2: concentration profile changing because of solids settling caused by reduced mixer pump flow rate
- Period 3: steady-state concentration profile at the reduced flow rate.

After the completion of Period 3 at 100% U_0D_0, the nozzle exit velocity is reduced to the next-lowest flow rate, and steps 2 and 3 are repeated until the desired number of equilibrium conditions is obtained. The concentration distribution throughout each of these periods was recorded and monitored to ensure that the experiment was conducted correctly and that valid results were obtained.

During Period 1, the mixer pump was operated at its maximum flow rate, ≥100% U_0D_0. To ensure that the nozzle exit velocity was above the 100% case, a second inlet line was installed. During some tests, a compressed air lance was used to keep the mixture in full suspension. Concentration was monitored to ensure that the tank was completely mixed.

During Period 2, the mixer pump was set to the operating conditions defined in Table 4.1. With constant mixer pump operation, steady-state concentration conditions were achieved. The settling time to reach steady state was assumed to be at least 110% of the settling time listed in Table 4.1. The settling time is defined as the length of time required for a particle of mean diameter (d_p) and density (ρ_s) to settle from the top of the tank to the bottom of the tank. Concentration will be monitored to determine whether the tank has reached steady-state concentration.

During Period 3, the tank contents attained a steady-state concentration distribution. Measurements were made to determine the concentration distribution throughout the tank. The measurements were sufficient to determine whether the tank concentration was uniform within ±10% of the mean concentration and statistically significant to within a 95% confidence interval.

4.3.2 Period 1 Operation

During Period 1, the simulant in the tank was fully mixed. To ensure this condition, the mixer pumps were operated at ≥100% flow rate for at least 1 hour. During this period, the concentration distribution throughout the tank was monitored using ultrasonic probes and bottle samples. If the average measurements were stable, the mixing pump flow rate was reduced to the rate required for the specific test, as listed in Table 4.1.

4.3.3 Period 2 Operation

At the start of Period 2, the flow rate was reduced to the test flow rate; therefore, the concentration changed because of particle settling. Two criteria were used to assess when steady-state concentration was attained:

1. The time plus 10% (110%) required for a particle of mean diameter (d_p) in a simulant with bulk density (ρ) to settle from the top to the bottom of the tank has passed.
2. The rate of change of the concentration as measured by each ultrasonic sampler has fallen to less than 5% of the root mean square (rms) of the rate of change detected by all ultrasonic samplers at the beginning of Period 2.

Criterion 1 was not relaxed under any circumstances. The approximate time required for a particle to fall from the top of the tank to the bottom, traveling with its unhindered settling velocity, for each test is provided in Table 4.1. After Criterion 1 was satisfied, the ultrasonic concentration data were evaluated to confirm that the tank contents reached a steady-state distribution.

4.3.4 Period 3 Operation

Once the criterion for steady state had been reached, testing entered Period 3, where detailed ultrasonic and bottle sample measurements were taken to characterize the concentration at steady state. These methods are described in Sections 4.4 and 4.5.

4.4 Data Acquisition

The data acquisition system (DAS) was operated in two sampling modes: 1) recording data every 10 seconds during initiation of the flow-rate transient (Period 1) and at equilibrium (Period 3), and 2) recording data every 10 minutes during Period 2. The quantities that were monitored and recorded are

- Elapsed time (t)
- Nozzle angular location (θ)
- Instantaneous tank temperature (T)

- Instantaneous concentration at three ultrasonic sensor locations (C)
- Volumetric flow rate to mixer pump (Q)
- Ambient temperature.

In addition, simulant concentration was measured manually at 12 locations using syringes to fill bottles. The samplers were operated manually, external to the automatic DAS. No attempt was made to coordinate filling the bottles with jet mixer pump angular location. The solids concentration of each bottle sample was analyzed, and at equilibrium bottle samples were taken for measuring particle size and viscosity.

4.5 Instrumentation

The test system was instrumented to measure the flow rate through dual jet mixing pump (Q), nozzle angular location (θ), the tank temperature (T), and real time and discrete concentration measurements.

4.5.1 Mixing Pump Flow Rate

An existing magnetic flow meter[a] was installed on the external flow line to measure the mixer pump total flow rate with an accuracy of ±1% of full scale. The flow rate was sampled every minute.

4.5.2 Jet Nozzle Exit Velocity

Each 1/12-scale mixer pump model contained two 1.27-cm-diameter (0.5-in.) nozzles. The flow rate (Q) to the nozzle pair was measured and used to calculate the nozzle exit velocity for each nozzle. The piping was designed to ensure that the flow was split equally between the nozzles. This was confirmed experimentally before testing. The signal from the flow meter was processed to provide nozzle exit velocity in two forms: mean velocity averaged over five cycles (14.45 min based on readings every 10 seconds) (U_{0c}) and instantaneous velocity measured every 10 seconds (U_{0i}). Based on the accuracy in flow rate and nozzle diameter, the accuracy in the nozzle exit velocity is estimated to be ±2%.

4.5.3 Mixer Pump Angular Location

The mixer pump was indexed to provide a reading of angular location (θ) as a function of time. Angular position was recorded every 10 seconds.

4.5.4 Temperature

Twelve thermocouples were mounted to measure temperatures at three elevations and four radial positions in the tank, as listed in Table 4.3.

(a) Krohne American, Peabody, Massachusetts.

Table 4.3. Location of Instrumentation

Sensor Type	Identification	Height [in. ±1 in. (2.5 cm)]	Radius [in. ±2 in. (5 cm)]	Angle (degrees ±5)
Thermocouple	TOL	7.5	0	0
	TOM	15.0	0	0
	TOH	22.5	0	0
	T1L	7.5	18	0
	T1M	15.0	18	0
	T1H	22.5	18	0
	T2L	7.5	28	90
	T2M	15.0	28	90
	T2H	22.5	28	90
	T3L	7.5	37.5	180
	T3M	15.0	37.5	180
	T3H	22.5	37.5	180
Bottle	B1L	7.5	28	0
	B1M	15.0	28	0
	B1H	22.5	28	0
	B2L	7.5	28	90
	B2M	15.0	28	90
	B2H	22.5	28	90
	B3L	7.5	18	180
	B3M	15.0	18	180
	B3H	22.5	18	180
	B4L	7.5	18	270
	B4M	15.0	18	270
	B4H	22.5	18	270
Ultrasonic Probe	U1L set 1	7.5	18	0
	U1M set 1	15.0	18	0
	U1H set 1	22.5	18	0
	U2L set 2	7.5	18	90
	U2M set 2	15.0	18	90
	U2H set 2	22.5	18	90
	U3L set 3	7.5	28	180
	U3M set 3	15.0	28	180
	U3H set 3	22.5	28	180
	U4L set 4	7.5	28	270
	U4M set 4	15.0	28	270
	U4H set 4	22.5	28	270

4.5.5 Concentration

The solids concentration was measured using two methods: 1) bottle samples to measure average concentration and 2) ultrasonic measurements to measure real time concentration. The concentration sampler locations are listed in Table 4.3. Both ultrasonic measurements and bottle samples were taken throughout the test.

4.5.5.1 Bottle Samples

Several syringe sample carriages that can be manually filled were used to obtain the batch samples. This technique was used successfully during experiments conducted in 1992 (Fort et al. 1993). The accuracy of using bottle samples to measure the local average concentration at a syringe sample location depends on 1) the degree to which the syringe samplers disturb the concentration distribution, 2) the accuracy with which the concentration of solids in a syringe can be measured, and 3) the number of syringe samples taken. The disturbance caused by the presence of the syringes was minimized by using small syringes.

4.5.5.2 Ultrasonic Concentration Measurement

Ultrasonic measurements were made using an ultrasonic concentration measurement system. A single probe based on this principle was demonstrated successfully in 1992 (Fort et al. 1993). The device provided voltage signals proportional to the concentration of slurry over a specified measurement distance. A calibration for voltage and concentration was determined before testing began. The probe consists of three transmitter-receiver pairs that are sampled simultaneously to measure concentration at three fixed elevations at one tank location. Four tank locations, listed in Table 4.3, were monitored sequentially during Period 3. The probe signal was monitored to allow the concentration to reequilibrate after the probe has been repositioned.

The signal from the ultrasonic concentration meter was monitored in two forms. The instantaneous concentration was monitored directly from the instrument every 10 seconds. The average concentration was monitored by taking a running average of the instantaneous concentration readings taken over five pump oscillation cycles.

4.5.6 Mean Concentration

The make-up tank was used for preparation of simulant. The simulant was prepared in batches and pumped into the 1/12-scale tank. Mass measurements of solids and total mass were used to calculate mean concentration.[a]

4.5.7 Temperature Control

No temperature control was instituted during these tests because it was not required to match simulant properties.

(a) The Fairbanks scale range was calibrated to 3000 lbm ±3 lbm (907 kg ±1.3 kg).

5.0 Experimental Results

Each of the tests provides data for one point on the Reynolds, Froude, and gravitational settling matrix shown in Figure 1.1. The specific data obtained for each test are described in Section 5.1. The data from tests with the four simulants are discussed in Section 5.2. Data analysis is described Section 5.3. Correlations based on 1/12-scale data and full-scale predictions are discussed in Sections 5.4 and 5.5, and the effect of nozzle diameter is analyzed in Section 5.6.

5.1 Results of Individual Tests

The data provided by each individual test consists of concentration data, dynamic data, simulant physical properties, and data to detect steady state. The majority of the data were obtained from measurements in the suspended solids layer. At the completion of each test, the supernatant liquid was drained from the tank, and data were obtained from the sludge layer. The types of data obtained are summarized and recorded in the following sections.

5.1.1 Concentration Data

Two types of concentration measurements were obtained:

- Mean concentration based on replicate bottle samples and ultrasonic probe measurements at each sample location.
- Standard deviation of mean concentrations.

The accuracy in determining the mean concentration was established based on the mean concentration measurements obtained using both ultrasound measurements and bottle sample measurements. The criterion for ultrasonic mean concentration was to measure concentrations to within ±1.8 wt% (10% of 18 wt%) with a confidence of 95%. The concentration data collected using the ultrasonic concentration probe were reviewed throughout the test.

5.1.2 Dynamic Data

Dynamic data included:

- Mean nozzle flow rate during Periods 1, 2, and 3
- Standard deviation of the nozzle flow rate
- Mixing pump oscillation rate during Periods 1, 2, and 3.

The mean nozzle velocity acceptance criterion was for the mean to fall within 4×10^{-2} m/s of the target value. This ensured that the target velocity was achieved to within ±3% of the target value. The mixer pump oscillation rate (rpm) acceptance criterion was for the rate to be within 5% of the target value. The dynamic quantities collected in Period 2, such as nozzle flow rate and rate of change in concentration, were reviewed prior to the decision to begin Period 3. The dynamic quantities collected during Period 3 were reviewed prior to the decision to end Period 3.

5.1.3 Data Associated with Simulant Properties

These data included:

- Mean temperature (T)
- Kinematic viscosity (ν)
- Density of simulant (ρ)
- Concentration of simulant (C)
- Mean particle diameter (d_p)
- Supernate density (ρ_f)
- Solids density (ρ_s).

The simulant properties at the measured mean test temperatures fell in the target range described in Table 3.1. The target value for the low-viscosity simulant was finalized during simulant development. The simulant kinematic viscosity at the end of testing matched the simulant kinematic viscosity at the same temperature measured prior to the test to within ±5%.

5.1.4 Data Associated with Detection of Steady State

1. Rate of change in concentration in Period 2.

The two criteria listed in Section 4.3.3 were used to determine the end of Period 2.

5.2 Test Summaries

The mixing tests conducted with the four simulants are discussed in the sections that follow. The log book data summaries that provide additional test details are attached in Appendixes B through E. The tests with simulant S1, low viscosity, small-diameter stimulant, were conducted first. Based on the results of these tests, procedures and measurement techniques were adapted to provide a streamlined, more efficient, test procedure. These updates are discussed below.

Initial and equilibrium test conditions for the tests are summarized in Table 5.1. The table summarizes concentration data at each of the sample probe locations. Ultrasonic and bottle sample positions are listed in Table 4.3. Particle size distribution data include the sample median, volume mean, and standard deviation. Absolute viscosity, derived from density and kinematic viscosity measurements, is also summarized. Detailed kinematic viscosity data are summarized in Table 5.2.

5.2.1 Simulant S1: Low Viscosity, Small Diameter

Log book details of the low viscosity, small diameter particulate simulant tests are listed in Appendix B. During this test, equilibria were established at 100%, 50%, and 25% U_0D_0. These equilibrium data support the full-factorial analysis between 100% and 50% U_0D_0 and the half-factorial analyses between 100%, 50%, and 25% U_0D_0.

Table 5.1. Initial and Equilibrium Data Summaries

Property	Simulant S1 Low Viscosity Small Diameter		Simulant S2 Low Viscosity Large Diameter		Simulant S3 High Viscosity Small Diameter		Simulant S4 High Viscosity Large Diameter	
Pretest ≥100% U_0D_0								
wt% solids	Ultrasonic	Bottle	Ultrasonic	Bottle	Ultrasonic	Bottle	Ultrasonic	Bottle
Position 1, N								
High		19.27 Avg		17.58		17.84		16.49
Mid		15.05 Avg		17.61		18.09		16.38
Low				17.83		17.94		16.59
Position 2, E								
High								
Mid								
Low								
Position 3, S								
High				17.21		18.49		16.51
Mid				17.48		18.32		16.50
Low				17.67		18.02		16.68
Position 4, W								
High								
Mid								
Low								

Property	S1 Pos	S1 Date	S1 Med.	S1 Mean Vol	S1 Std. Dev.	S2 Pos	S2 Date	S2 Med.	S2 Mean Vol	S2 Std. Dev.	S3 Pos	S3 Date	S3 Med.	S3 Mean Vol	S3 Std. Dev.	S4 Pos	S4 Date	S4 Med.	S4 Mean Vol	S4 Std. Dev.
Particle Size, μm	B1M	2/11	5.39	6.18	3.73	B1H	5/25	20.18	22.14	13.59	B1HAv	4/22	5.45	6.49	4.17	B1H	6/23	17.41	19.29	12.14
	B1M	2/15	5.03	5.34	2.59	B1M	5/25	20.83	22.21	13.90	B1MAv	4/22	4.97	5.52	2.87	B1M	6/23	22.41	24.08	14.59
	B1M	2/19	5.41	6.19	3.41	B1L	5/25	20.46	22.08	13.61	B1LAv	4/22	6.67	6.64	4.19	B1L	6/23	17.02	18.81	12.30
						B3H	5/25	15.49	17.64	12.21	B3HAv	4/22	6.05	7.38	5.25	B3H	6/23	19.60	20.78	12.44
						B3M	5/25	17.32	18.75	12.08	B3MAv	4/22	5.63	7.83	7.07	B3M	6/23	18.41	20.46	13.82
						B3L	5/25	12.31	15.92	12.21	B3LAv	4/22	5.38	6.33	3.96	B3L	6/23	14.33	17.33	12.74
Viscosity, cP	B1M	2/2	1.50			B4M	5/25	1.75			B1M	4/22	3.46			B1M	6/24	2.85		
	B1M	2/11	1.61			B4L	5/25	1.75			B1M	4.22	3.55			B1M	6/24	2.73		
	B1M	2/15	1.55								B1M	4.22	3.59							
	B1M	2/16	1.53																	

Table 5.1 (contd)

Property	Simulant S1			Simulant S2			Simulant S3			Simulant S4		
	Low Viscosity Small Diameter			Low Viscosity Large Diameter			High Viscosity Small Diameter			High Viscosity Large Diameter		
Equilibrium 100% U_0D_0												
wt% solids	Ultrasonic		Bottle	Ultrasonic		Bottle	Ultrasonic		Bottle	Ultrasonic		Bottle
Position 1, N	Mean	St Dev		Mean	St Dev		Mean	St Dev		Mean	St Dev	
High	16.23	0.009	16.30 Avg	9.23	0.008	9.05	18.2	0.48	17.53 Avg	8.18	0.30	7.26
Mid	17.92	0.022		8.98	0.007	8.90	18.0	0.31	17.81 Avg	10.8	1.33	7.15
Low	15.19	0.011		8.72	0.011	8.93	18.2	0.44	17.67 Avg	8.24	0.58	7.23
Position 2, E	Mean	St Dev		Mean	St Dev		Mean	St Dev		Mean	St Dev	
High	16.21	0.014	15.78	9.09	0.009		17.6	0.03	17.74	7.54	0.190	7.17
Mid	17.95	0.047	18.26	8.96	0.010		17.7	0.04	17.61	9.58	0.933	7.18
Low	15.15	0.025		8.69	0.015		17.7	0.09	17.57	7.93	0.357	7.29
Position 3, S	Mean	St Dev		Mean	St Dev		Mean	St Dev		Mean	St Dev	
High	16.24	0.012		9.08	0.021	8.95	17.6	0.03	17.53	7.63	0.121	
Mid	17.96	0.024		8.84	0.058	9.02	17.7	0.03	17.59	9.15	0.589	
Low	15.26	0.010		8.60	0.081	8.98	17.5	0.03	17.69	7.51	0.196	
Position 4, W	Mean	St Dev		Mean	St Dev		Mean	St Dev		Mean	St Dev	
High	16.24	0.009		8.99	0.028	9.04	17.5	0.03	17.75	6.70	0.166	7.11
Mid	17.79	0.055		8.82	0.033	8.94	17.6	0.04	17.69	7.06	0.251	7.15
Low	15.19	0.010		8.55	0.011	9.05	17.5	0.03	17.62	6.89	0.132	7.05

Property	S1 Pos	Date	Med	Mean Vol	Std. Dev.	S2 Pos	Date	Med.	Mean Vol	Std. Dev.	S3 Pos	Date	Med.	Mean Vol	Std. Dev.	S4 Pos	Date	Med.	Mean Vol	Std. Dev.
Particle Size, μm	B1H	2/24	4.63	4.88	2.25	B1H	6/3	7.06	9.11	6.06	B1HAv	4/28	5.18	5.92	3.38	B1H	6/28	6.01	8.70	7.37
	B1M	2/24	4.95	5.37	2.66	B1M	6/3	6.31	8.08	5.37	B1MAv	4/28	5.02	5.73	3.26	B1M	6/28	6.08	8.51	6.72
	B1L	2/24	4.93	5.36	2.71	B1L	6/3	5.98	7.49	4.88	B1LAv	4/28	4.87	5.53	3.15	B1L	6/28	5.85	7.87	5.88
						B3H	6/3	8.81	12.22	9.58	B3HAv	4/28	5.01	5.76	3.32					
						B3M	6/3	6.49	9.44	7.44	B3MAv	4/28	5.15	5.91	3.36					
						B3L	6/3	6.52	9.07	6.82	B3LAv	4/28	5.18	6.24	4.32					

Property	S1			S2			S3			S4		
Viscosity, cP	B1M	2/24	1.47	B1H	6/3	1.65	B1H	4/28	3.12	B4H	6/28	2.96
				B4L	6/3	1.58	B1M	4/28	3.42	B4M	6/28	3.27
							B1L	4/28	3.37	B4L	6/28	3.08

Table 5.1 (contd)

Property	Simulant S1 Low Viscosity Small Diameter		Simulant S2 Low Viscosity Large Diameter			Simulant S3 High Viscosity Small Diameter			Simulant S4 High Viscosity Large Diameter		
Equilibrium 75% U_0D_0											
wt% solids	Ultrasonic	Bottle	Ultrasonic		Bottle	Ultrasonic		Bottle	Ultrasonic		Bottle
Position 1, N			Mean	St Dev		Mean	St Dev		Mean	St Dev	
High			6.91	0.046	6.85	13.4	0.06	13.29	7.08	0.119	6.99
Mid			6.81	0.016	6.82	13.4	0.06	13.26	7.08	0.140	7.05
Low			6.74	0.094	6.76	13.7	0.08	13.29	7.13	0.130	7.11
Position 2, E			Mean	St Dev		Mean	St Dev		Mean	St Dev	
High			6.78	0.015	6.79	13.5	0.12	13.61	6.95	0.060	
Mid			6.81	0.011	6.90	13.4	0.07	13.45	6.96	0.063	
Low			6.70	0.021	6.82	13.6	0.08	13.56	6.90	0.546	
Position 3, S			Mean	St Dev		Mean	St Dev		Mean	St Dev	
High			6.80	0.015	6.79	13.5	0.06	13.59	7.30	0.068	6.99
Mid			6.82	0.014	6.72	13.4	0.06	13.53	7.20	0.075	7.05
Low			6.74	0.047	6.78	13.7	0.08	13.61	7.08	0.083	7.11
Position 4, W			Mean	St Dev		Mean	St Dev		Mean	St Dev	
High			6.71	0.016	6.79	13.5	0.12	13.65	6.85	0.034	6.96
Mid			6.77	0.014	6.80	13.4	0.07	13.41	6.72	0.032	6.76
Low			6.62	0.013	6.60	13.6	0.08	13.56	6.72	0.036	6.97

Property	Simulant S1	Simulant S2					Simulant S3					Simulant S4				
Particle Size, µm		Pos	Date	Med	Mean Vol	Std. Dev.	Pos	Date	Med.	Mean Vol	Std. Dev.	Pos	Date	Med.	Mean Vol	Std. Dev.
		B1H	6/7	5.29	6.56	4.54						B1H	7/1	6.17	8.19	5.77
		B1M	6/7	5.27	6.42	4.11						B1M	7/1	5.87	7.96	5.91
		B1L	6/7	5.83	7.59	5.38						B1L	7/1	5.97	7.84	5.57
		B3H	6/7	5.82	9.30	10.00	B3H	5/5	4.93	5.84	3.52	B3H	7/1	5.52	7.49	5.89
		B3M	6/7	5.65	7.04	4.66	B3M	5/5	4.66	5.18	2.74	B3M	7/1	5.67	7.59	5.64
		B3L	6/7	5.39	6.28	3.80	B3L	5/5	4.82	5.36	2.92	B3L	7/1	5.78	7.49	5.19
Viscosity, cP		B4H	6/7	1.52			B4H	5/5	3.20			B4H	7/1	3.08		
		B4M	6/7	1.41			B4M	5/5	3.16			B4M	7/1	3.31		
		B4L	6/7	1.63			B4M	5/5	3.49			B4L	7/1	3.23		

Table 5.1 (contd)

Property	Simulant S1 Low Viscosity Small Diameter			Simulant S2 Low Viscosity Large Diameter			Simulant S3 High Viscosity Small Diameter			Simulant S4 High Viscosity Large Diameter		
Equilibrium 50% U_0D_0												
wt% solids	Ultrasonic		Bottle	Ultrasonic		Bottle	Ultrasonic		Bottle	Ultrasonic		Bottle
Position 1, N	Mean	St. Dev		Mean	St. Dev		Mean	St. Dev		Mean	St. Dev	
High	6.84	0.004	6.81	3.32	0.011	3.30	7.34	0.009	7.31	2.67	0.015	2.60
Mid	7.50	0.056	6.77	3.33	0.010	3.38	7.52	0.010	7.42	2.64	0.008	2.53
Low	7.04	0.004		3.29	0.014	3.30	7.52	0.049	7.35	2.84	0.016	2.48
Position 2, E	Mean	St. Dev		Mean	St. Dev		Mean	St. Dev		Mean	St. Dev	
High	6.82	0.004		3.27	0.011	3.22	7.30	0.095	7.49	2.73	0.381	2.62
Mid	6.73	0.006		3.29	0.030	3.22	7.40	0.107	7.45	2.62	0.446	2.41
Low	7.04	0.006		3.25	0.024	3.35	7.53	0.010	7.46	2.52	0.002	2.65
Position 3, S	Mean	St. Dev		Mean	St. Dev		Mean	St. Dev		Mean	St. Dev	
High	6.81	0.004		3.31	0.097	3.46	7.25	0.006	7.39	2.44	0.136	2.40
Mid	6.52	0.012		3.34	0.136	3.43	7.34	0.011	7.29	2.34	0.115	2.49
Low	7.00	0.006		3.27	0.002	3.17	7.52	0.010	7.39	2.45	0.121	2.45
Position 4, W	Mean	St. Dev		Mean	St. Dev		Mean	St. Dev		Mean	St. Dev	
High	6.80	0.006		3.39	0.037	3.25	7.25	0.008	7.09	2.27	0.007	2.50
Mid	6.73	0.007		3.41	0.038	3.30	7.35	0.012	7.35	2.19	0.005	2.42
Low	7.02	0.003		3.28	0.003	3.29	7.44	0.057	7.42	2.29	0.006	2.60

Property	Simulant S1					Simulant S2					Simulant S3					Simulant S4				
Particle Size, µm	Pos	Date	Med.	Mean Vol	Std Dev.	Pos	Date	Med.	Mean Vol	Std. Dev.	Pos	Date	Med.	Mean Vol	Std. Dev.	Pos	Date	Med.	Mean Vol	Std. Dev.
	B1H	3/4	2.20	2.35	1.08	B3H	6/14	4.23	4.82	3.02	B1H	5/16	3.13	3.28	1.67	B1H	7/11	3.27	3.37	1.66
	B1M	¾	2.62	2.64	1.16	B3M	6/14	4.27	4.84	2.94	B1M	5/16	3.56	3.68	1.75	B1M	7/11	2.94	3.14	1.65
	B1L	¾	2.92	2.92	1.31	B3L	6/14	4.14	4.52	2.39	B1L	5/16	3.28	3.39	1.60	B1L	7/11	3.17	3.26	1.58
											B3H	5/16	3.53	3.65	1.78	B3H	7/11	3.16	3.27	1.61
											B3M	5/16	3.28	3.41	1.66	B3M	7/11	3.07	3.19	1.56
											B3L	5/16	3.49	3.67	1.83	B3L	7/11	3.12	3.22	1.55
Viscosity, cP						B4M	6/14	1.45			B4H	5/16	2.92			B4H	7/11	2.91		
						B4L	6/14	1.52			B4M	5/16	3.08			B4M	7/11	2.99		
											B4L	5/16	3.12			B4L	7/11	3.11		

Table 5.1 (contd)

Property	Simulant S1 Low Viscosity Small Diameter		Simulant S2 Low Viscosity Large Diameter		Simulant S3 High Viscosity Small Diameter		Simulant S4 High Viscosity Large Diameter	
Equilibrium 25% U_0D_0								
wt% solids	Ultrasonic	Bottle	Ultrasonic	Bottle	Ultrasonic	Bottle	Ultrasonic	Bottle
Position 1, N High Mid Low	Mean St. Dev 3.28 0.004 3.20 0.004 3.53 0.008	 3.33 Avg 3.34 Avg 3.26 Avg					Mean St. Dev 1.22 0.005 1.22 0.004 1.29 ~0	 1.29 1.21 1.28
Position 2, E High Mid Low	Mean St. Dev 3.26 0.003 3.22 0.002 3.51 0.002						Mean St. Dev 1.15 0.006 1.20 ~0 1.29 ~0	 1.30 1.25 1.33
Position 3, S High Mid Low	Mean St. Dev 3.29 0.016 3.20 0.016 3.52 0.006						Mean St. Dev 1.18 0.005 1.20 ~0 1.29 ~0	 1.26 1.19 1.30
Position 4, W High Mid Low	Mean St. Dev 3.27 0.015 3.81 0.018 3.50 0.020	 3.41 Avg 3.41 Avg 3.32 Avg					Mean St. Dev 1.16 0.008 1.20 ~0 1.29 ~0	 1.28 1.24 1.31
Particle Size, μm	Pos Date Med. Mean Vol Std. Dev B1H 3/21 1.05 1.03 0.26 B1L 3/21 1.07 1.05 0.28		Pos Date Med. Mean Vol Std. Dev.		Pos Date Med. Mean Vol Std. Dev.		Pos Date Med. Mean Vol Std. Dev. B1H 7/26 1.27 1.38 0.53 B1MAv 7/26 1.17 1.28 0.49 B1L 7/26 1.46 2.15 2.54 B3H 7/26 1.35 1.99 2.35 B3M 7/26 1.45 1.82 1.18 B3L 7/26 1.44 1.79 1.05	
Viscosity, cP	B1M 3/21 1.28						B1H 7/26 2.36 B4H 7/26 2.51 B4M 7/26 2.89	

Table 5.2. Kinematic Viscosity Data

Date	Position	Run Time (sec)			Kinematic Viscosity (mm^2/s)				Std. Dev. (mm^2/s)
		Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Avg	
2/2	B1M	13	13	13	1.3559	1.3559	1.3559	1.3559	0.0000
2/11	B1M	14	14	14	1.4602	1.4602	1.4602	1.4602	0.0000
2/15	B1M	14	13	13	1.4602	1.3559	1.3559	1.3907	0.0602
2/16	B1M	13	13	13	1.3559	1.3559	1.3559	1.3559	0.0000
2/19	B1M	13	12	12	1.3559	1.2516	1.2516	1.2864	0.0602
2/24	Comb. S1	13	12	13	1.3559	1.2516	1.3559	1.3211	0.0602
3/4	Comb. S1	12	11	12	1.2516	1.1473	1.2516	1.2168	0.0602
3/21	Comb. S1	12	12	12	1.2516	1.2516	1.2516	1.2516	0.0000
4/22	B4H	27	28	27	2.8161	2.9204	2.8161	2.8509	0.0602
	B4M	29	29	28	3.0247	3.0247	2.9204	2.9899	0.0602
	B4L	28	29	28	2.9204	3.0247	2.9204	2.9552	0.0602
4/28	B1H	24	25	25	2.5032	2.6075	2.6075	2.5727	0.0602
	B1M	28	27	26	2.9204	2.8161	2.7118	2.8161	0.1043
	B1L	26	27	27	2.7118	2.8161	2.8161	2.7813	0.0602
5/5	B4H	26	26	26	2.7118	2.7118	2.7118	2.7118	0.0000
	B4M	27	25	25	2.8161	2.6075	2.6075	2.6770	0.1204
	B4L	29	28	28	3.0247	2.9204	2.9204	2.9552	0.0602
5/16	B4H	25	24	25	2.6075	2.5032	2.6075	2.5727	0.0602
	B4M	27	26	25	2.8161	2.7118	2.6075	2.7118	0.1043
	B4L	27	25	25	2.8161	2.6075	2.6075	2.6770	0.1204
5/25	B4H	15	15	15	1.5645	1.5645	1.5645	1.5645	0.0000
	B4M	16	15	15	1.6688	1.5645	1.5645	1.5993	0.0602
	B4L	16	13	12	1.6688	1.3559	1.2516	1.4254	0.2171
5/30	B2H	14	13	13	1.4602	1.3559	1.3559	1.3907	0.0602
	B2M	14	13	14	1.4602	1.3559	1.4602	1.4254	0.0602
	B2L	14	13	13	1.4602	1.3559	1.3559	1.3907	0.0602
6/3	B4M	15	15	15	1.5645	1.5645	1,5645	1.5645	0.0000
	B4L	15	14	14	1.5645	1.4602	1.4602	1.4950	0.0602
6/7	B4H	14	14	14	1.4602	1.4602	1.4602	1.4602	0.0000
	B4M	13	13	13	1.3559	1.3559	1.3559	1.3559	0.0000
	B4L	15	15	15	1.5645	1.5645	1.5645	1.5645	0.0000
6/14	B4M	13	14	14	1.3559	1.4602	1.4602	1.4254	0.0602
	B4L	15	14	14	1.5645	1.4602	1.4602	1.4950	0.0602
6/24	B4L	24	23	22	2.5032	2.3989	2.2946	2.3989	0.1043
	B1L	25	24	23	2.6075	2.5032	2.3989	2.5032	0.1043
6/28	B4H	25	25	25	2.6075	2.6075	2.6075	2.6075	0.0000
	B4M	29	27	27	3.0247	2.8161	2.8161	2.8856	0.1204
	B4L	26	26	26	2.7118	2.7118	2.7118	2.7118	0.0000
7/1	B4H	27	26	25	2.8161	2.7118	2.6075	2.7118	0.1043
	B4M	29	28	27	3.0247	2.9204	2.8161	2.9204	0.1043
	B4L	28	27	27	2.9204	2.8161	2.8161	2.8509	0.0602
7/11	B4H	26	25	25	2.7118	2.6075	2.6075	2.6423	0.0602
	B4M	27	26	25	2.8161	2.7118	2.6075	2.7118	0.1043
	B4L	28	27	26	2.9204	2.8161	2.7118	2.8161	0.1043
5/25	B4H	41	37	37	1.5018	1.3553	1.3553	1.4042	.0.0846
	B4M	38	34	-	1.3919	1.2454	-	1.3187	0.1036
	B4L	16	13	12	1.6688	1.3559	1.2516	1.4254	0.2171
7/26	B1H	63	64	64	2.3077	2.3443	2.3443	2.3321	0.0211
	B1H	22	19	21	2.2946	1.9817	2.1903	2.1555	0.1593
8/1	B4H	13	13	13	1.3559	1.3559	1.3559	1.3559	0.0000

5.2.1.1 Simulant Mixing

The low-viscosity, small-diameter simulant physical and rheological properties are summarized in Table 3.2. All properties except bulk density met the target simulant property ranges specified in Table 3.1. The bulk density target was revised as shown in Table 3.3 based on the chosen simulant recipe. The simulant properties were acceptable for conducting the experiment. To ensure that all solids were fully suspended before the test began, an air lance was used to provide additional agitation.

5.2.1.2 100% U_0D_0 Test

The 100% case was initiated twice. The first time the pump experienced a flow rate decrease during unattended operation. After this was noted, the simulant was remixed and the test restarted. Data files associated with Period 2, particulate settling, are S1-44 through S1-52. This settling occurred over a 5-day period. At times during the settling period, entrained gas would accumulate in the mixer pump line. This air was vented by briefly (~1 min) stopping and restarting the pump. Except for these brief planned stoppages, the mixer pump flow rate remained steady at 19.8 gal/min throughout this period. At equilibrium, ultrasonic concentration data were taken at each sampling location. These data are in files S1-54 through S1-57. The equilibrium concentration data are plotted in Figure 5.1.

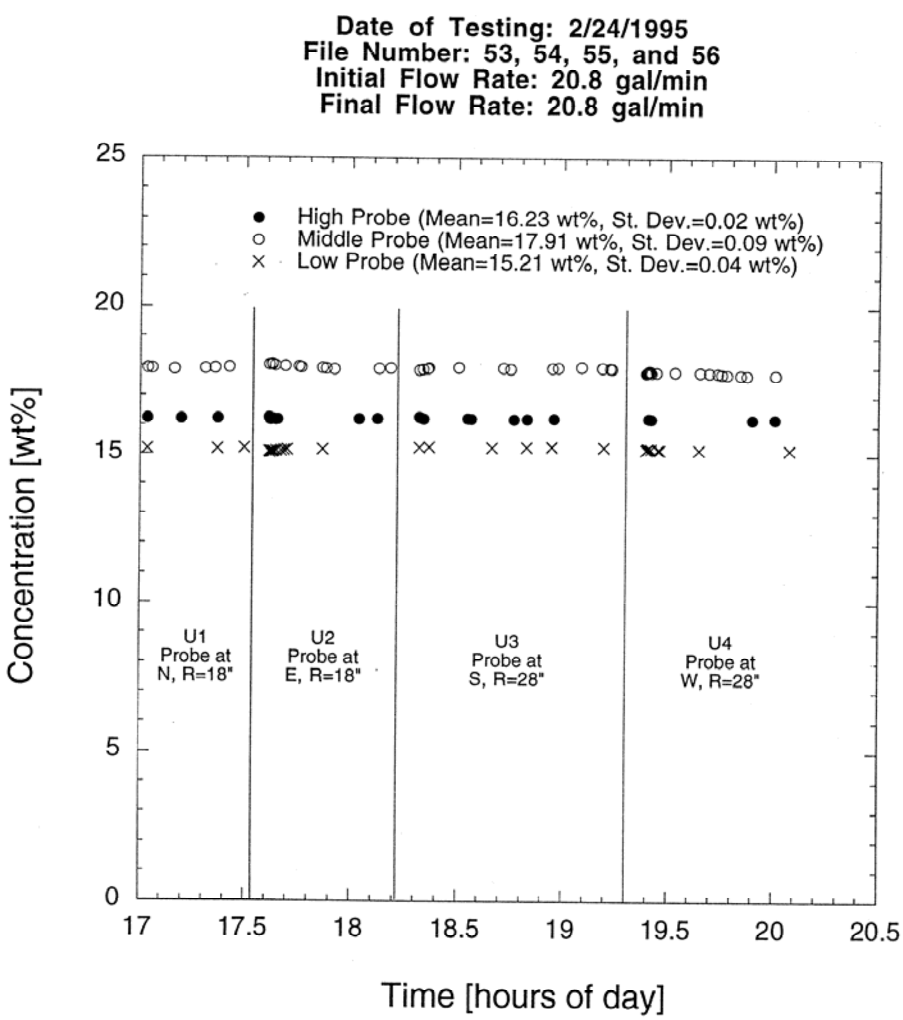

Figure 5.1. Simulant S1 Equilibrium Data at 100% U_0D_0

5.2.1.3 50% U_0D_0 Test

The 50% case was initiated immediately after attaining the 100% equilibrium data. Data files associated with Period 2, particulate settling, are S1-58 through S1-65. This settling occurred over a 7-day period. The mixer pump flow rate remained steady at 10.4 gal/min throughout this period.

At equilibrium, ultrasonic concentration data were taken at each sampling location; these data are in files S1-66 through S1-69. Samples were also taken to measure particle size distribution at location B1, radius = 28 in., and kinematic viscosity at location B1, radius = 28 in. The equilibrium concentration data are plotted in Figure 5.2.

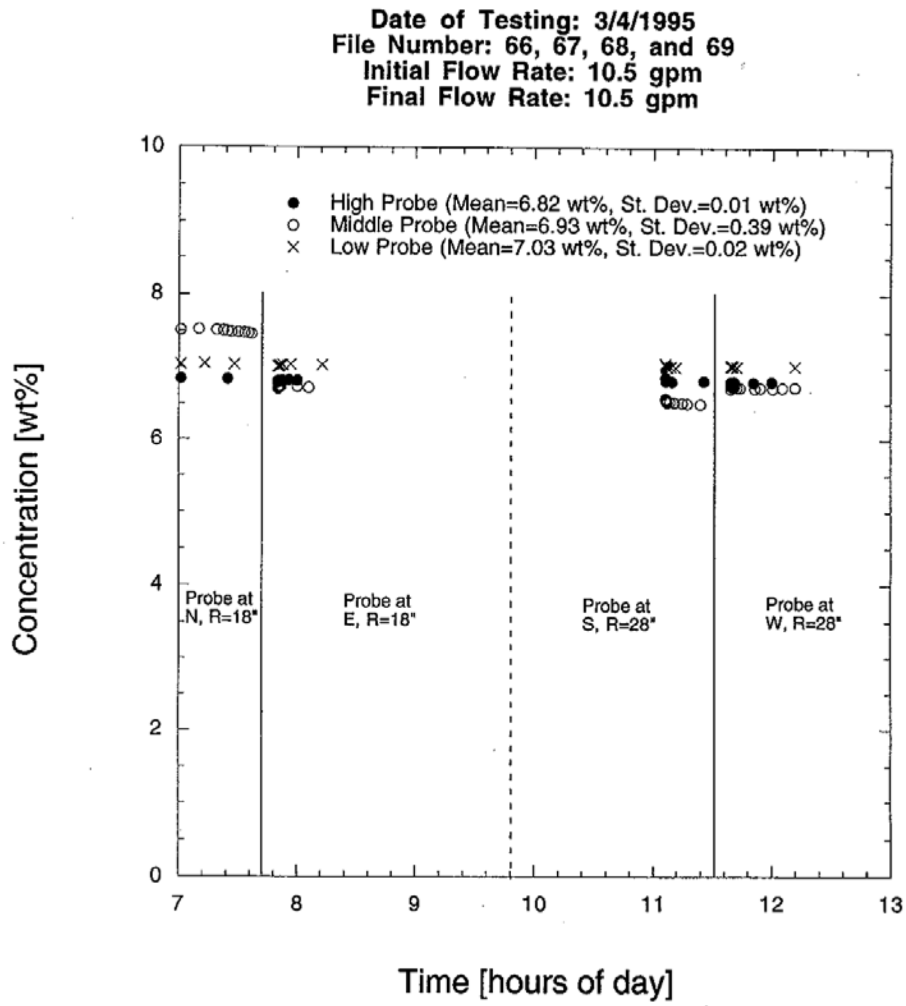

Figure 5.2. Simulant S1 Equilibrium Data at 50% U_0D_0

5.2.1.4 25% U_0D_0 Test

The 25% case was initiated immediately after gathering the 50% equilibrium data. Data files associated with Period 2, particulate settling, are S1-70 through S1-87. This settling occurred over an 18-day period. The mixer pump flow rate remained steady at 5.3 gal/min throughout this period.

At equilibrium, ultrasonic concentration data were taken at each sampling location; these data are summarized in files S1-88 through S1-91. Samples were also taken to measure particle size distribution at location B1, radius = 28 in. and kinematic viscosity at location B1, radius = 28 in. The equilibrium concentration data are plotted in Figure 5.3.

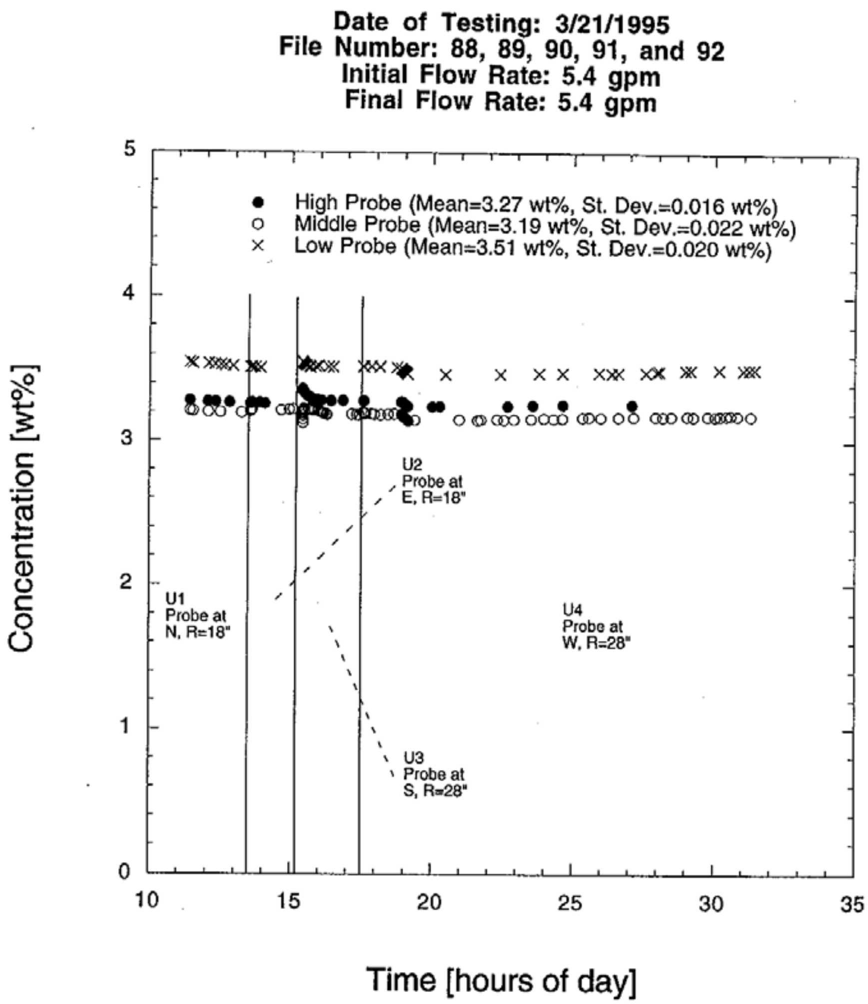

Figure 5.3. Simulant S1 Equilibrium Data at 25% U_0D_0

5.2.1.5 Settled Solids Profiles

After attaining equilibrium at each flow rate, the profile of the settled solids layer was measured. These data are summarized in Table 5.3 and plotted in Figure 5.4. At 100% U_0D_0, settled solids were detected at a radial distance of 20 in. At 50% and 25% U_0D_0, solids were detected at a radial support structure distance of about 4 in. The peak solids depth occurred at a radial distance of about 34 in.

5.2.2 Simulant S2: Low Viscosity, Large Diameter

Logbook details of low-viscosity, large-diameter particulate simulant tests are in Appendix C. During the test, equilibria were established at 100, 75, and 25% U_0D_0. The equilibrium data support the full factorial analysis between 100 and 50% U_0D_0 and half-factorial analyses between 100, 50, and 25% U_0D_0.

Table 5.3. Simulant S1 Profile of Settled Solids Level Above Tank Floor

Radial Distance from Tank Center (in.)	Depth of Settled Solids (in.)											
	Position 1, North			Position 2, East			Position 3, South			Position 4, West		
	100%	50%	25%	100%	50%	25%	100%	50%	25%	100%	50%	25%
Date	2/24	3/4	3/21	2/24	3/4	3/21	2/24	3/4	3/21	2/24	3/4	3/21
4	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	NA	0	0.125	0.75	0	0.125	NA	0	0	0.75
8	0	0.125	0.50	0	0.125	0.875	0	0.25	0.25	0	0.125	1.00
10	0	0.125	0.625	0	0.25	1.63	0	0.25	0.375	0	0.375	1.50
12	0	0.375	1.13	0	0.25	1.63	0	0.75	1.00	0	0.375	1.63
14	0	0.375	1.75	0	0.375	2.38	0	1.00	1.13	0	1.00	2.25
16	0	0.50	2.5	0	1.50	2.50	0	1.25	2.25	0	1.13	2.25
18	0	0.75	2.75	0	1.63	NA	0	1.88	2.25	0	1.88	2.63
20	~0.4	NA	3.50	~0.4	NA	3.25	~0.4	2.25	2.75	~0.4	2.38	3.00
22	~0.7	2.25	NA	~0.7	2.00	3.88	~0.7	2.25	3.75	~0.4	2.63	3.5[(a)]
24	~1.1	2.75	3.88	~1.1	3.13	4.13	~1.1	2.75	4.50	~1.1	NA	NA
26	~1.4	3.00	4.13	~1.4	3.63	4.50	~1.4	NA	5.00	~1.4	NA	4.25
28	1.75	4.13	4.75	1.75	4.13	4.75	1.75	3.50	NA	1.75	4.00	4.75
30	1.75	4.50	5.25	1.75	NA	4.75	1.75	4.25	4.88	1.75	4.50	5.13
32	~1.4	4.50	5.38	~1.4	5.13	5.63	~1.4	4.75	5.25	~1.4	5.00	5.38
34	~1.1	5.13	5.75	~1.1	NA	5.88	~1.1	4.75	5.75	~1.1	5.00	5.75
36	~0.8	4.50	NA	~0.8	4.88	NA	~0.8	4.75	NA	~0.8	NA	NA
37.5	0.50	4.50	NA	0.50	4.88	NA	0.50	4.75	NA	0.50	4.75	NA

(a) Measurements made at a slight angle from vertical to measure around hardware support structures.
NA means not applicable.

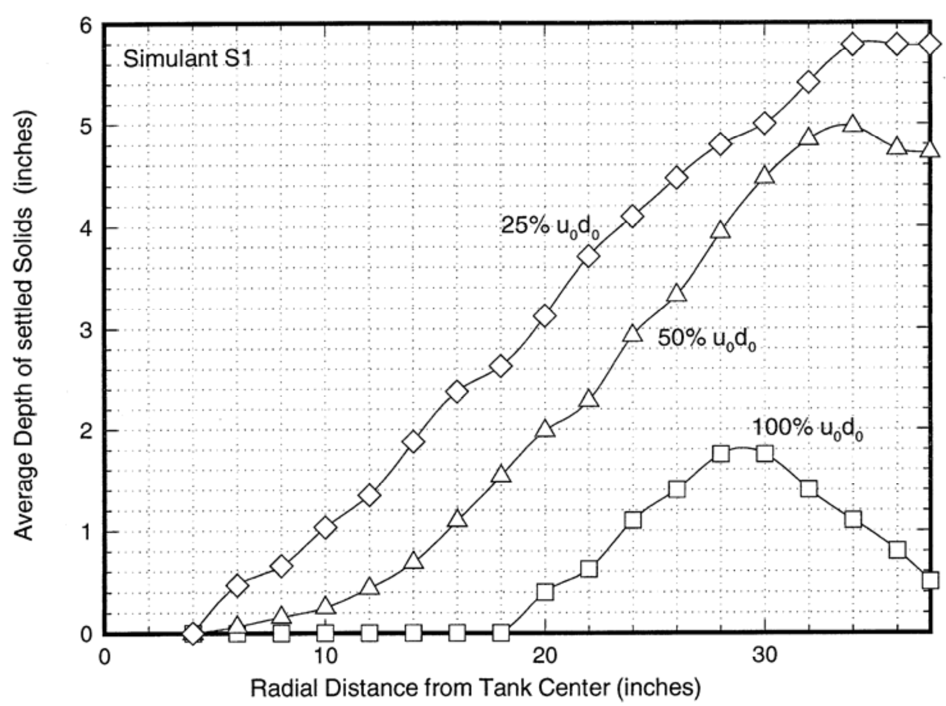

Figure 5.4. Simulant S1 Settled Solids Profiles at 100%, 50%, and 25% U_0D_0

5.2.2.1 Simulant Mixing

The low viscosity, large diameter simulant physical and rheological properties are summarized in Table 3.2. All properties except bulk density met the target simulant property ranges specified in Table 3.1. The bulk density target was revised as shown in Table 3.3 based on the chosen simulant recipe. The simulant properties were acceptable for conducting the experiment. To ensure that all solids were fully suspended before the testing started, an air lance was used to provide additional agitation.

5.2.2.2 100% U_0D_0 Test

The 100% case was initiated twice. The first time, the pump experienced an abrupt shut off and the system had to be remixed and the test restarted. The simulant was remixed using the air lance and a secondary mixer pump inlet in the supernatant. After the mixer pump was reconfigured with bottom suction, the maximum sustainable obtained flow rate was 18.5 gal/min; this corresponded to 88% U_0D_0. The test was continued in this condition. After two hours of operation and some particle settling, the 100% U_0D_0 flow rate was regained. Eventually, the flow rate stabilized at 18.5 gal/min. Data files associated with Period 2, particulate settling, are S2-1 through S2-3. This settling occurred over a 5-day period. At equilibrium, the mixer pump flow rate remained steady at 18.5 gal/min.

At equilibrium, ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S2-4 through S2-5. During equilibrium for the 100% case, the mixer pump came off the sprocket and the test was stopped; simulant was remixed and the test restarted. Equilibrium was reattained after 3 days of settling.

At equilibrium ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S2-7 through S2-10. Also samples were taken to measure particle size distribution at location B1, radius = 28 in.; at location B3, radius = 18 in.; and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.5.

5.2.2.3 75% U_0D_0 Test

The 75% case was initiated immediately after attaining the 100% equilibrium data. Data files associated with Period 2, particulate settling, are S2-11 and S2-12. This settling occurred over a 4-day period. The mixer pump flow rate remained steady at 15.7 gal/min throughout this period.

At equilibrium ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S2-13 through S2-16. Also samples were taken to measure particle size distribution at location B1, radius = 28 in.; at location B3, radius = 18 in.; and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.6.

5.2.2.4 50% U_0D_0 Test

The 50% case was initiated immediately after gathering the 75% equilibrium data. Data files associated with Period 2, particulate settling, are S2-17 through S2-19. This settling occurred over a 7-day period. The mixer pump flow rate remained steady at 10.3 gal/min throughout this period.

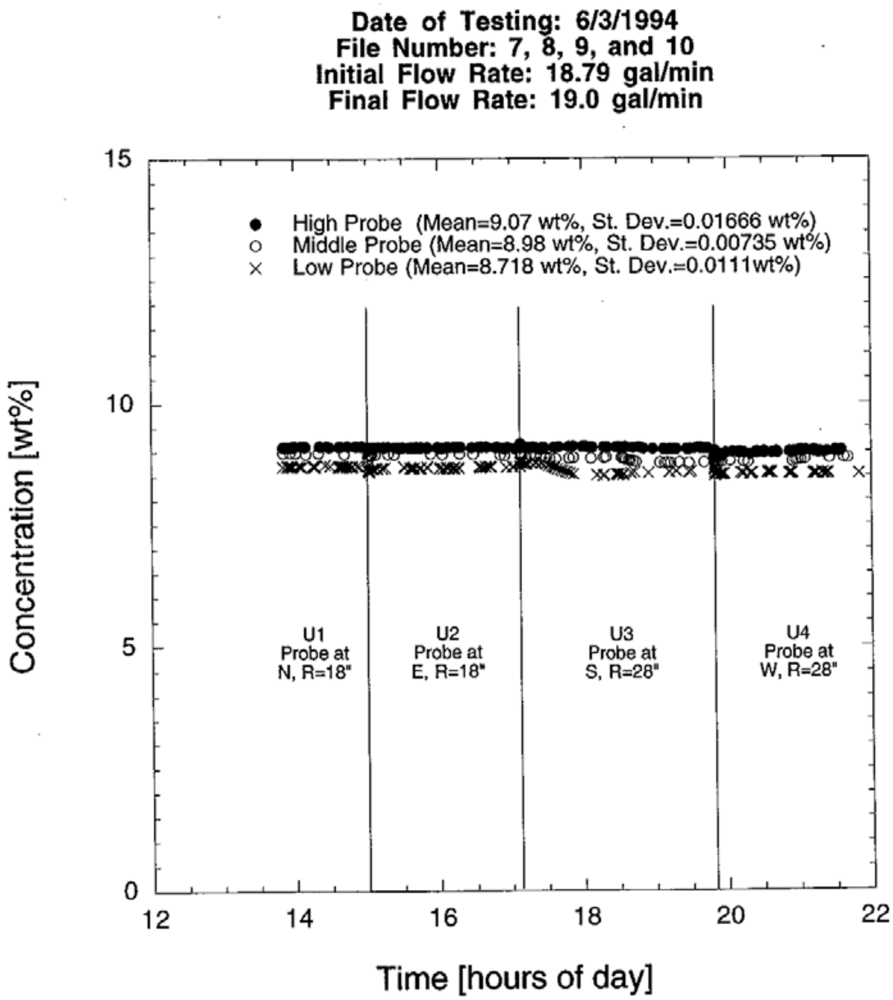

Figure 5.5. Simulant S2 Equilibrium Data at 100% U_0D_0

At equilibrium ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S2-20 through S2-23. Also samples were taken to measure particle size distribution at location B3, radius = 18 in. and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.7.

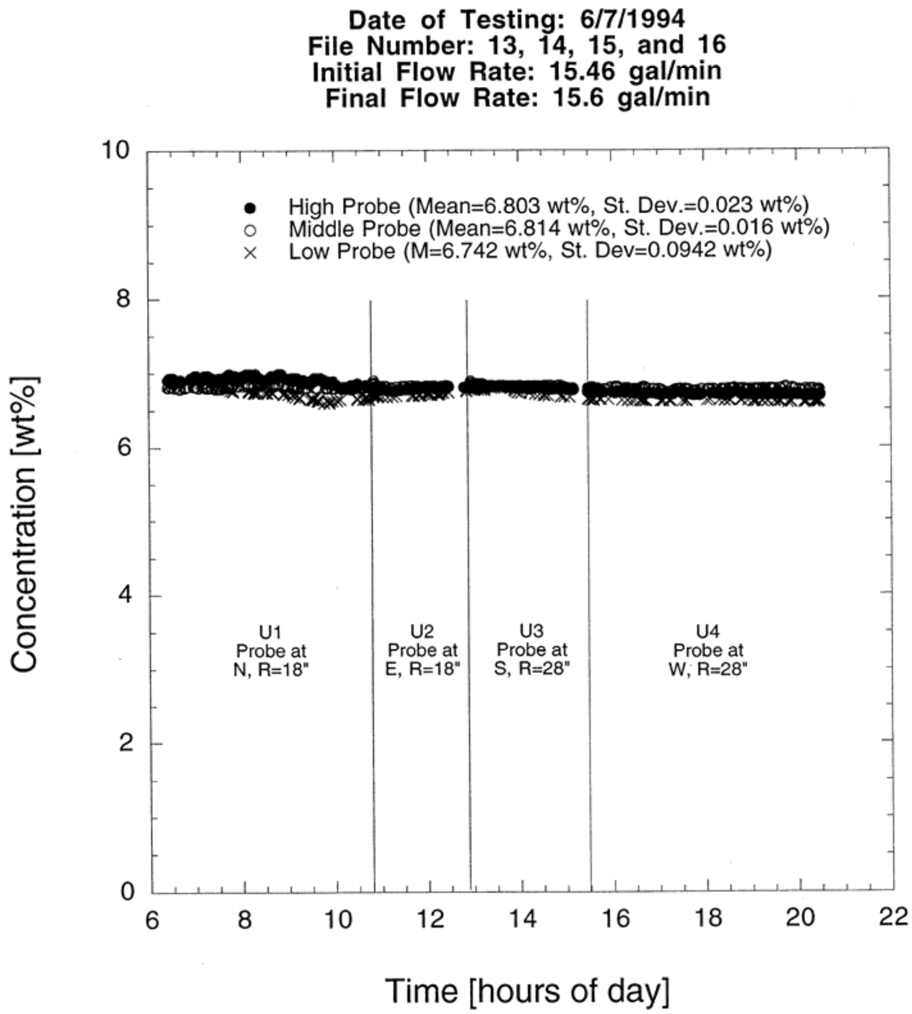

Figure 5.6. Simulant S2 Equilibrium Data at 75% U_0D_0

5.2.2.5 Settled Solids Profiles

After attaining equilibrium at each of the flow rates the profile of the settled solids layer was measured. These data are summarized in Table 5.4 and plotted in Figure 5.8. At 100% and 75% U_0D_0 settled solids were detected at a radial distance of 20 in. At 50% U_0D_0 solids were detected at a radial distance of about 14 in. The peak solids depth occurred at a radial distance of about 34 in.

After completion of the test, the supernatant was pumped out of the tank. Samples at four radii and several depths were taken to analyze the particle size distribution of the settled solids. These data are listed in Table 5.5. The solids were stratified based on particle size. The volume mean diameter of particulate 0.25 in. above the tank floor ranged from 35 to 39 μm. The volume mean diameter of particulate decreased with elevation above the tank floor. The volume mean diameter of particulate 0.25 in. beneath the top layer ranged from 8 to 11 μm.

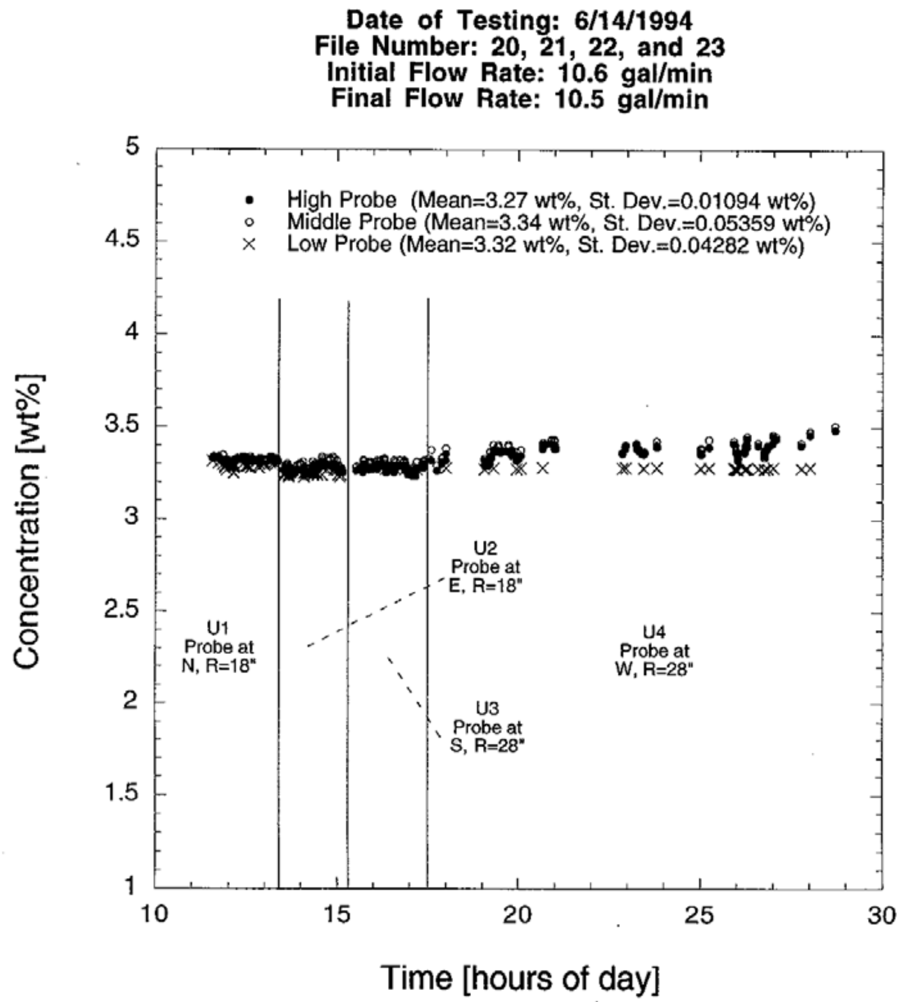

Figure 5.7. Simulant S2 Equilibrium Data at 50% U_0D_0

5.2.3 Simulant S3: High Viscosity, Small Diameter

Log book details of the high viscosity, small diameter particulate simulant tests are listed in Appendix D. During this test, equilibria were established at 100, 75, and 50% U_0D_0. These equilibrium data support the full-factorial analysis between 100% and 50% U_0D_0 and the half-factorial analyses between 100, 50, and 25% U_0D_0.

Table 5.4. Simulant S2 Profile of Settled Solids Level Above Tank Floor

Radial Distance from Tank Center (in.)	Depth of Settled Solids (in.)											
	Position 1, North			Position 2, East			Position 3, South			Position 4, West		
	100%	75%	50%	100%	75%	50%	100%	75%	50%	100%	75%	50%
Date	6/3	6/7	6/14	6/3	6/7	6/14	6/3	6/7	6/14	6/3	6/7	6/14
4	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0.125
8	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0.125	0	0	0.75	0	0	0.375	0	0	0.75
16	0	0	0.25	0	0	1.75	0	0	0.75	0	0	0.75
18	0	0.125	0.50	0	0	2.3[a]	0	0	1.63	0	0	1.13
20	0.125	0.50	1.00	0	0	2.75	0.125	0	2.00	0	0.375	1.50
22	0.625	1.8[a]	2.0[a]	0.375	0.50	3.13	0.125	0.25	2.50	0.50	0.50	3.13
24	0.125	1.63	2.25	0.75	1.25	4.00	0.875	0.875	3.25	0.75	0.25[a]	3.0[a]
26	0.875	2.25	2.75	1.38	3.00	4.38	1.63	1.63	3.63	1.38	1.75	4.00
28	1.13	2.88	3.13	2.00	3.00	5.13	1.25	1.5[a]	3.8[a]	2.13	2.63	4.63
30	2.50	4.00	4.00	2.0[a]	3.00	4.8[a]	1.9[a]	2.88	3.88	3.25	3.63	5.75
32	3.25	5.00	4.63	3.50	4.25	6.00	3.25	3.88	5.50	5.13	4.38	5.75
34	5.38	5.75	6.3[a]	5.13	6.00	6.6[a]	3.88	4.00	5.50	4.50	5.38	6.75
36	4.8[a]	6.5[a]	6.5[a]	4.25	6.3[a]	6.8[a]	3.0[a]	4.1[a]	6.0[a]	4.4[a]	6.25	6.8[a]
37.5	5.0[a]	6.6[a]	6.8[a]	4.3[a]	6.5[a]	6.8[a]	3.0[a]	4.1[a]	6.1[a]	4.4[a]	6.3[a]	6.75

(a) Measurements made at a slight angle from vertical to measure around hardware support structures.

5.2.3.1 Simulant Mixing

The high-viscosity, small-diameter simulant physical and rheological properties are summarized in Table 3.2. This simulant was mixed from the low-viscosity, small-diameter simulant. The liquid was decanted and mixed with sugar to increase viscosity. All properties met the target simulant property ranges specified in Table 3.1. The simulant properties were acceptable for conducting the experiment. During the test, small quantities of chlorine and algicide were added to the sugar-based simulant to inhibit organism growth. This addition did not affect the simulant properties. To ensure that all solids were fully suspended prior to test start, an air lance was used to provide additional agitation.

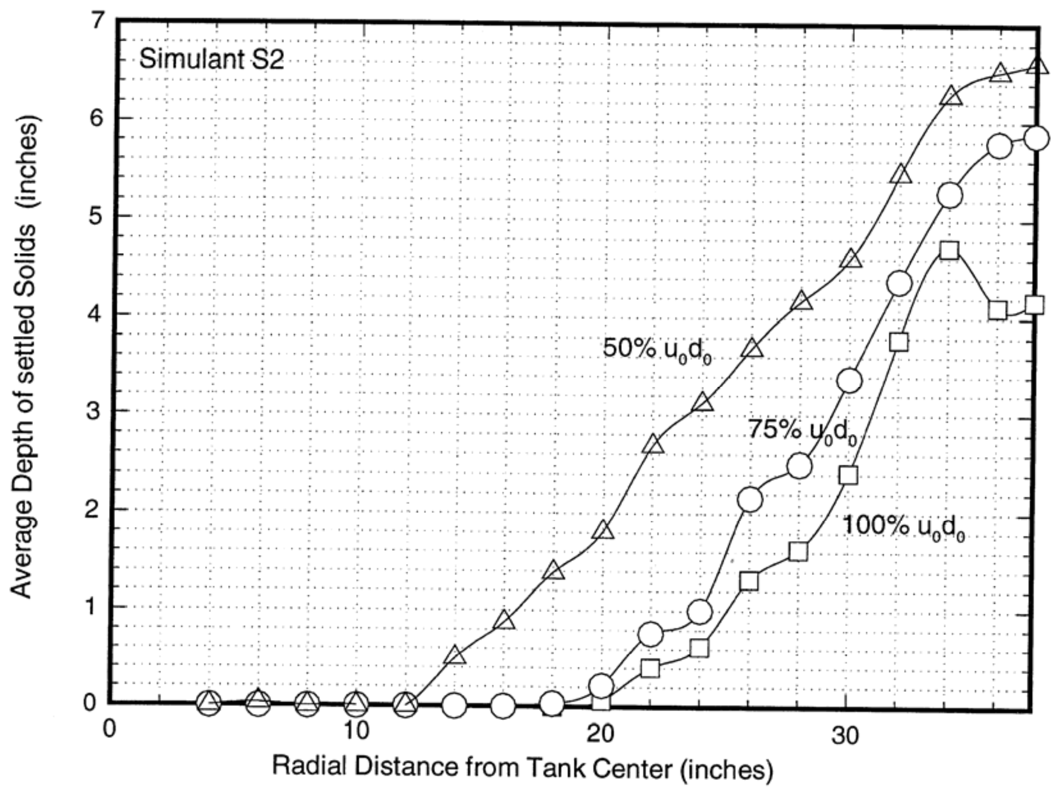

Figure 5.8. Simulant S2 Settled Solids Profiles at 100%, 75% and 50% U_0D_0

Table 5.5. Particle Size Distribution Data in the Settled Solids Layer

Particle Size (μm)					**Sample Location**	
Median	Mean Vol.	S.D. Vol.	Confidence Interval (%)	Number of Counts	Radial Position (in.)	Elevation from tank bottom (in.)
4.73	8.20	8.33	99.99	196681	18	0.5
6.36	9.08	7.90	99.99	138944	28	3.125
25.17	26.28	12.99	100.00	85559	28	1.125
36.30	36.01	11.72	99.99	67080 #1	28	0.25
36.34	39.78	20.09	99.90	112041 #2	28	0.25
9.38	11.06	7.09	99.99	207726	34	6.25
17.04	19.02	10.88	99.99	70803	34	5.375
33.85	33.39	12.60	99.99	41996 #1	34	0.25
35.19	36.99	17.12	99.99	53701 #2	34	0.26
14.22	16.58	10.47	99.99	86630	37.5	6.75
16.79	18.55	10.55	99.99	90469	37.5	5.00
33.10	35.35	17.29	100.00	101719	37.5	0.25
#1, #2: Two measurements taken at the same location						

5.2.3.2 100% U_0D_0 Test

The 100% case was initiated twice. On the second day of mixing, the pump flow rate dropped below the target value and remained there for several days. Thus the simulant was remixed and the test restarted. Data files associated with Period 2, particulate settling, are S3-5 through S3-7. This settling occurred over three days. The mixer pump flow rate remained steady after 100% U_0D_0 flow rate was regained.

At equilibrium, ultrasonic concentration data were taken at each sampling location; the data are summarized in data files S3-8 through S3-11. Samples were taken to measure particle size distribution at location B1, radius = 28 in.; at location B4, radius = 18 in.; and kinematic viscosity at location B1, radius = 28 in. The equilibrium concentration data are plotted in Figure 5.9.

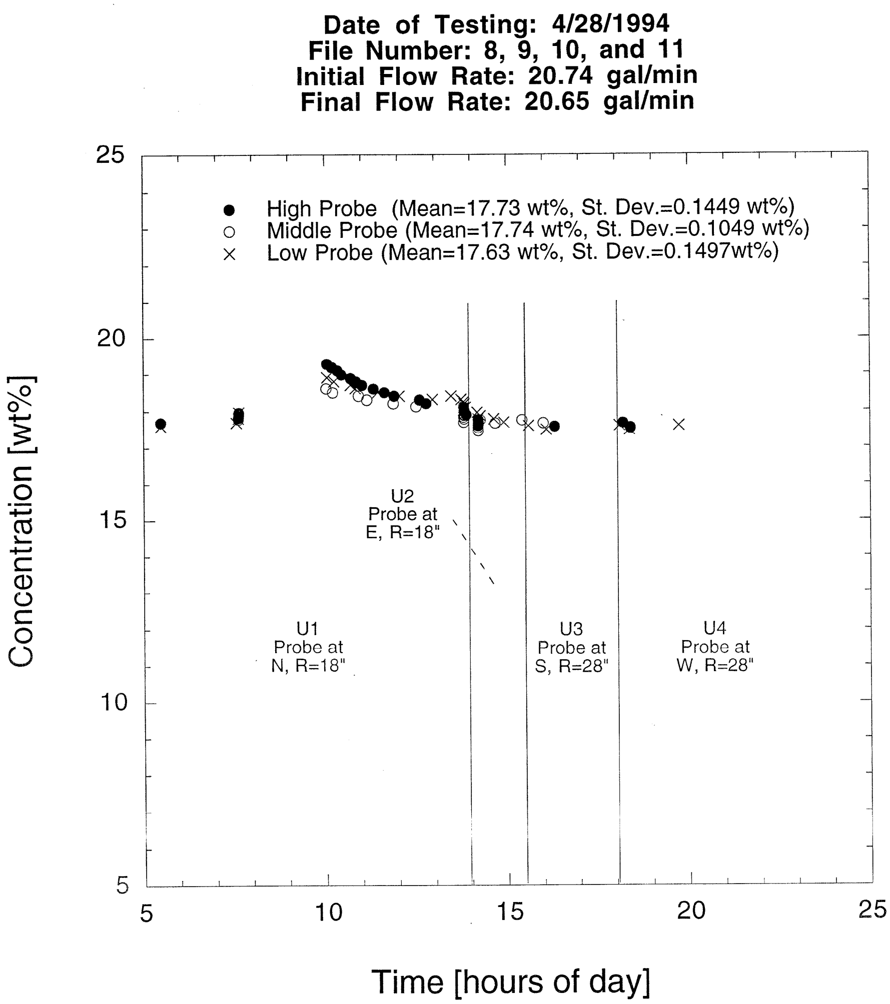

Figure 5.9. Simulant S3 Equilibrium Data at 100% U_0D_0

5.2.3.3 75% U_0D_0 Test

The 75% case was initiated immediately after attaining the 100% equilibrium data. Data files associated with Period 2, particulate settling, are S3-12 through S3-14. This settling occurred over a 7-day period. The mixer pump flow rate remained steady at 15.7 gal/min throughout this period.

At equilibrium ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S3-15 through S3-18. Samples were also taken to measure particle size distribution at location B3, radius = 18 in. and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.10.

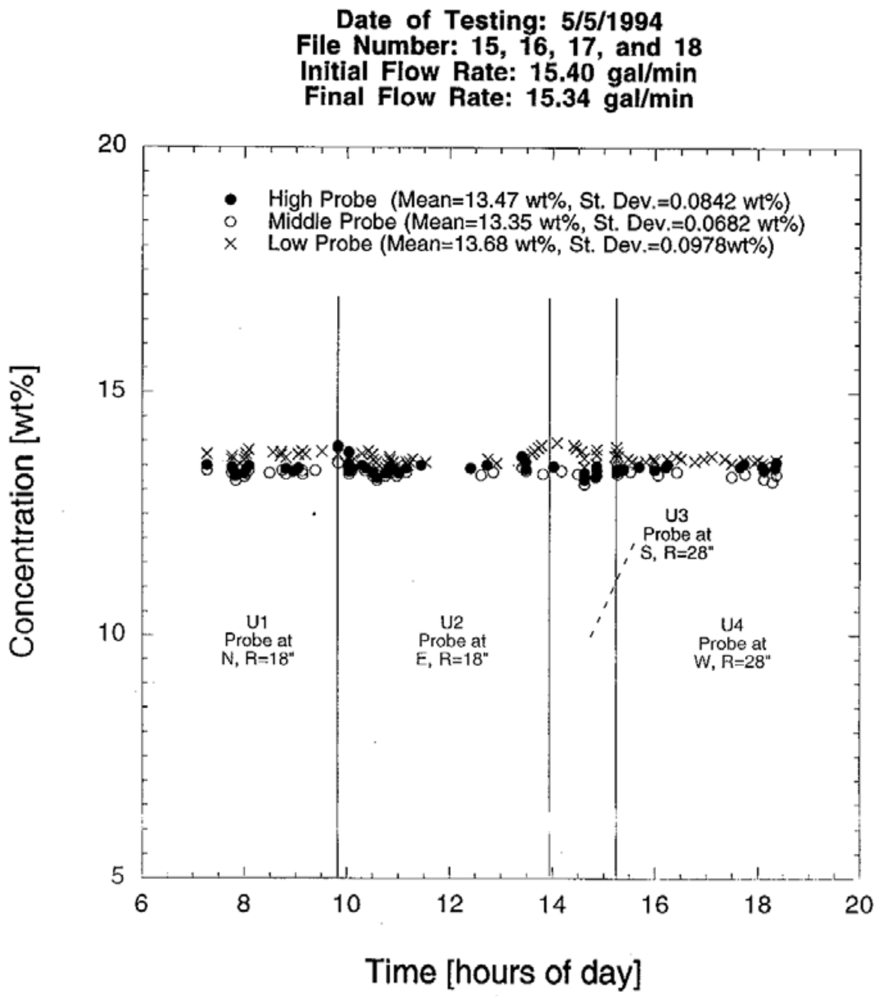

Figure 5.10. Simulant S3 Equilibrium Data at 75% U_0D_0

5.2.3.4 50% U_0D_0 Test

The 50% case was initiated immediately after gathering the 75% equilibrium data. Data files associated with Period 2, particulate settling, are S3-19 through S3-22. This settling occurred over an 11-day period. The mixer pump flow rate remained steady at 10.5 gal/min throughout this period.

At equilibrium, ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S3-23 through S3-26. Also samples were taken to measure particle size distribution at location B1, radius = 28 in.; at location B3, radius = 18 in.; and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.11.

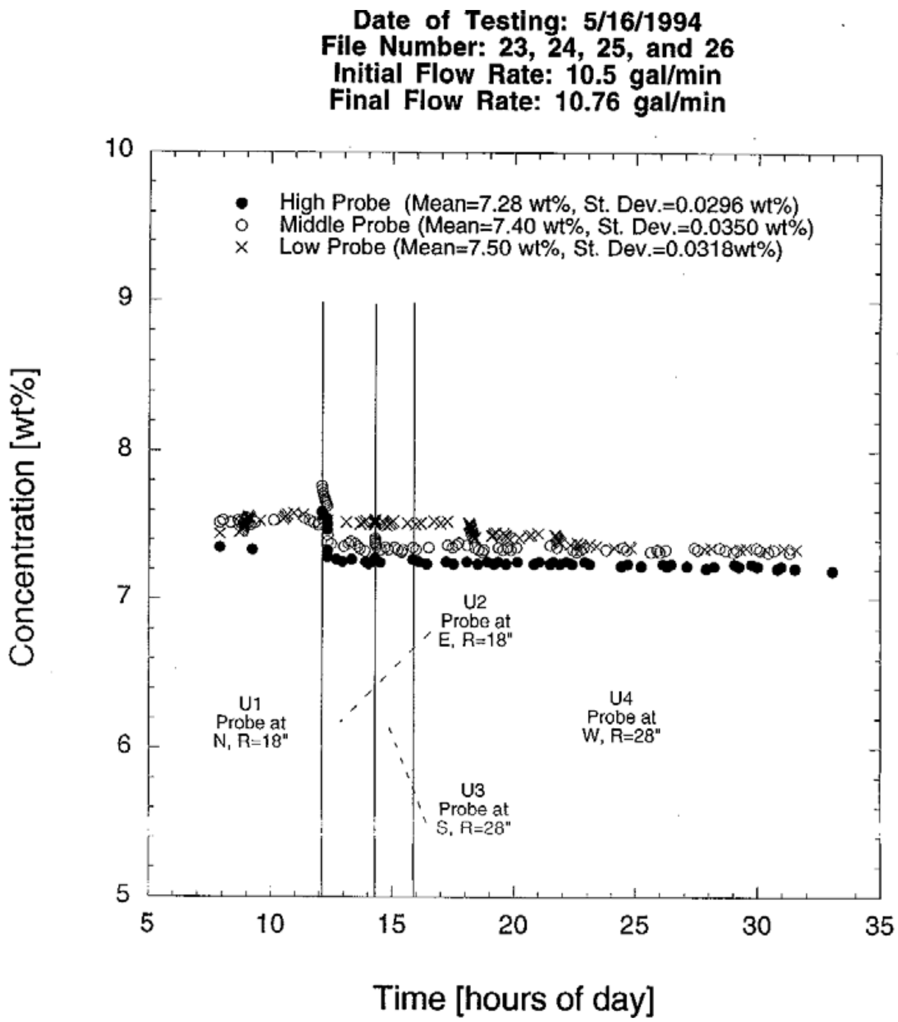

Figure 5.11. Simulant S3 Equilibrium Data at 50% U_0D_0

5.2.3.5 Settled Solids Profiles

After attaining equilibrium at each of the flow rates the profile of the settled solids layer was measured. These data are summarized in Table 5.6 and plotted in Figure 5.12. At 100% U_0D_0 settled solids were detected at a radial distance of 20 to 24 in. At 75% U_0D_0 the solids were detected at a radial distance of about 14 in.; this distance decreased to about 10 in. at 25% U_0D_0. The peak solids depth occurred at a radial distance from 30 to 34 in.

After the test was completed, the supernatant was pumped out of the tank. Samples at four radii and several depths were taken to analyze the particle size distribution of the settled solids. These data are listed in Table 5.7. The solids were stratified based on particle size. The volume mean diameter of particulate 0.25 in. above the tank floor ranged from 6 to 11 μm. The volume mean diameter of particulate decreased with elevation above the tank floor. The volume mean diameter of particulate 0.25 in. beneath the top layer ranged from 4 to 6 μm.

Table 5.6. Simulant S3 Profile of Settled Solids Level Above Tank Floor

Radial Distance from Tank Center (in.)	Depth of Settled Solids (in.)											
	Position 1, North			Position 2, East			Position 3, South			Position 4, West		
	100%	75%	50%	100%	75%	50%	100%	75%	50%	100%	75%	50%
Date	4/28	5/5	5/16	4/28	5/5	5/16	4/28	5/5	5/16	4/28	5/5	5/16
4	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0.125	0	0	0	0	0	0
10	0	0	0	0	0	0.25	0	0	0	0	0	0
12	0	0	0.125	0	0	0.50	0	0	0	0	0	0
14	0	0	0.50	0	0	0.875	0	0	0.25	0	0	0.25
16	0	0	0.75	0	0.375	1.00	0	0	0.375	0	0.125	0.50
18	0	0.25	1.00	0	0.88[a]	1.0[a]	0	0.25	0.75	0	0.75	0.75
20	0	0.625	1.25	0	1.50	2.50	0	0.75	1.25	0	1.00	1.63
22	0	1.13	2.00	0.50	1.50	3.50	0	1.50	2.25	0.375	1.75	2.50
24	0	1.5[a]	1.5[a]	0.75	2.25	3.66	0.375	1.75	3.25	1.0[a]	2.0[a]	3.5[a]
26	0.75	2.25	2.25	1.38	2.88	3.75	0.50	2.00	4.25	0.875	1.8[a]	3.50
28	0.875	2.25	3.5	1.25	3.13	5.38	0.50	2.3[a]	4.3[a]	1.50	3.25	5.00
30	0.375	2.50	3.25	0.75	3.4[a]	5.5[a]	0.50	2.50	3.5	1.00	3.63	5.50
32	0	2.38	3.00	0.75	2.75	4.25	0.125	1.75	2.75	0.50	3.75	5.00
34	0	1.13	4.38	0.25	2.6[a]	4.9[a]	0.125	0.88[a]	4.0[a]	0	3.13	5.50
36	0	1.0[a]	4.3[a]	0	2.6[a]	5.0[a]	0	0.75	4.00	0	2.3[a]	5.3[a]
37.5	0	0.75[a]	4.25	0	2.6[a]	5.5[a]	0	0.75	4.0[a]	0	2.3[a]	5.50

(a) Measurements made at a slight angle from vertical to measure around hardware support structures.

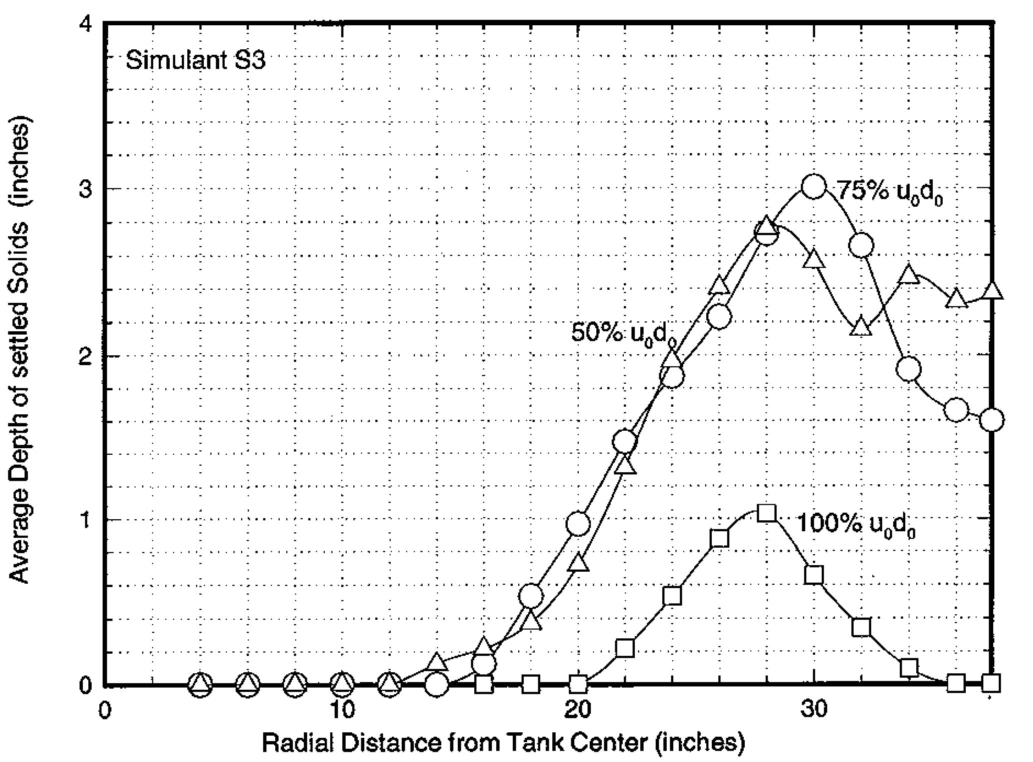

Figure 5.12. Simulant S3 Settled Solids Profiles at 100%, 75%, and 50% U_0D_0

Table 5.7. Particle Size Distribution Data in the Settled Solids Layer

Particle Size (μm)					Sample Location	
Median	Mean Vol	S.D. Vol	Confidence Interval (%)	Number of Counts	Radial Position (in.)	Elevation from tank bottom (in.)
4.72	5.47	3.73	100.00	71567	18	1.25
6.14	7.34	4.16	99.99	54391	18	0.25
5.39	5.92	2.82	99.99	40720	28	2.00
5.78	6.58	3.38	100.00	43932	28	1.00
4.59	5.37	3.95	99.99	101518	34	4.38
8.68	10.95	7.61	99.99	101197	34	1.00
4.27	4.47	1.88	100.00	34739	37.5	4.25
7.75	8.90	4.86	99.99	70520	37.5	1.00

5.2.4 Simulant S4: High Viscosity, Large Diameter

Log book details of the high viscosity, large diameter particulate simulant tests are listed in Appendix E. During this test, equilibria were established at 100, 75, 50, and 25% U_0D_0. These equilibrium data support the full-factorial analysis between 100% and 50% U_0D_0 and the half-factorial analyses between 100, 50, and 25% U_0D_0.

5.2.4.1 Simulant Mixing

The high-viscosity, large-diameter simulant physical and rheological properties are summarized in Table 3.2. This simulant was mixed from the low-viscosity, large-diameter simulant. The liquid was decanted and mixed with sugar to increase the simulant viscosity. All properties except absolute viscosity and wt% concentration met the target simulant property ranges specified in Table 3.1. The viscosity value was just below the acceptance criteria and judged to be acceptable. The wt% concentration recipe showed that adequate solids were in the tank; however, the solids settled so rapidly that it was difficult to get a fully mixed vessel, even with the air lance. The simulant properties were judged acceptable for conducting the experiment.

5.2.4.2 100% U_0D_0 Test

The 100% case was initiated once. At the start of Period 2, the pump was unable to provide the target flow rate of 20.88 gal/min; 17.1 gal/min was the maximum sustained. This value dropped to 16.5 gal/min at equilibrium (79% of the target value). With the high-viscosity simulant and large-diameter particulate, this was the maximum flow rate attainable. The test was completed at this value. Data files associated with Period 2, particulate settling, are S4-2 through S4-5. This settling occurred over a 5-day period.

At equilibrium ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S4-6 through S4-9. Also samples were taken to measure particle size distribution at location B1, radius = 28 in. and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.13.

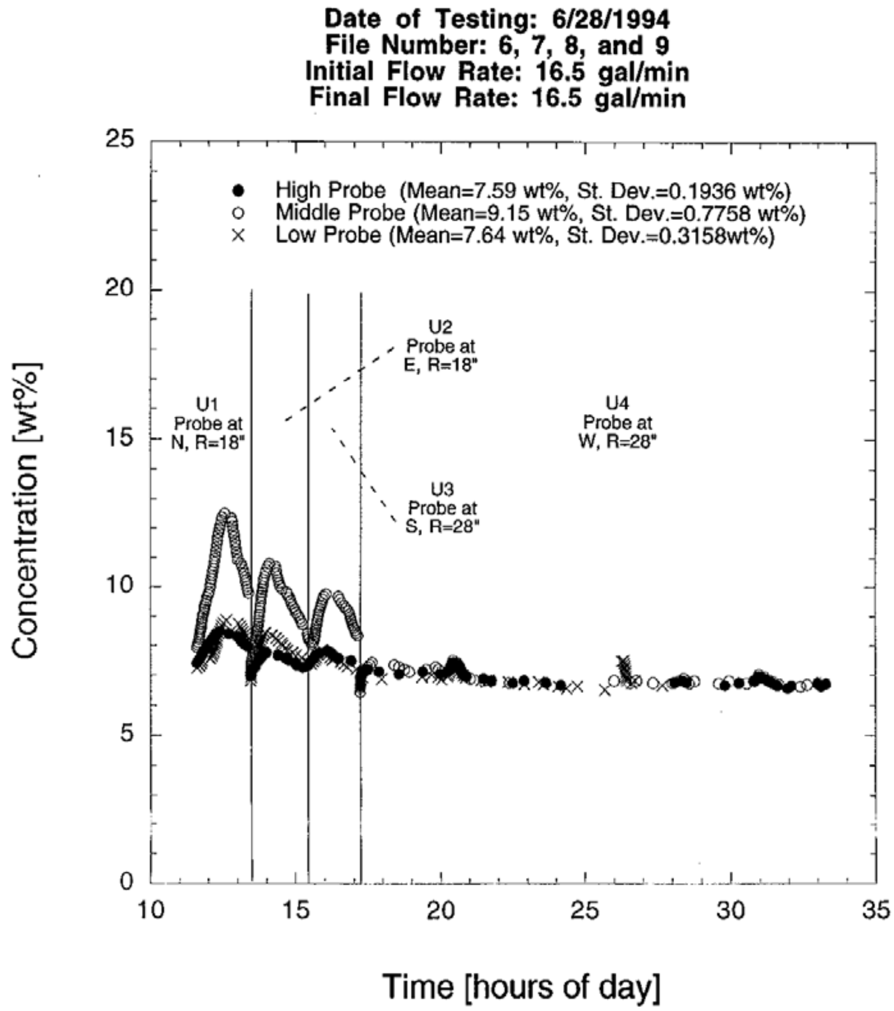

Figure 5.13. Simulant S4 Equilibrium Data at 100% U_0D_0

5.2.4.3 75% U_0D_0 Test

The 75% case was initiated immediately after attaining the 79% equilibrium data. Data files associated with Period 2, particulate settling, are S4-10 and S4-11. This settling occurred over a two-day period. The mixer pump flow rate remained steady at 15.7 gal/min throughout this period.

At equilibrium, ultrasonic concentration data were taken at each sampling location. These data are summarized in data files S4-12 through S4-15. Also samples were taken to measure particle size distribution at location B1, radius = 28 in.; at location B3, radius = 18 in.; and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.14.

5.2.4.4 50% U_0D_0 Test

The 50% case was initiated immediately after gathering the 75% equilibrium data. Data files associated with Period 2, particulate settling, are S4-15 through S4-17. This settling occurred over a 10-day period. The mixer pump flow rate remained steady at 10.5 gal/min throughout this period.

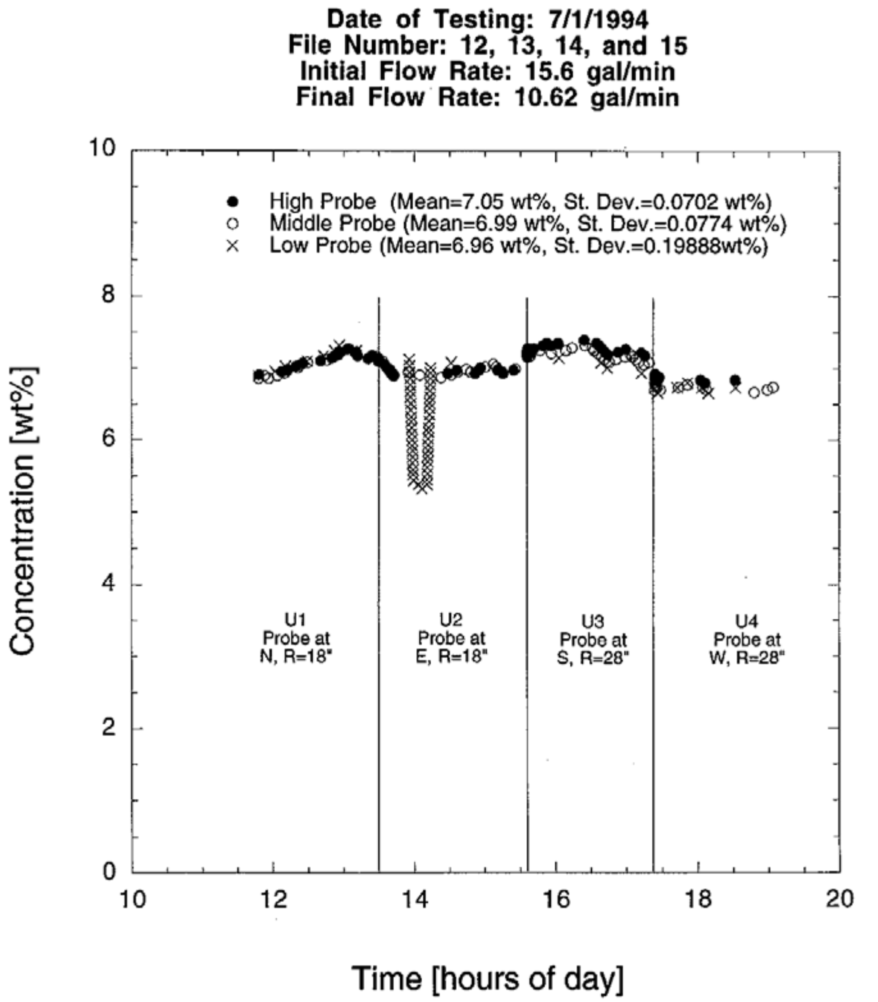

Figure 5.14. Simulant S4 Equilibrium Data at 75% U_0D_0

At equilibrium ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S4-18 through S4-21. Also samples were taken to measure particle size distribution at location B1, radius = 28 in.; at location B3, radius = 18 in.; and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.15.

5.2.4.5 25% U_0D_0 Test

The 25% case was initiated immediately after gathering the 50% equilibrium data. Data files associated with Period 2, particulate settling, are S4-22 through S4-17. This settling occurred over a 14-day period. The mixer pump flow rate remained near 6 gal/min (29%) throughout the majority of this period. The flow rate was attained by implementing a secondary bypass line around the pump to maintain pump flow rate above that which passed through the nozzles.

At equilibrium ultrasonic concentration data were taken at each sampling location; these data are summarized in data files S4-28 through S4-31. Also samples were taken to measure particle size distribution at location B1, radius = 28 in.; at location B3, radius = 18 in.; and kinematic viscosity at location B4, radius = 18 in. The equilibrium concentration data are plotted in Figure 5.16.

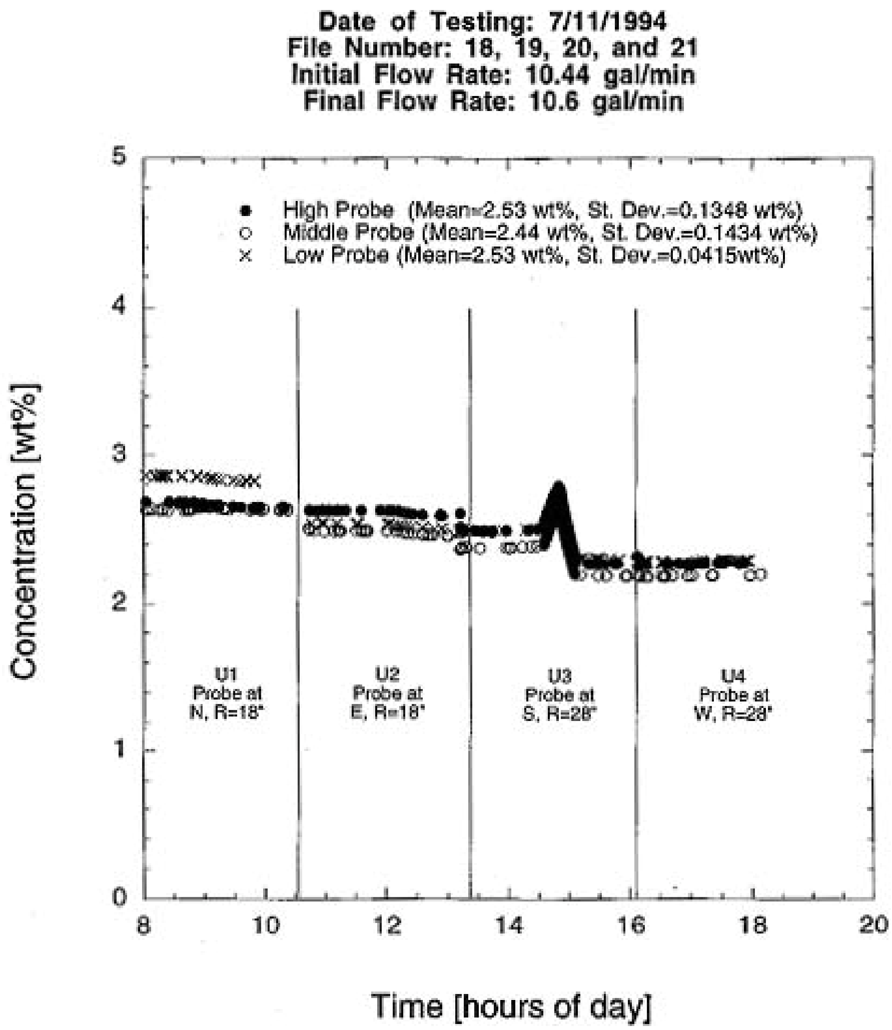

Figure 5.15. Simulant S4 Equilibrium Data at 50% U_0D_0

5.2.4.6 Settled Solids Profiles

After attaining equilibrium at each of the flow rates, the profile of the settled solids layer was measured. These data are summarized in Table 5.8 and plotted in Figure 5.17. At 100, 75, and 50% U_0D_0, settled solids were detected at a radial distance of about 14 to 16 in. At 25% U_0D_0, the distance decreased to 4 to 6 in. The peak solids depth occurred at a radial distance of about 34 in.

After completion of the test, the supernatant was pumped out of the tank. Samples were taken at four radii and several depths to analyze the particle size distribution of the settled solids. These data are listed in Table 5.9. The solids were stratified based on particle size; the volume mean diameter of particulate 0.25 in. above the tank floor ranged from 20 to 34 μm. The volume mean diameter of particulate decreased with elevation above tank floor. The volume mean diameter of particulate 0.25 in. beneath the top layer ranged from 4 to 8 μm.

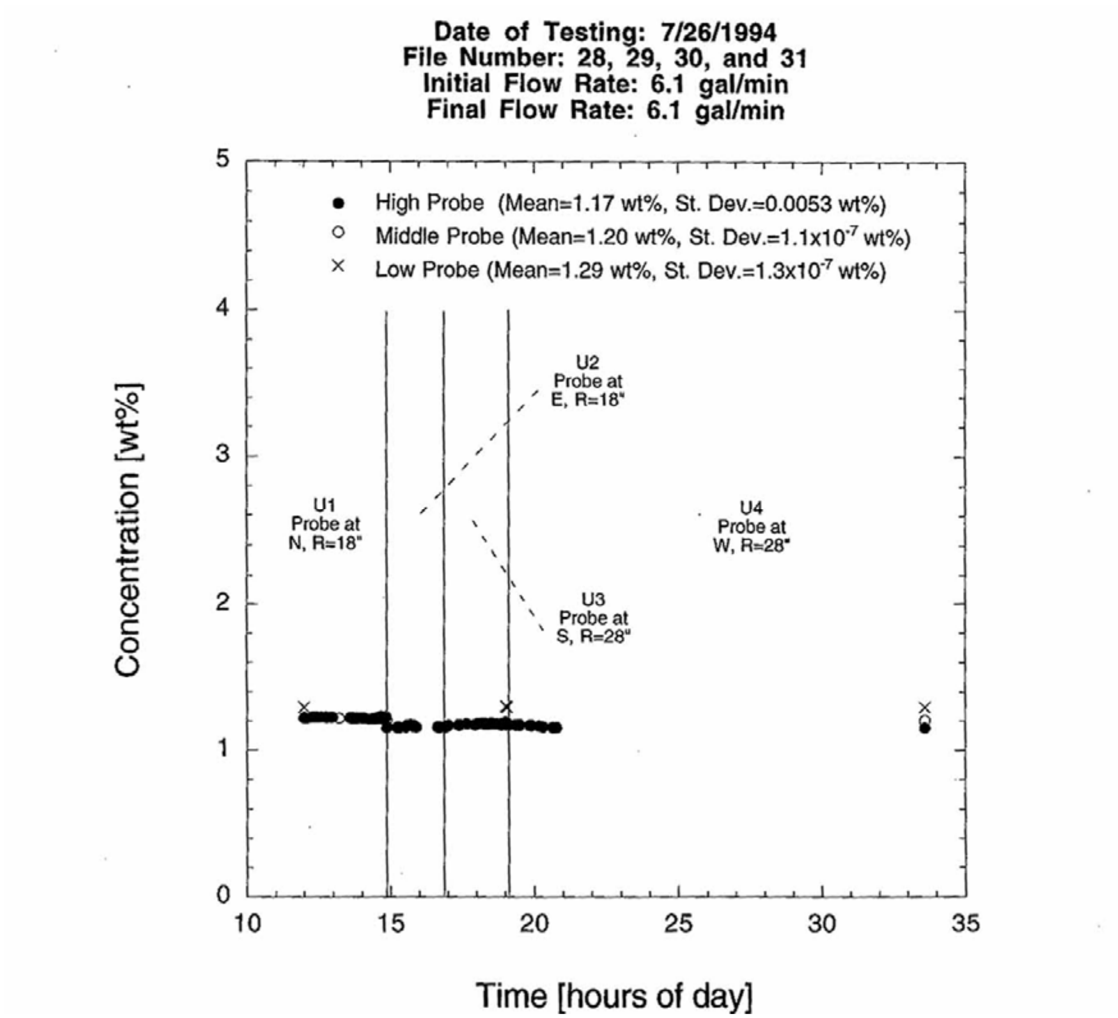

Figure 5.16. Simulant S4 Equilibrium Data at 25% U_0D_0

5.3 Data Analysis

Data analysis to determine the effect of the physical parameters on the degree of uniformity achieved in the tank was performed as data were acquired. The types of analyses are described here. The following quantities will be calculated for each test:

- magnitude of the gravitational settling parameter
- magnitude of the Reynolds number
- magnitude of the Froude number
- mean simulant concentration at each sample location as measured by bottle samples and the ultrasonic concentration probe
- standard deviation of the simulant concentration at each sample location as measured using both bottle samples and the ultrasonic concentration probe.

The degree of uniformity achieved was assessed by comparing the mean concentration at each location to the concentration of the tank as a whole. Analysis of variance was used to determine whether the tank as a whole is uniform or nonuniform.

Table 5.8. Simulant S4 Profile of Settled Solids Level Above Tank Floor

Radial Distance from Tank Center (in.)	Depth of Settled Solids (in.)															
	Position 1, North				Position 2, East				Position 3, South				Position 4, West			
	100%	75%	50%	25%	100%	75%	50%	25%	100%	75%	50%	25%	100%	75%	50%	25%
Date	6/28	7/1	7/11	7/26	6/28	7/1	7/11	7/26	6/28	7/1	7/11	7/26	6/28	7/1	7/11	7/26
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0.125	0	0.25	0	0	0	0.25	0	0.25	0	0.375
8	0	0	0	0.375	0	0	0	0.375	0	0	0	0.375	0	0	0	0.375
10	0	0	0	0.375	0	0	0	0.375	0	0	0	0.375	0	0	0	0.375
12	0	0	0	0.50	0	0	0	0.50	0	0	0	0.50	0	0	0	0.375
14	0	0	0	0.75	0	0	0	0.75	0.25	0	0	0.50	0	0	0	0.625
16	0.25	0	0	0.875	0	0	0	1.13	0.25	0	0	0.875	0	NA	0	0.75
18	0.375	0	0.125	1.00	0.25(a)	0	0.25(a)	1.0(a)	0.25	0.25	0.625	1.25	0.25	NA	0.75	1.50
20	0.50	0.625	0.625	2.13	0.50	0.125	1.25	1.13	0.75	1.00	1.38	2.25	0.75	.75	0	2.25
22	0.875	2.0(a)	1.88	3.5	1.25	0.50	2.13	3.13	1.13	1.88	1.63	2.50	0.75	1.50	1.88	3.25
24	1.2(a)	2.00	2.6(a)	3.8(a)	1.63	1.25	2.25	4.25	1.75	1.88	2.50	3.00	0.63(a)	1.5(a)	1.9(a)	2.5(a)
26	2.38	1.88	3.88	4.5	1.88	2.75	3.25	6.00	2.63	3.38	3.25	4.25	2.13	3.00	3.50	4.5
28	3.25	2.63	5.38	5.13	3.3(a)	4.9(a)	4.88	6.75	2.6(a)	3.5(a)	6.3(a)	3.8(a)	2.63	3.25	4.88	5.5
30	4.5	3.63	4.75	6.13	3.8(a)	5.1(a)	5.50	7.3(a)	5.50	4.00	5.00	5.13	3.88	4.50	5.63	6.5
32	4.5	5.13	6.63	7.50	5.25	5.50	7.50	7.38	5.00	4.75	5.13	6.13	5.25	4.75	6.38	7.5
34	6.75	7.3(a)	8.13	8.8(a)	2.3(a)	6.25	8.1(a)	8.3(a)	4.50	5.25	5.63	7.0(a)	5.50	5.88	7.13	8.25
36	6.8(a)	7.5(a)	8.1(a)	8.6(a)	1.6(a)	6.75	7.5(a)	8.0(a)	4.3(a)	5.0(a)	5.1(a)	7.0(a)	5.0(a)	6.1(a)	6.6(a)	7.6(a)
37.5	7.0(a)	7.5(a)	8.1(a)	8.6(a)	1.5(a)	6.75	7.1(a)	7.8(a)	4.3(a)	4.9(a)	5.4(a)	7.0(a)	5.0(a)	6.38	6.6(a)	7.8(a)

(a) Measurements made at a slight angle from vertical to measure around hardware support structures.

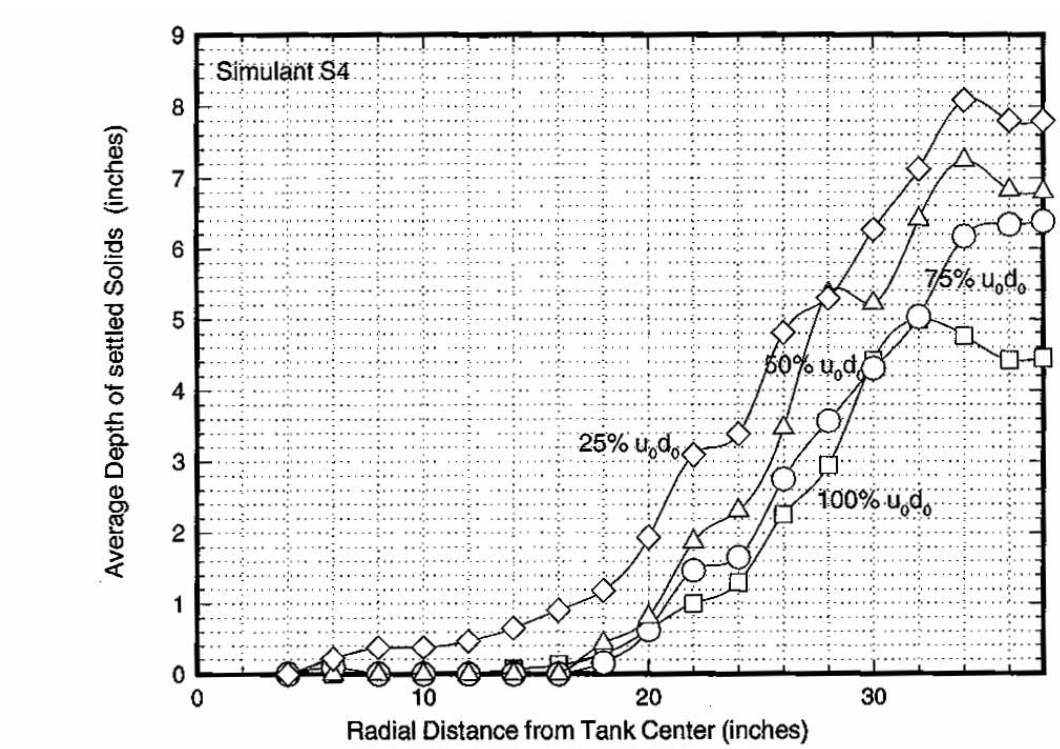

Figure 5.17. Simulant S4 Settled Solids Profiles at 100, 75, 50 and 25% U_0D_0

Table 5.9. Particle Size Distribution Data in the Settled Solids Layer

Particle Size (μm)					Sample Location	
Median	Mean Vol.	S.D. Vol	Confidence Interval (%)	Number of Counts	Radial Position (in.)	Elevation from tank bottom (in.)
5.92	7.57	5.20	100.00	104314	1.08	1.00
16.84	20.48	14.28	99.99	119821	18.0	0.25
3.64	5.27	5.94	99.99	148068	28.0	5.125
25.00	26.57	12.19	100.00	76671	28.0	2.625
31.42	31.66	13.07	100.00	58121	28.0	0.25
5.22	6.14	3.59	100.00	75108	34.0	8.75
6.20	7.83	5.19	100.00	111752	34.0	8.125
13.10	15.78	10.69	100.00	134982	34.0	7.25
16.46	19.69	12.62	99.99	117865	34.0	6.75
34.22	34.35	12.72	100.00	35112	34.0	0.25
3.83	4.14	2.19	100.00	37082	37.5	8.625
4.36	4.77	2.52	100.00	50920	37.5	8.125
13.86	16.11	10.24	100.00	133986	37.5	7.50
15.87	18.59	11.63	100.00	274279	37.5	7.00
32.88	32.30	12.18	100.00	49845	37.5	0.25

Models were developed to predict the difference in concentration at the upper and lower sample location by performing multiple linear regression on the Reynolds number, Froude number, and gravitational settling parameter.

5.3.1 Definition of Dimensionless Numbers

Dimensional analysis of the behavior of Newtonian slurries of equivalent concentration indicates that the concentration inhomogeneity in the geometrically similar tanks may be a function of three dimensionless parameters (Bamberger et al. 1990). These are jet Reynolds number (Re), Froude number (Fr), and gravitational settling parameter (Gs).

The Reynolds number characterizing the nozzle discharge rate in this experiment will be calculated as

$$Re = U_0 D_0/\nu \tag{5.1}$$

where

U_0 = jet nozzle discharge velocity calculated from mixer pump volumetric flow rate

D_0 = nozzle diameter

ν = kinematic viscosity of the mixture as a whole.

The Froude number in this experiment is defined as

$$Fr = U_0^2/g\,H \tag{5.2}$$

where

g = acceleration due to gravity

H = level of the tank contents.

The gravitational settling parameter is defined as

$$Gs = 2\, D_t^2\, H\, (s - 1)\, C\, U_s\, g/s\, U_0^3\, D_0^2 \qquad (5.3)$$

where

D_t = tank diameter

H = level of tank contents

s = ratio of solids to liquid density (ρ_s/ρ)

C = concentration of solids in mixture as a whole (wt%)

U_s = settling velocity

U_0 = nozzle discharge velocity

D_0 = nozzle diameter.

Equation (5.3) is identical to Eq. (3.26) in Bamberger et al. (1990), where the relationship between the volume fraction, Φ_s and the concentration, C, has been substituted to allow evaluation of gravitational settling parameter in terms of quantities measured during these experiments.

5.3.2 Uncertainty in the Experimental Reynolds Number

The uncertainty in the Reynolds number caused by the uncertainty in the measurement of the nozzle velocity, the fluid kinematic viscosity, and the diameter of the nozzle can be shown to be

$$\Delta Re/Re = \{(\Delta U_0/U_0)^2 + (\Delta D_0/D_0)^2 + (\Delta \nu/\nu)^2\}^{0.5} \qquad (5.4)$$

The uncertainty in the Reynolds number for each experiment is expected to be dominated by the uncertainty in the value of the kinematic viscosity. The uncertainty in the measurement of the nozzle velocity based on the uncertainty in the volumetric flow rate (Q) is calculated to be ±2%,[a] and the uncertainty in the measurement of the nozzle diameter is expected to be less than 1 mil or ±0.2%. The kinematic viscosity of the fully mixed simulant is expected to be measured to within ±0.5%. However, because the kinematic viscosity of the mixture varies as a function of temperature, its magnitude must be evaluated at the tank temperature. It is anticipated that the tank temperature will be known to within ±1°C. If the kinematic viscosity of the simulant varies as much as that of water, the uncertainty in the temperature will result in an uncertainty of approximately ±2% in the kinematic viscosity. Consequently, the net uncertainty in the Reynolds number at which the experiment will be run will be less than ±2.2%.

5.3.3 Uncertainty in the Froude Number

The uncertainty in the Froude number caused by uncertainty in the nozzle velocity and fluid depth in the tank is

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(a) Uncertainty in velocity is calculated as $(\Delta U_0/U_0)^2 = (\Delta Q_0/Q_0)^2 + 4(\Delta D_0/D_0)^2$.

$$\Delta Fr/Fr = \{4(\Delta U_0/U_0)^2 + (\Delta H/H)^2\}^{0.5} \quad (5.5)$$

The uncertainty in the nozzle velocity and the fluid depth in the tank will be approximately 1% and 0.5%, respectively; this results in a total uncertainty in the Froude number of ±1.1%.

5.3.4 Uncertainty in the Gravitational Settling Parameter

The uncertainty in the gravitational settling parameter is

$$\Delta Gs/Gs = \{4(\Delta D_t/D_t)^2 + (\Delta H/H)^2 + (\Delta\rho_s/\rho_s)^2 + (\Delta\rho_l/\rho_l)^2 +$$

$$(\Delta C/C)^2 + (\Delta U_s/U_s)^2 + 9(\Delta U_0/U_0)^2 + 4(\Delta D_0/D_0)^2\}^{0.5} \quad (5.6)$$

The main contributor to uncertainty is the accuracy of the settling velocity determination. This quantity is difficult to measure, and a consistent measuring technique is required from test to test. For the test performed here, the particle settling velocity was determined by measuring the velocity of the slurry supernate interface. The expected uncertainties in the contributing properties are

- tank diameter (D_t) 0.1%
- fluid depth in tank (H) 0.5%
- ratio of solids to liquid density (s) 2%
- concentration of solids in mixture as a whole (C) 2%
- settling velocity of particles (U_s) 10%
- nozzle exit velocity (U_0) 1%
- nozzle diameter (D_0) 0.2%.

The uncertainty in the particle settling velocity dominates the uncertainty calculation, which indicates that the gravitational settling parameter will be known to within ±11%. The uncertainty in this value can be reduced significantly by developing better methods of characterizing and measuring the particle settling velocity.

5.4 Correlations Based on 1/12-Scale Data

A correlation was developed to predict the maximum concentration of particles that can be suspended at a given power input to the tank.

As discussed in Bamberger et al. (1990), correlations for the maximum solids loading may be presented in terms of a total of three dimensionless parameters that describe the dynamics of mixing, a number of geometric parameters, the ratio of the density of the solids to liquid and a dimensionless rate of rotation for the jet. Correlations to predict the maximum concentration of particles that can be suspended in a tank are developed based on linear combinations of the parameters in Bamberger et al. (1990). The following assumptions were made when developing correlations:

- All tests were assumed to be at steady state. Concentration as a function of time has not been examined in detail to verify this assumption.

- The simulants were assumed to be Newtonian with a constant viscosity. The rheograms were not examined to determine whether this assumption was valid.
- The solids concentration of the simulants was based on ultrasonic measurements for the individual test cases.
- The volume fraction of the solids in the mixture was determined based on the measured solids concentration, density of the supernatant, and density of the solids.

The two correlations were found to represent the data with a correlation coefficient greater than 80%; these are of the form

$$\Phi_p = \alpha \text{ (geometry, density ratio) } Re_0^m \, Fr_0^n \, (d_p/D_0)^p \tag{5.7}$$

The loading is represented in terms of the volume fraction of solids Φ_p. The action of the jet is captured in two terms, the jet Reynolds number based on nozzle velocity and diameter, $Re_d = (U_0 D_0)/\nu_m$, and the Froude number based on the nozzle velocity, and level of the tank contents, $Fr = U_0^2/gH$. The dimensionless particle size, d_p/D_0, captures the tendency of particles to settle in the tank. Algebraic relations to determine the magnitude of one set of dimensionless parameters from the others are presented in Bamberger et al. (1990).

The first fit was performed allowing the coefficient on the Reynolds number to take on a finite value. The best fit coefficients α, m, n, and p are indicated in the first row of Table 5.10. The standard error in these coefficients is also provided. The standard errors represent the uncertainty in the coefficients based on the measured data. For example, roughly speaking, the coefficient m is expected to fall between [m-s] and [m+s] with probability 68%.

A new fit was performed assuming that the coefficient m = 0. This decision was made for three reasons. First, the mean value of the coefficient was very small compared to the standard error, indicating that the probability that m differed from 0 was very low. Second, results from the mixing literature suggest mixing is not strongly affected by Reynolds number at large Reynolds numbers. Finally, neglecting the Reynolds number results in conservative scale-up predictions for full scale in the following sense: when the effect of Reynolds number is included in the scale-up prediction, lower nozzle velocities are predicted at full scale.

The coefficients for the second curve fit are shown in the second row of Table 5.10.

Table 5.10. Correlation Coefficients

Correlation Coefficient	**α [alpha/log s alpha * log s]**	**m (Re) ± s**	**n (Fr) ± s ±p (U_s/U_0) ± s**	**Standard Error**
0.83	3.850×10^{-6} [0.060×10^{-6}]	0.0213 ±0.320	1.478 ±0.360	-1.027 ±0.415
0.83	3.85×10^{-6} [0.16×10^{-6}, 90.40×10^{-6}]	0 0	1.491 ±0.291	-1.033 ±0.386

Inserting the coefficients in Table 5.10 into the correlations results in the following correlations (Eq. 5.8 and 5.9). The error bounds provide the range within 1 standard error.

$$\Phi_p = 10^{(-5.415\pm1.80124)}\, Re_0^{\;0.021\pm0.320}\, Fr_0^{\;1.478\pm0.360}\, (d_p/D_0)^{-1.03\pm0.41} \quad (5.8)$$

$$\Phi_p = 10^{(-5.34\pm1.37)}\, Fr_0^{\;1.49\pm0.29}\, (d_p/D_0)^{-1.03\pm0.39} \quad (5.9)$$

Scatter plots comparing the data to the correlations are provided in Figures 5.18 and 5.19. Froude number is indicated on the ordinate because it represents the most important dependence for the data. Comparing the two scatter plots, it appears that the addition of the Reynolds number has no noticeable effect on the agreement.

In addition, examining the maximum difference between the data and the curve fit indicates that data point describing the measured volume fraction is over predicted by approximately a factor of 2.5, a second is underpredicted by an equal amount. Looked at conversely, this means that when the nozzle velocity required to suspend a known concentration is calculated using this curve, the nozzle velocity predicted using the correlation was as much as 30% different from the velocity required during the two test cases. The correlations in Eq. (5.8) and (5.9) are based on data collected using oscillating mixer pumps installed in double-shell tanks that operate in the range provided in Table 5.11.

The dimensionless rate of rotation, the density ratio, and the ratio of the tank contents level to the nozzle diameter do not appear in Eq. (5.8) or (5.9). None of these parameters were varied systematically during tests. However tests were done near in ranges applicable to double-shell tanks, so the correlations here are expected to apply to that specific problem.

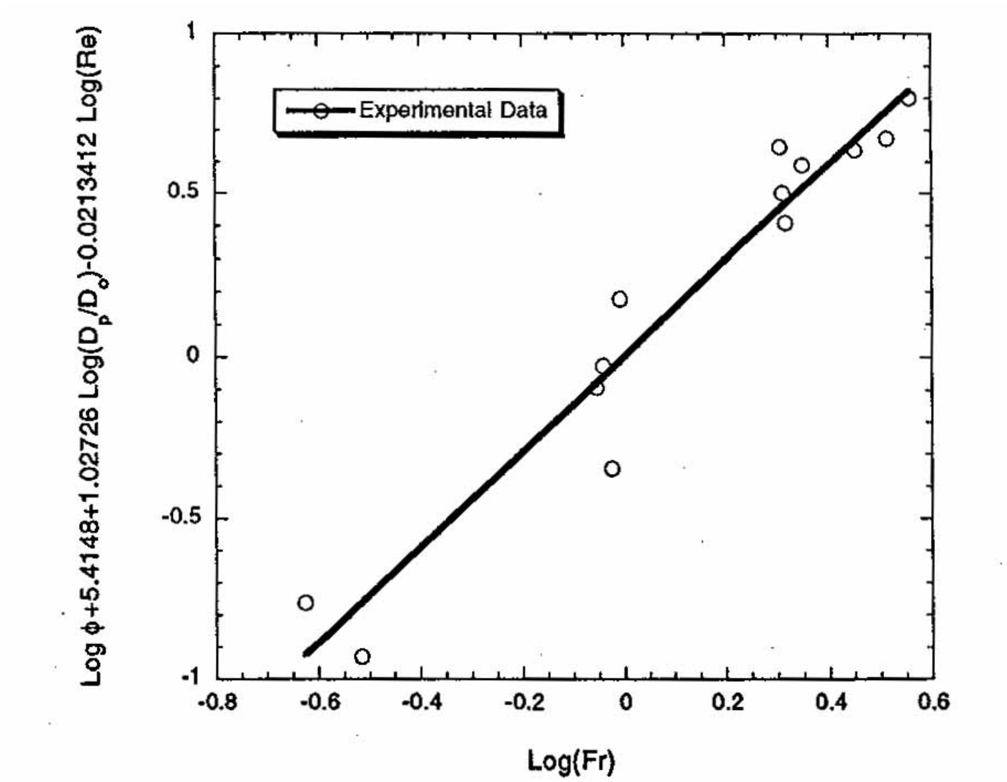

Figure 5.18. Scatter Plot for Correlation in Eq. (5.8)

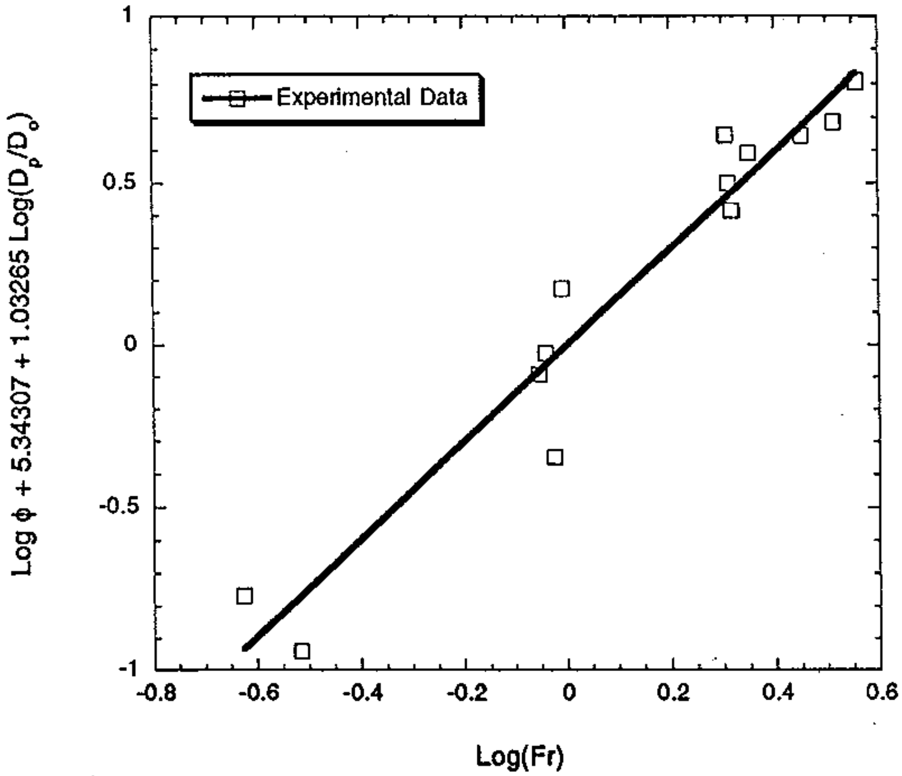

Figure 5.19. Scatter Plot for Correlation in Eq. (5.9)

Table 5.11. Mixer Pump Operating Range

Dimensionless Parameter	Lower Bound	Upper Bound
$Re_D = U_0 D_0/\nu_m$	8.1×10^3	4.7×10^4
$Fr = U_0^2/gH$	0.24	3.62
d_p/D_0	8×10^{-5}	7.3×10^{-4}
N/U_0D_0	1.4×10^{-5}	5.6×10^{-5}
ρ_s/ρ_l	2.43	2.65
H/D_0	60	60

5.5 Predictions at Full Scale

Both correlations (5.8) and (5.9) were used to estimate the U_0 required to maintain the solids in Tank 241-101-AZ suspended using 4-, 6-, and 8-in.-diameter nozzles. The physical properties in AZ-101 are assumed to be those described in Bamberger et al. (1990). Calculations should be repeated if new information regarding the physical properties in this tank has been obtained since 1990.

A range of properties is used because the property values varied from core to core. Velocities were predicted for the full range of physical properties. Results are provided for the property values indicated in bold which result in the largest predicted nozzle velocity.

Predictions were made using both Eq. (5.8) and (5.9) to illustrate the effect of neglecting the Reynolds number dependence on the predicted nozzle. Predictions are made using the best-fit values for m, n and p only. Ideally, predictions would also be made using the maximum and minimum values of parameters m, n, and p. This was not done, and it is recommended that this calculation be performed in the future. The following assumptions are made when applying these correlations.

1) It was assumed that the correlations apply to pseudoplastic slurries. The viscosity of 101-AZ may be pseudoplastic. This presents two difficulties. First, Eq. (5.8) and (5.9) were developed for Newtonian fluids, so there is an inherent uncertainty associated with applying the correlations to yield-pseudoplastic slurries. Second, a strain rate must be selected to evaluate the viscosity in the tank. The viscosity of the slurry in the tank was estimated using the average strain rate of the jet. This results in the following functional dependency.

$$\mu_b = \tau_y + K\,(2\,U_0/D_0))^n/(2\,U_0/D_0) \qquad (5.10)$$

where K is the consistency index, n is the flow behavior index, and τ_y is the yield stress.

Predictions using correlation in Eq. (5.8) are independent of strain rate. However, the predictions based on the correlation in Eq. (5.9) are slightly sensitive to the exact value selected.

Five sets of (τ_y, K, n) are provided in Table 3.2 of Bamberger et al. (1990). Four were selected as typical and are provided in Table 5.12. The required velocity was determined at full scale for all sets of physical properties. The highest predicted velocity occurred for the property set is indicated in bold in the table.

2) It was assumed the correlations can be extrapolated to smaller particle diameters than tested. This is thought to be reasonable because the correlation was collected using very small particle sizes. Particles settled at very low Reynolds numbers during testing, so the flow regime around individual particles matches in both tests and in full-scale tanks.

Table 5.12. Properties of Tank 241-AZ-101

Dimensional Quantities	Notes	Range
ρ_s, solids density	estimated based on core sample data	2100 to 2300 kg/m^3
ρ_l, supernatant density	estimated based on core sample data	1200 to 1220 kg/m^3
τ_y, yield stress	Pa	1.26, 1.29, 0.00, 0.00
K, consistency index	Pa-s	0.05, 0.03, 0.08, 0.24
n, behavior coefficient		0.787, 0.866, 0.595, 0.686
C, % solids concentration when fully mixed	assumed	25%
H, tank contents level	assumed	9.144 m (30 ft)
g, gravitational constant		9.8 m^2/s
d_p, volume average particle diameter	estimated based on core sample data	5 μm
D_0, nozzle diameter	design parameter	0.1524 m (6 in.)
U_0, nozzle exit velocity	worst-case predicted minimum value	8.9 m/s correlation (Eq. 5.8) 8.9 m/s correlation (Eq. 5.9)
μ_b, bulk viscosity anticipated when fully mixed	$\frac{\tau_y + K\,(2\,U_0/D_0)^n}{2\,U_0/D_0}$	54 x 10^{-3} Pa/s correlation (Eq. 5.8); not used in Eq. (5.9)
Re	predicted	3.44 x 10^3 correlation (Eq. 5.8) not used in correlation (Eq. 5.9)
Fr	predicted minimum value	0.89 correlation (Eq. 5.8) 0.89 correlation (Eq. 5.9)
d/D_0		3.28 x 10^{-5} correlations in Eq. (5.8) and (5.9)

5.6 Effect of Nozzle Diameter

The nozzle diameter was not varied during tests; therefore, the effect of varying nozzle diameter cannot be known with certainty. In general, the quantity α for correlations of type (Eq. 5.8 and 5.9) is geometry dependent. The form of this geometry dependence has not been explored in any way and is not known on the basis of literature. However, the data were extrapolated to different nozzle diameters using the three following possible interpretations of the correlations in Eq. (2.1 and 5.8) and (2.2 and 5.9).

5.6.1 Extrapolation 1

The required U_0 is estimated for other nozzle diameters by assuming that the coefficient α is not a function of geometric parameters and that the correlations in Eq. (2.1 and 5.8) and (2.2 and 5.9) apply for any nozzle diameter. The physical properties indicated in bold in Table 5.12 were used for the extrapolation.

Of the three possible correlations examined, this correlation predicts the highest nozzle velocities are required of the smallest-diameter nozzles. The largest power requirements occur for the largest-diameter nozzle. The predicted values for 4-, 6-, and 8-in.-diameter nozzles based on Eq. (2.1 and 5.8) and (2.2 and 5.9) and the physical properties listed in Table 5.12 are summarized in Table 5.13.

Table 5.13. Conditions for Extrapolation 1

D_0, in.	4	6	8
U_0, m/s	10.2 correlation (5.8) 10.3 correlation (5.9)	8.9 correlation (5.8) 8.9 correlation (5.9)	8.1 correlation (5.8) 8.1 correlation (5.9)
U_0D_0, m^2/s	1.0 correlation (5.8) 1.0 correlation (5.9)	1.4 correlation (5.8) 1.4 correlation (5.9)	1.6 correlation (5.8) 1.6 correlation (5.9)
Power, kW	11.8 correlation (5.8) 11.9 correlation (5.9)	17.6 correlation (5.8) 17.7 correlation (5.9)	23.1 correlation (5.8) 23.3 correlation (5.9)

5.6.2 Extrapolation 2

The required U_0 is estimated assuming that the correct correlation is

$$\Phi_p = \alpha \text{ (density ratio) } (D_0/H)_{test}{}^{n} \, Re_0{}^{m} \, (U_0{}^2/gD_0)^n \, (d_p/D_0)^p \qquad (5.11)$$

Of the three correlations examined, this one provides the highest predictions for the nozzle velocity required when an 8 in. nozzle diameter is used and the lowest for the 4 in. nozzle in 101-AZ. This correlation is equally consistent with the data collected at 1/12 scale because the ratio of H/D_0 was held constant in all tests. According to this correlation, a lower velocity is required with a smaller nozzle.

The predicted values for 4-, 6-, and 8-in.-diameter nozzles based on Eq. (5.11), the physical properties in Table 5.12, and exponents n, m, and p from Table 5.9 are shown in Table 5.14.

Table 5.14. Conditions for Extrapolation 2

D0, in.	4	6	8
U_0, m/s	8.4 correlation (5.8) 8.4 correlation (5.9)	8.9 correlation (5.8) 8.9 correlation (5.9)	9.3 correlation (5.8) 9.3 correlation (5.9)
U_0D_0, m^2/s	0.85 correlation (5.8) 0.85 correlation (5.9)	1.4 correlation (5.8) 1.4 correlation (5.9)	1.9 correlation (5.8) 1.9 correlation (5.9)
Power, kW	6.5 correlation (5.8) 6.5 correlation (5.9)	17.6 correlation (5.8) 17.7 correlation (5.9)	35.4 correlation (5.8) 35.8 correlation (5.9)

5.6.3 Extrapolation 3

The required U_0 is estimated assuming that the correct correlation is

$$\Phi_p = \alpha \text{ (density ratio) } (H/D_0)_{test}{}^{p} \, Re_0{}^{m} \, (U_0{}^2/gH_0)^n \, (d_p/H_0)^p \qquad (5.12)$$

This correlation is equally consistent with the data collected at 1/12 scale because the ratio of H/D_0 was held constants in all tests. According to this correlation, the nozzle velocity required for suspension remains constant as the nozzle diameter increases. The predicted values for 4-, 6-, and 8-in.-diameter nozzles based on Eq. (5.12), the physical properties in Table 5.12, and exponents n, m, and p from Table 5.10 are shown in Table 5.15.

Table 5.15. Conditions for Extrapolation 3

D_0, in.	4	6	8
U_0, m/s	8.9 correlation (5.8) 8.9 correlation (5.9)	8.9 correlation (5.8) 8.9 correlation (5.9)	8.9 correlation (5.8) 8.9 correlation (5.9)
U_0D_0, m^2/s	0.9 correlation (5.8) 0.9 correlation (5.9)	1.4 correlation (5.8) 1.4 correlation (5.9)	1.8 correlation (5.8) 1.8 correlation (5.9)
Power, kW	7.8 correlation (5.8) 7.8 correlation (5.9)	17.6 correlation (5.8) 17.7 correlation (5.9)	31.2 correlation (5.8) 31.2 correlation (5.9)

5.6.4 Summary

- Extrapolation method 1 suggests that the power requirements increase with nozzle diameter, but the jet velocity decreases.
- Extrapolation method 2 suggests that both power and nozzle velocity increase with nozzle diameter.
- Extrapolation method 3 suggests that the nozzle velocity is unaffected by diameter, but power increases.

The predictions based on these extrapolations can be compared to some data from solids suspension with agitators. The agitator results are not expected to be identical, but provide some basis for evaluating whether the effect of size assumed here is plausible. According to Oldshue (1983, Figure 5-16), power requirements dropped by a factor of approximately 4.3 when an impeller diameter increased by a factor of 2 in a particular solids mixing application. This behavior is more consistent with the use of extrapolation 1 than the other 2 methods. Extrapolation 1 would suggest that nozzle velocity decreases with nozzle diameter, but the decrease is not sufficient to lower the power requirement.

The possible effects of geometry explored here are highly speculative. One data point at a second nozzle diameter would improve the predictions dramatically.

5.6.5 Correlations in the Literature

Results from this experiment were compared with correlations describing the minimum power requirements to achieve complete suspension of a known quantity of solids in a tank. The specific comparisons are made with correlations predicting the minimum power to mix a known volume of solids in Oldshue (1983), those appearing in Weisman and Efferding (1960), and the limiting correlation for large tanks provided by Giesler (1993). All are presented in dimensionless form. In all cases, the published correlations are based on algebraic combinations of the parameters in Bamberger et al. (1990) and appear in the literature with the simple adjustment that "tip" velocity for a blade replaces nozzle diameter.

The two dynamic parameters appearing most frequently in the literature are the mixer Reynolds number based on the tip velocity and blade diameter, $Re_t = U_t D_B/\nu$, and the mixer Froude number based on the tip velocity, and level of the tank contents, $Fr_t = U_t^2/gH$. One parameter to describe the size or settling velocity of the slurry is then required. Some correlations are based on the dimensionless particle size and others on the dimensionless settling velocity.

Three important differences exist between the flows that can be predicted using the correlations developed here and those in the literature. First, those in the literature were developed for mechanical agitators; the correlations developed here apply to jet mixing. Second, the correlations in the literature were developed based on data collected in smaller tanks than those used in the PNNL tests. Third, the published correlations were developed for mixtures containing much larger particles so are expected to differ somewhat. However, the fundamental physics related to mixing is expected to be similar.

Three correlations for suspension using mechanical agitators can be described in the following form.

$$C = \alpha \text{ (geometry, density ratio) } Re_T^{m} \, Fr_T^{n} \, (d_p/D)^{p} \tag{5.13}$$

The coefficients m, n, and p are described in Table 5.16. In all cases, the coefficient is a function of geometry and the density ratio of the solids to supernatant, and it is not expected to be similar in any of the separate correlations.

Table 5.16. Equation Coefficients for Eq. (5.13)

Authors	**m (Reynolds)**	**n (Froude)**	**p (d_p/D)**
Zweitering as cited in Weisman and Efferding (1960)	0.769	3.46	-1.53
Lamade as cited in Oldshue (1983)	0	3.33	-1.4
Kotzek et al. as cited in Oldshue (1983)	0	3.33	-1.4

Two authors present correlations in the form:

$$\Phi_p/(1 - \Phi_p) = \alpha\text{(geometry, density ratio) } Re_{Tt}^{m} \, Fr_T^{n} \, (U_s/U_T)^{p} \tag{5.14}$$

Expanding this relation in a Taylor series, this can be shown to be of the form at small volume fractions of particles:

$$\Phi_p = \alpha\text{(geometry, density ratio) } Re_T^{m} \, Fr_T^{n} \, (U_s/U_T)^{p} \tag{5.15}$$

For very large tanks, Geisler et al. (1993) provide a correlation of the form

$$\Phi_p \, (1 - \Phi_p)^{5} = \alpha\text{(geometry, density ratio) } Re_T^{m} \, Fr_T^{n} \, (U_s/U_T)^{p} \tag{5.16}$$

For small volume fractions this becomes identical to Eq. (5.15). The magnitudes of m, n and p for correlations of Eq. (5.15) are provided in Table 5.17.

Table 5.17. Equation Coefficients for Eq. (5.15)

Authors	m (Reynolds)	n (Froude)	p (d_p/D)
Kneule as cited in Weisman and Efferding (1960)	0	2	-2
Weisman and Efferding (1960)	0	2	-2
Einenkel and Mersmann as cited in Oldshue (1983)	0.2701	1	-1
Geisler et al. (1993)	0	1	-1

Finally, one set of authors provides a correlation in the form

$$\Phi_p/(1 - \Phi_p) = \alpha(\text{geometry, density ratio})\ Re_T^m\ Fr_T^n\ (d_p/D)^p \tag{5.17}$$

At small volume fractions, this is identical to

$$\Phi_p = \alpha(\text{geometry, density ratio})\ Re_T^m\ Fr_T^n\ (d_p/D)^p \tag{5.18}$$

Coefficients m, n, and p for Eq. (5.17) and (5.18) are provided in Table 5.18.

Table 5.18. Equation Coefficients for Eq. (5.17) and (5.18)

Authors	m (Reynolds)	n (Froude)	p (d_p/D)
Hobler and Zablocki, as cited in Oldshue (1983)	+0.59	+2.64	-1.47

When the correlations using agitators are compared to the correlation based on 1/12 scale data, the following similarities are apparent:

- The strongest dependence is on the Froude number. More solids can be suspended at larger Froude numbers.
- The next strongest dependence is on a parameter that describes the tendency of particles to settle. This tendency is either captured in the settling velocity ratio or the size ratio.
- Finally, some correlations exhibit a Reynolds number dependence, others do not. Geisler (1992) and Bamberger et al. (1990) indicate that the Reynolds number dependence decreases with the scale of the mixing vessel.

The correlation developed here exhibits the same general trends. Ideally, the data could be compared to determine the correlation between the data and a curve fit with the specific coefficients from each author. This has not been performed but is recommended.

6.0 Computational Modeling of Jet Mixing

This section presents the results of TEMPEST computer modeling that simulated 1/12-scale test cases S1 and S3. The experimental data were used to both aid in the development and validate the computer modeling approach. In Section 6.1, the modeling objectives and approach are described in detail. Section 6.2 addresses some code validation and testing that was performed, and Section 6.3 describes the numerical approach and physical models used for the simulations. Section 6.4 presents the simulation results and conclusions.

6.1 Modeling Objectives and Approach

The modeling objectives and approach are described in this section.

6.1.1 Objectives of Computer Modeling

The main objective of the computational modeling was to establish a methodology that would be robust, accurate, and computationally efficient in simulating tank mixing processes. The data set from the 1/12-scale uniformity experiments provided a means to both develop and validate the modeling approach. Additionally, the trends and observations from the modeling results allowed for comparisons against the experimental data in real time because both experiments and computations were carried out simultaneously. This parallel approach made the 1/12-scale experiments an appropriate developmental tool for the numerical model.

The physics associated with tank mixing of solid/liquid mixtures is complex. The complete governing equations for modeling particle-liquid interactions for a practical system are not computationally tractable. As a result, approximate computational approaches, such as TEMPEST, are needed that can capture the essential features of the mixing process within a reasonable amount of time and computer resources.

Validating the computational method against the 1/12-scale experiments enables it to be applied to a full-scale problem with confidence. A computational model aids the design of full-scale mixing systems as well as helping to identify off-design performance.

6.1.2 The TEMPEST Computer Code

TEMPEST is a three-dimensional, time-dependent, computational fluid dynamics analysis computer program developed at Pacific Northwest Laboratory (Trent and Eyler 1992) that solves discrete equations for the conservation of mass, momentum, thermal energy, turbulence, and species transport.[a] The code is well suited to model the turbulent, jet-induced mixing in waste storage tanks.

(a) Transient, Energy, Momentum, and Pressure Equation Solver in Three Dimensions.

6.1.3 Modeling Constraints

Limitations of the TEMPEST program and computational speed relevant to this study are as follows:

- The TEMPEST computer program requires a fixed computational grid to model continuously rotating jets. Discretized approximation to continuous rotation is employed. This does not present a problem because sufficient resolution is available.
- The TEMPEST computer program uses a solid, free-slip boundary condition to represent the free liquid surface. This boundary condition can be applied because during these experiments the free surface is sufficiently far from the jet.
- The solution time increment used by the TEMPEST program is constrained when high-speed jets flow through small computational cells. The computer time for one solution time increment is proportional to the total number of computational cells. Therefore, modeling high-speed jets in large tanks is computationally intensive. These computational speed limitations require particle transport models to be decoupled from fluid flow computations. For this problem, the validity of this decoupling has been demonstrated.
- The TEMPEST modeling approach treats the solid phase as small, inertialess particles that can be represented as a continuum. This model is accurate for small particles (less than 200 μm in diameter) and low concentrations where buoyancy effects can be ignored. The model also assumes thin layers of settled material at the floor of the tank. Settled material is allowed to be resuspended, and suspended material is allowed to settle via deposition and erosion models. These models were performed adequately to simulate these conditions.

6.1.4 Modeling the 1/12-Scale Experiments

The TEMPEST model was applied to experimental test cases S1 and S3. In S1, the 100%, 50%, and 25% U_0D_0 cases were modeled. In S3, only the 100% and 25% U_0D_0 cases were modeled. Each simulation began by assuming uniform, well-mixed particle distributions. This corresponded to the initial maximum U_0D_0 mixing phase of the experiments. Particle concentrations were monitored at several spatial locations that corresponded to the locations of the concentration probes in the experiments. For each U_0D_0 case, the simulation was terminated after the same amount of mixing time as the corresponding experimental case. The initial conditions for the 50 and 25% U_0D_0 cases corresponded to the experimental initial conditions, not necessarily the simulation 100% U_0D_0 equilibrium conditions.

For both the S1 and S3 test cases, particle properties such as mean particle size, approximate particle size distribution, and particle density were approximately matched. Erosion and deposition data were also obtained in separate experiments for simulants S1 and S3. These data helped refine the choice of an empirical constant required for the floor erosion/deposition model in TEMPEST.

6.2 Code Validation and Testing

In performing a numerical simulation of a complex fluid dynamic system, it is important to demonstrate that the computer program can accurately predict basic features of the flow. The TEMPEST computer program is regularly tested by comparing code predictions with analytical flow solutions or experimental data where available. Code assessment and validation results have been reported by Meyer and Fort (1994). The most essential and basic fluid dynamic features of the mixing process in the 1/12-scale tanks are turbulent jet dynamics and particle transport throughout the tank, including erosion and deposition occurring at the tank floor.

6.2.1 Turbulent Jet Simulations

A free jet is one that is far enough removed from any walls or other obstructions to ensure that its behavior is not affected by the obstructions. A floor jet, on the other hand, is one that is located directly above a floor and flows horizontally. The position of the turbulent jets in the 1/12-scale tanks is neither that of a free or floor jet. These jets initially behave like free jets. However, as the jets spread, however, restricted entrainment caused by the solid floor causes the jets to turn towards the floor and eventually attach. At this point, the jets behave like floor jets. Because of this intermediate behavior, the free jet and the floor jet serve as excellent validation cases to test TEMPEST's ability to accurately predict the behavior of the mixing jets in the 1/12-scale tanks.

The TEMPEST program's ability to accurately model high-speed turbulent free jets in large tanks has been extensively tested and reported by Trent and Michener (1993). They found that computed jet velocity decay agreed well with experimental data. They also determined that excellent results could be obtained with fairly coarse node resolution. The fact that TEMPEST accurately predicts turbulent free-jet behavior is not surprising in light of the turbulence model in TEMPEST. This model, which approximates true turbulence by using turbulent energy production and decay equations, uses empirical constants that have been "tuned" to match free-jet behavior. The model also accurately predicts other turbulent flows such as pipe and channel flows, and is the industry standard for simulation of turbulent flows.

TEMPEST simulations of floor jets were addressed by Meyer (1994). Peak velocities, jet spreading angle, and floor shear stress were all examined. The TEMPEST program was found to overpredict both maximum velocity and floor shear stress. At a distance of 60 nozzle diameters downstream, the maximum velocity was overpredicted by 75% and the floor shear stress by 50%.

Jet growth rates (spreading angle) predicted by TEMPEST were also found to differ from the experimental data. Horizontal growth was underpredicted by a factor of 2 to 3, and vertical growth was overpredicted by about a factor of 2. These results were consistent with the assumptions implicit to the isotropic turbulence model used in TEMPEST. Developing turbulence models that account for non-isotropic effects such as those encountered in turbulent floor jets is the subject of current research in the computational fluid dynamics community. Presently, there is no robust model available that has been successfully tested.

In spite of the discrepancies mentioned above, Meyer concluded that the model could still be applied to near floor jets with reasonable accuracy for four reasons: First, the total jet momentum is accurately predicted, so many mixing characteristics are matched. Second, near-floor jet behavior is bounded by free-jet and floor-jet behavior, that inaccuracies are reduced. Third, the total integrated shear stress on the floor was found to be predicted quite well. This is significant because it is the integral over the jet footprint that contributes to the net erosion of settled solids from the floor. Finally, the exact details of the actual erosion process on the floor are not predicted by known models. Therefore, actual erosion can only be computed to within the accuracy of available erosion models.

While the validation tests mentioned above are valid for fixed jets, they are thought to generally apply to rotating jets as long as the rotation period is large compared to the fluid transient time. The fluid transient time is that required for a fluid parcel to go from the jet nozzle to the tank wall and is proportional to the nozzle diameter divided by the discharge velocity. This condition is found to be satisfied for all the test cases considered in the 1/12-scale experimental program.

6.2.2 Particle Transport

In addition to turbulent jet mixing, the other essential and basic fluid dynamic feature of the mixing process in the 1/12-scale tanks is particle transport, including mass erosion and deposition occurring at the tank floor. For many high-speed mixing applications, convective currents and particle settling dictate solids concentrations. The TEMPEST code has been tested to ensure that transport of a passive scalar is handled accurately.

The erosion and deposition processes occurring on the tank floor are not, in general, well-understood processes. The literature reports that there are some empirical relations relating floor shear stress to erosion and deposition rates. One of these models is used by the TEMPEST program and is described in Section 6.4. In general, there are no adequate, applicable validation data sets available. One of the major goals of this computational effort was to see whether such processes could be modeled accurately. Therefore, comparison of computed results with 1/12-scale data, if successful, will serve as a validation of the modeling approach.

6.3 Numerical Model

This section presents a description of the TEMPEST numerical model used to simulate the 1/12-scale experiments, including the computational geometry and descriptions of the particle transport submodels.

6.3.1 Mixer Pump – Tank Model

The 1/12-scale tank geometry was modeled using a cylindrical computational domain, as shown in Figures 6.1 and 6.2. The model used a special periodic boundary so that only half of the tank needed to be modeled. This was possible because the experiments used identical, yet opposed jets. The computational model used only one jet; however, the effects of the opposed jet were fully captured by the periodic boundary. The liquid surface was modeled as a free-slip solid boundary. This model, while not allowing any vertical surface motions such as boiling or splashing, was determined to be sufficient because near-surface fluid motions were observed to be quite small in the experiments.

A total of approximately 10,000 computational cells were used, with 19 in the radial direction, 24 in the vertical direction, and 22 angular cells in the horizontal plane. Variable cell spacings were employed in the vertical and radial directions so computational efficiency was maximized while maintaining good resolution in required areas such as the tank floor and outer walls. The higher resolution near the floor was required to accurately predict floor shear stress distribution needed for the erosion/deposition models. The increased resolution near the outer tank walls provided accurate modeling jet turn-up near the walls.

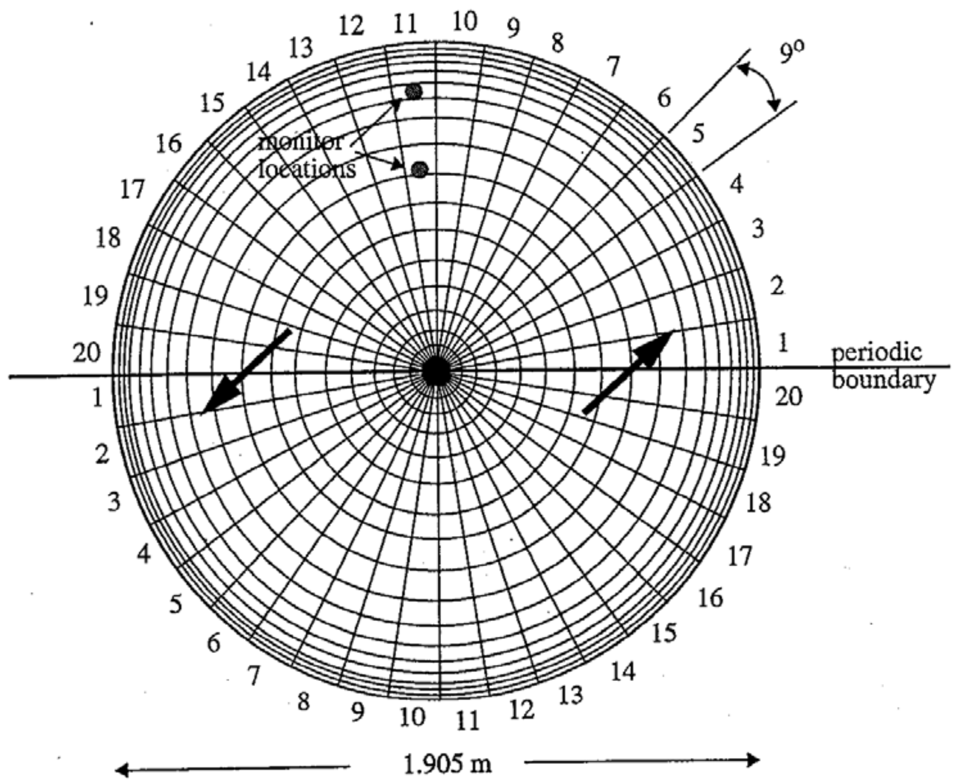

Figure 6.1. Cylindrical Coordinate System Used for the TEMPEST Model. Monitor cells and periodic symmetry boundary are shown.

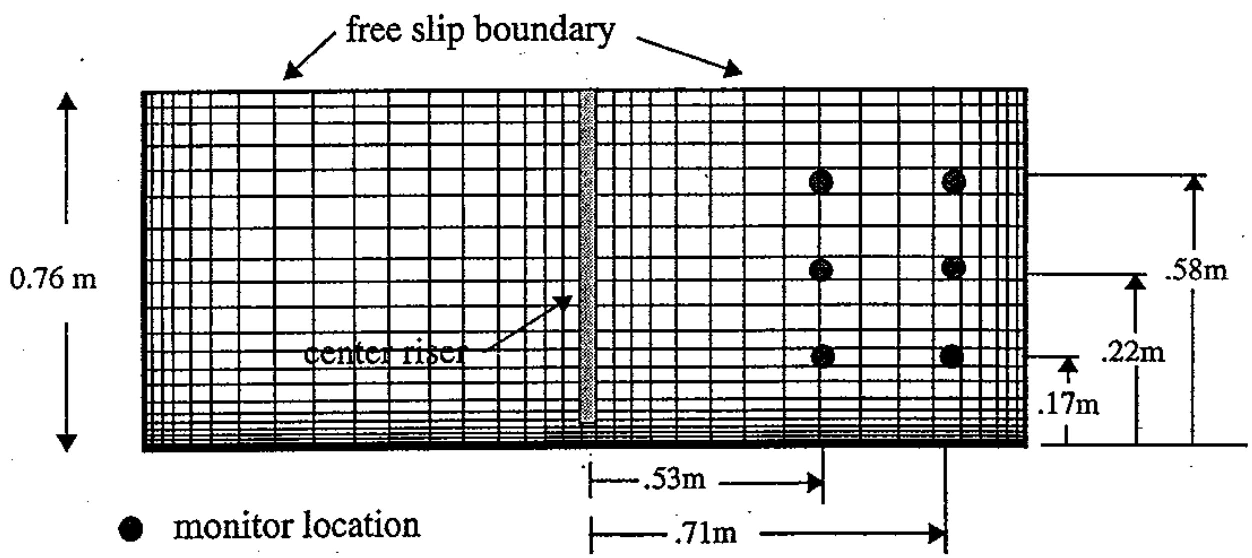

Figure 6.2. Side View of Cylindrical Coordinate System Used for TEMPEST Model. Monitor cell locations and the free slip boundary at the fluid surface are shown.

Additional features of the computational model include the central riser, which housed the mixer pump. Also, six monitor cells were located at the same locations as the concentration probes in the experiment. These monitor cells were used to provide time histories of particle concentrations.

6.3.2 Rotating Mixer Pump Model

One of the critical aspects of the computational model was to develop a method to accurately simulate the rotating jet mixer pumps. After a significant exploratory effort, a means was devised that was computationally efficient as well as accurate. Figure 6.3 is a representation of the jet mixer pump model. The pump inlet was on the bottom with a horizontally located discharge nozzle. Computationally, the inlet/nozzle flow path was connected so that true particle transport was simulated. The nozzle was modeled as a ring of computational cells; the flow through the cells was turned on and off to simulate actual rotation.

Figure 6.4 shows the flow logic employed in the rotating jet model. The horizontal line marked "n" gives the velocity time history for a single computational cell in the nozzle ring. The lines marked "n-1" and "n+1" refer to the cells located just before and just after cell "n," respectively. Each cell experiences an initial velocity ramp up, followed by a period of steady velocity, and then a period of velocity decrease. This velocity history is repeated for each cell; however, it is offset by the amount of time, I. This period was chosen such that the flow history in each cell repeats once every jet rotation period (173 seconds).

A significant analysis was performed to ensure that a continuously rotating jet was approximated as closely as possible. Mass, momentum, and impulse integrals were performed on the velocity time histories to select the appropriate nozzle cell dimensions and peak velocity, U_0. It was determined that an effective (circular) nozzle diameter of 1.35 cm (0.53 in.) was required to approximately simulate all conserved quantities. This effective nozzle diameter was about 6% larger than that used in the experiments.

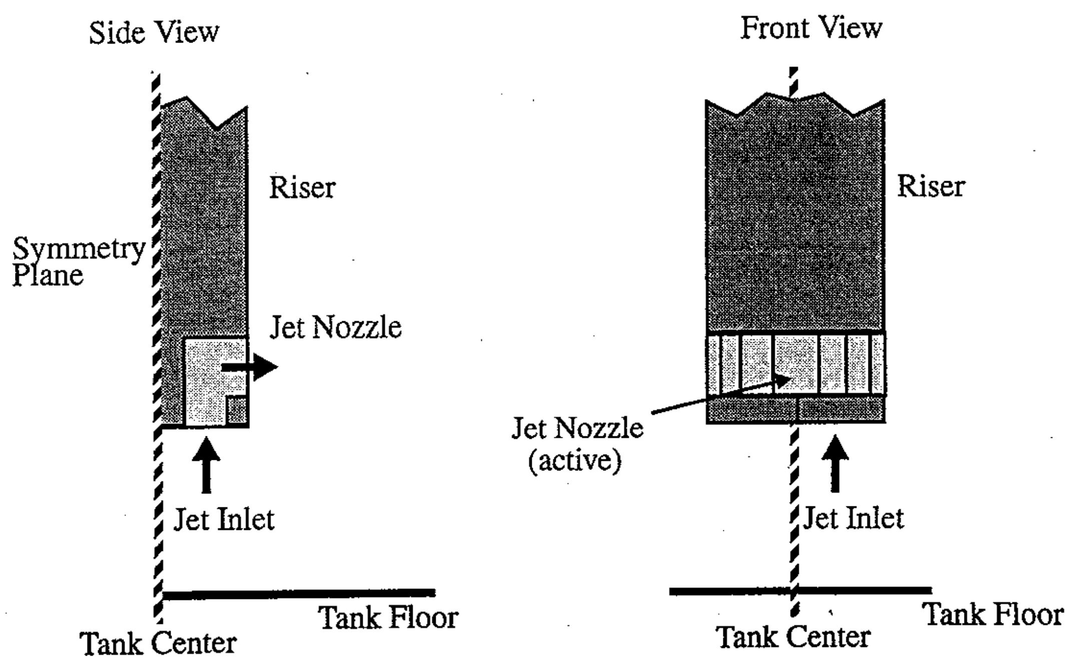

Figure 6.3. Detail of Mixer Pump Model. Jet nozzle consists of ring of computational cells that are periodically activated.

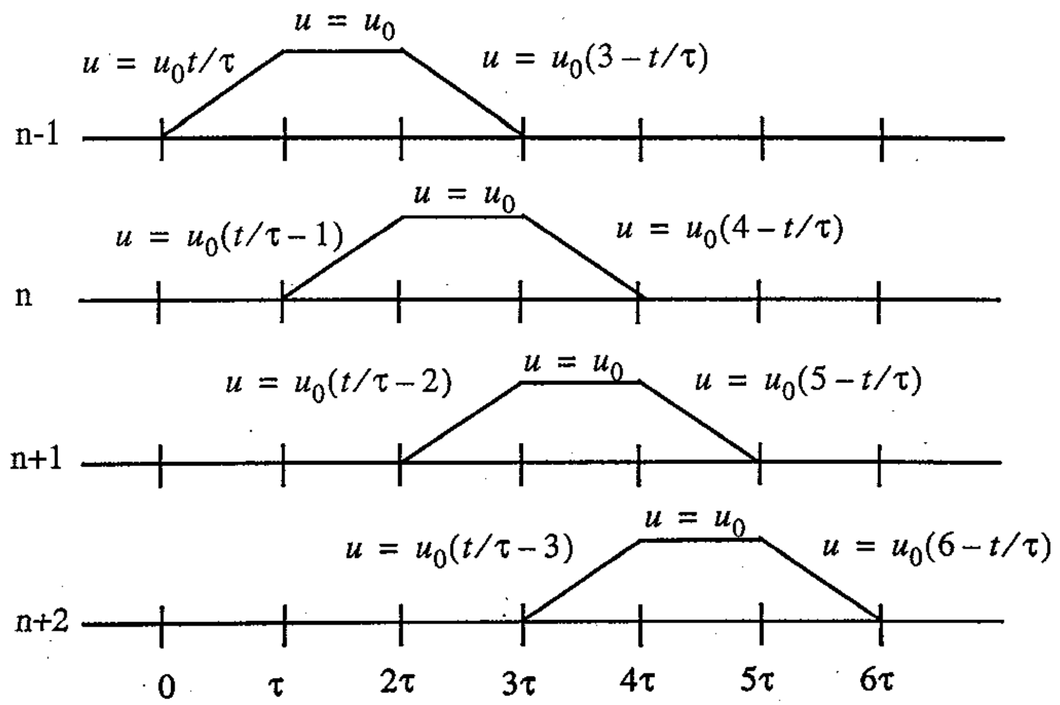

Figure 6.4. Periodic Jet Discharge Used to Simulate Rotating Jet. Each nozzle computational cell experiences velocity ramp up, constant velocity, then velocity turndown. Flow rates through cells are sequenced so that total jet momentum is constant with time.

Numerical tests were performed to ensure that the rotating jet logic functioned in an acceptable manner. Additionally, velocities were monitored near the tank wall to examine how the jet behaved far from the nozzle. Some velocity fluctuations were observed near the tank walls that had the same frequency as the discretized rotation. These fluctuations are believed to be caused by the somewhat impulsive (as opposed to continuous) nature of the rotation scheme. The effect of these high-frequency fluctuations was believed to be small because their relative magnitudes were found to be only a few percent of mean velocities.

6.3.3 Particle Transport Models

Several particle transport processes could potentially be important in the 1/12-scale uniformity mixing experiments. It was important to identify and model the essential features of the most fundamental processes to accurately simulate the overall mixing. Particle transport processes thought to be of potential significance were:

- particle settling
- particle convection
- turbulent diffusion
- buoyancy effects
- deposition of particle on floor
- erosion of particles off floor
- transport of particles on floor.

TEMPEST treats particle settling according to the Stokes settling law given by

$$v_s = g\, d_p^2\, (\rho_s - \rho_f)/18\, \mu \tag{6.1}$$

where g is the gravitational constant, d_p is the particle diameter, ρ_s is the particle density, and ρ_f and μ are the fluid density and viscosity, respectively. Hindered settling caused by finite particle concentrations was modeled in TEMPEST by applying a factor to Eq. (6.1) that depends on local particle concentration.

Particle convection in the TEMPEST program is handled by assuming the particle moves with the same speed as the local fluid (with the exception of the added gravitational settling component). This implies there are no slip or transient accelerations between the particles and the fluid. Turbulent diffusion can be treated by specification of a "turbulent Schmidt number"; however, it has been found through experience that numerical diffusion is sufficient to diffuse particle concentrations sufficiently without explicitly solving the turbulent diffusion equation.

Buoyancy effects are normally handled by allowing the gravitational body force to be dependent on local particle concentration. In this way, concentration gradients can lead to induced flows when particle densities differ from fluid densities, hence coupling fluid and particle motions. It was speculated for the 1/12-scale experiments, and later confirmed, that there would be enough mixing that concentration gradients within the tank would be small, thereby minimizing these particle/fluid interactions. Therefore, it was determined that the velocity calculation could be performed independent of particle concentrations.

Modeling the erosion and deposition of solids on the tank floor was found to be a challenging undertaking. Historically, much of the research pertaining to the erosion of settled solids has been in the field of hydrology, where transport of silt and sediment in rivers has been of interest. Expressions to determine the erodibility of solids are usually formulated differently for cohesive and noncohesive sediments. The S1 and S3 simulants clearly produced noncohesive sediments because particle sizes were large. Onishi (1993) summarized the comparisons of 23 different formulas used to predict erosion and deposition of solids. He recommended a widely used expression originally suggested by Partheniades (1962), which gives a relationship between erosion rate and fluid shear stress in the form

$$m_e = E\, (\tau_f/\tau_e - 1) \quad \tau_f > \tau_e \tag{6.2}$$

where τ_f is the shear stress exerted on the sludge by the fluid and m_e is the mass flux of solids away from the sludge layer. The terms E and τ_e are the erodibility and critical shear stress for erosion, respectively. These are empirical constants that must be determined for a given settled solids layer or sludge. To determine the net mass transport of solids into the fluid, Eq. (6.2) must be integrated over the area where erosion is occurring. A similar expression for the solids deposition flux to the floor (or, for example, a river bed) caused by particle settling was suggested by Krone (1962). This relation has the same form as Eq. (6.2) and is given by

$$m_d = U_s\, \Phi_s\, (1 - \tau_f/\tau_d) \quad \tau_f \leq \tau_d \tag{6.3}$$

where U_s is the particle settling velocity, Φ_s is the species mass fraction, and τ_d is the critical shear stress for deposition that must be determined from measurements for a given sludge material.

Equations (6.2) and (6.3) are used in TEMPEST with a logical subroutine that accounts for mass accumulating and leaving the floor. The model assumes that mass loadings are light, so no significant piling occurs, and the boundary condition on the tank floor remains a horizontal no-slip condition. TEMPEST computes the settling velocity, mass concentration, and floor shear stresses automatically. However, the subroutines do require particle size (for computing settling velocity), erodibility, and the two critical shear stresses to be specified. It was therefore necessary to determine these parameters with some accuracy to perform the simulations.

6.3.4 Determining Critical Particle Data

As mentioned, particle sizes, critical shear stress for erosion, critical shear stress for deposition, and erodibility needed to be specified for the two simulants considered. Particle size distributions were obtained from particle size analysis performed on bottled samples of simulant at initial and equilibrium conditions. Particle size distributions were obtained for cases S1-100, S1-75, S1-50, S3-100, and S3-50. These size distributions were converted to volume distributions, assuming spherical particles. A typical volume fraction distribution is shown in Figure 6.5. This particular example was from case S3-100. The sample indicated that there were significant fractions of particles from 1 to 20 μm with the mean around 5 μm. For the simulations, these distributions were approximated by a finite number of particle size "bins," as shown in Figure 6.5. For the case shown, 8 bins were chosen, and volume fractions and average particle sizes were assigned to each. Choosing an appropriate number of bins was an important factor in developing the particle transport model in TEMPEST because the simulation time is approximately

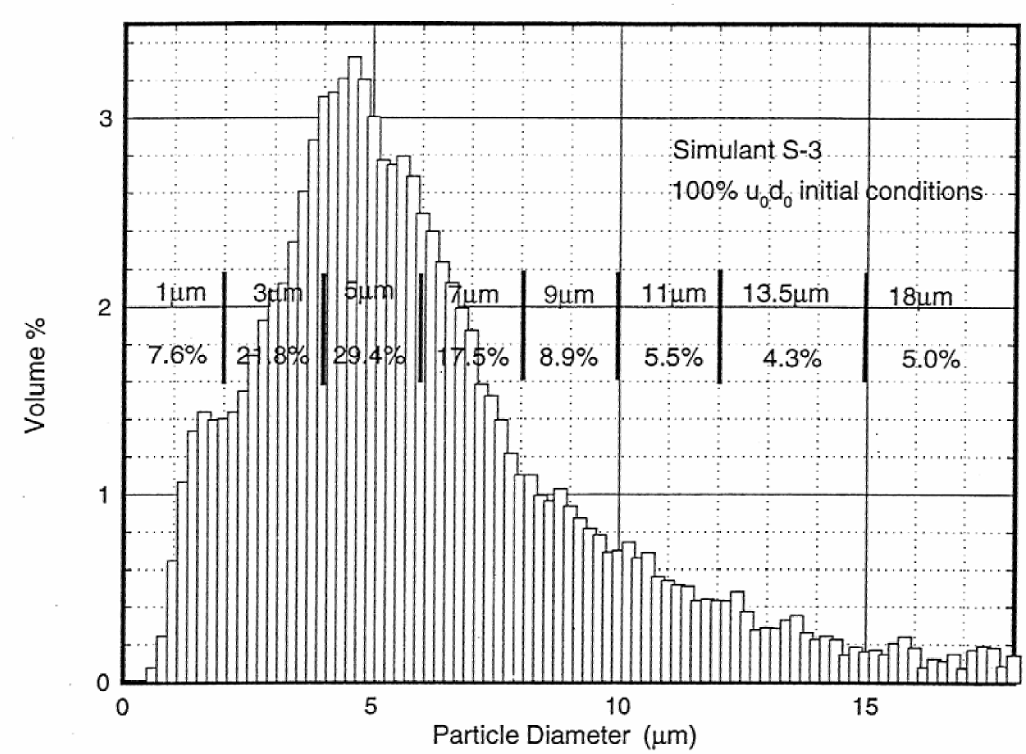

Figure 6.5. Example of Particle Size Binning. A continuous size distribution is approximated by a finite number of particle sizes.

proportional to the number of species, or particle size classes considered. It was believed, however, that size-dependent particle transport (settling, erosion, and deposition) would be present in the 1/12-scale experiments. This was found to be the case. For the S1 tests 5 particle sizes were used, while 8 were used for the S3 cases.

Determining the critical shear constants required by the erosion and deposition models in TEMPEST was a challenging undertaking. While there is a theory that predicts these parameters based on particle size, density, and other solids properties, there is no general method that has proven acceptable. A method was devised to estimate these parameters for simulants S1 and S3. The method involved the use of a small, bench-top jet apparatus consisting of a small jet nozzle oriented horizontally and located just above the floor of a 20-gallon rectangular aquarium. Experiments proceeded in two ways. First, all the solids in a given simulant were allowed to settle to the bottom of the bench-top tank. The jet was then turned on and the erosion of the settled layer at the tank floor was observed over time. This produced an effective cleaning radius, which was a function of time. The second approach was to run the jet with all the solids fully suspended and then record the settling pattern on the tank floor.

To use this data to estimate the critical shear constants, a TEMPEST simulation was performed for the identical geometry. The simulation was for fluid only, with fluid density and jet velocity matched to the experiment. Once in steady state, shear stress distributions were computed for the tank floor. The critical shear stress for erosion was determined by the predicted floor shear stress at the same location as the experimental cleaning radius. This critical shear stress was assumed to be for the largest particle, and values for smaller particles were obtained by scaling.

The erodibility constant was obtained by applying Eq. (6.2) and noting the mass flux (rate of change of settled layer thickness) from the bottom of the tank after measuring. This computed erodibility was assumed to be an average value for all particle sizes. Because the TEMPEST program treats each particle size class separately, erodibility constants were assigned to each class by volume fraction weighting, so the total erodibility was equal to the average measured value.

The experiments did not provide a way to directly measure the critical shear stress for deposition. However, the cleaning "footprint" was larger for the case where all the solids were initially suspended than for when all the solids were initially settled. This implied that the deposition stress was somewhat less than the erosion stress.

6.4 Case S1 and S3 Results

6.4.1 Simulation Methodology

Five test cases were simulated: S1-100, S1-50, S1-25, S3-100, and S3-50. The trailer after the simulant number refers to the percent of full nozzle discharge, U_0D_0. There were several elements to each of the simulations. First, fluid-only simulations were performed. Jet velocities were matched to experimental conditions, and multiple jet revolutions were computed. These simulations were carried out until velocities throughout the tank were found to be periodic in time. This was generally accomplished in five complete revolutions of the jet. This aspect of the simulation corresponded to the initial fully mixed condition in each of the test cases. Once this condition was achieved for each test case, all the velocity data were recorded to file for one complete mixing cycle. The next step simulated the beginning of a mixing test. The entire computational domain was initialized with a uniform mass concentration that corresponded to the experimental fully mixed concentration. The simulation proceeded using a special "recycle" option in the TEMPEST program, which periodically read in the stored velocity data from the previous step. During this aspect of the simulation, only particle transport equations were solved because velocity data had already been computed. These simulations continued for a simulated time equal to the time for equilibrium in the experiments. The simulations took approximately 2 to 3 days of real time for every day simulated; thus, many of the simulations took several weeks. Particle concentrations were monitored and recorded in time at locations corresponding to the locations of the ultrasonic concentration sensors.

6.4.2 Simulation Results

The results of the simulations are shown in Figures 6.6 and 6.7, corresponding to simulants S1 and S3, respectively. Shown in each plot are monitored total mass concentrations (wt%) versus time for different values of U_0D_0. The concentrations of individual particle size bins are also shown. The plots are arranged so the time scale (days) is consecutive for each simulation. One of the findings of the TEMPEST simulations was that spatial variations in concentrations were insignificant (less than 1% relative variation). Therefore, the particular location of a monitor cell is not noted in the figures. The computations were carried out for a simulation time approximately equal to the time to reach equilibrium found in the experiments. Initial conditions for the simulations were based on estimated initial mass concentrations in the experiments. More accurate values for the experimental initial conditions were determined after completing the simulations and thus differ somewhat. The simulated results are compared with concentrations taken from analysis of bottle samples.

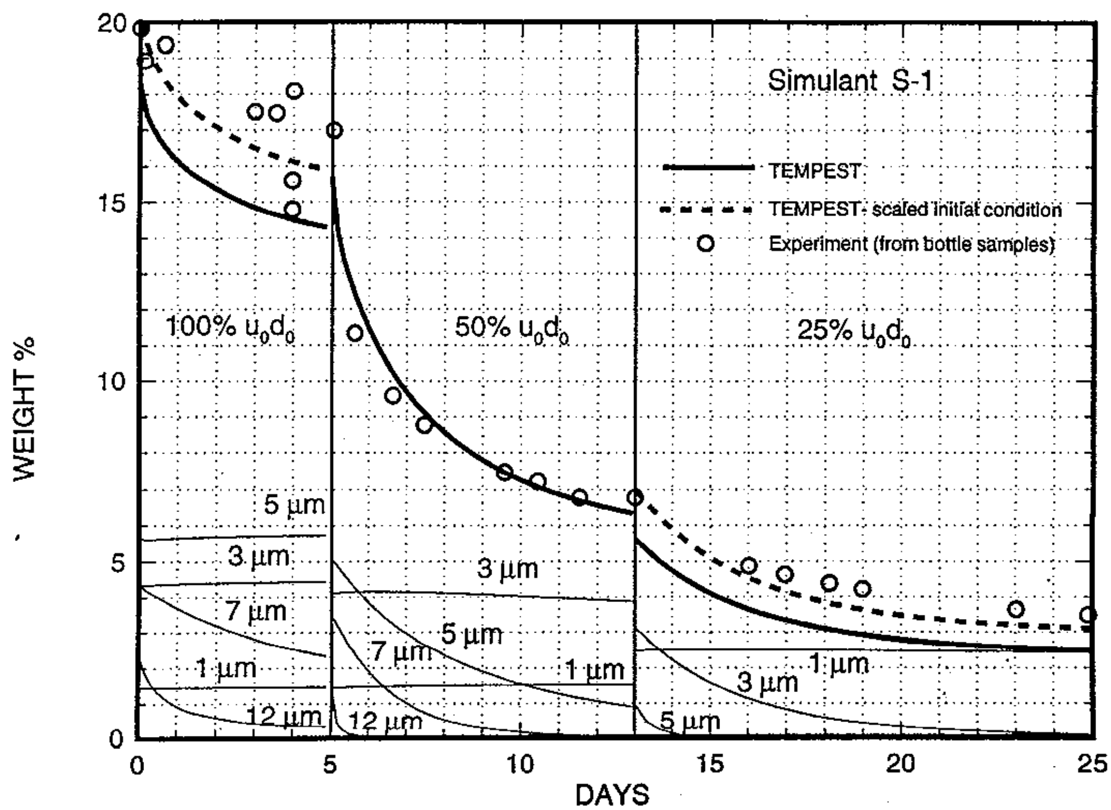

Figure 6.6. TEMPEST Results for S1 Simulant Test and Comparison with Experimental Results

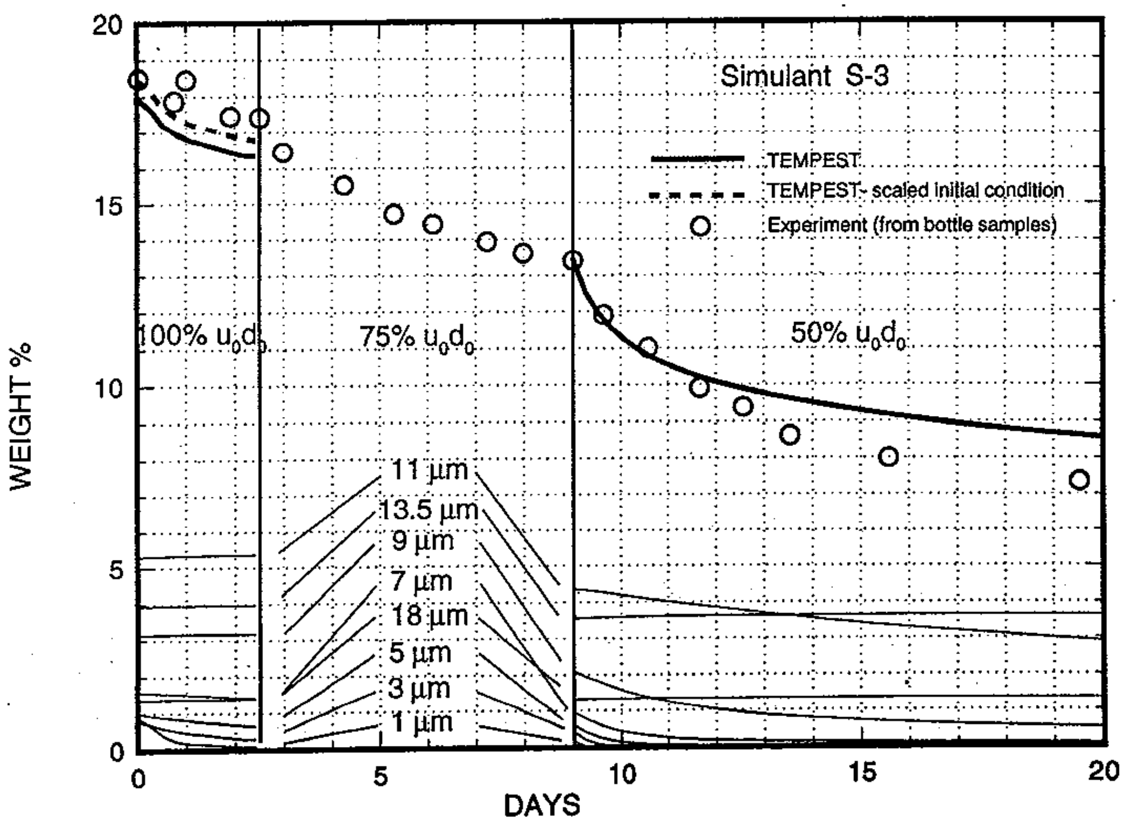

Figure 6.7. TEMPEST Results for S3 Simulant Test and Comparison with Experimental Results

Figure 6.6 shows that TEMPEST simulated the concentration decay for the S1 experiments quite well. For these simulations, particles were assumed to be distributed in one of five bins ranging from 1 to 12 μm. The dashed lines in the figure are the TEMPEST results scaled up to account for the fact that, in some cases, experiment and simulation had slightly different initial, fully mixed concentrations. The TEMPEST model clearly captures the basic decay trend for each of the U_0D_0 values. For each value of U_0D_0, the computed concentrations are still decaying somewhat upon reaching the experimental time for equilibrium. With corrections for differing initial conditions, however, concentration values are very close.

Figure 6.7 shows that TEMPEST also performed quite well in simulating the S3 experiments. For these simulations, eight particle size bins were used, ranging from 1 to 18 μm. The equilibrium concentration was underpredicted by about 1% for the 100% U_0D_0 and overpredicted by about 1.5% for the 50% U_0D_0. Evidently, there was no benefit to increasing the number of particle bins above that used in S1 simulations.

These simulations demonstrate that TEMPEST has great potential application to modeling jet mixing of liquid/solid systems where particle settling, erosion, and deposition are important. These results represent a first attempt at developing an accurate and robust computational model with diverse applicability. Additional improvements, testing, and validation will be required to fully refine the model.

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Appendix A

Ultrasonic Probe

Appendix A – Ultrasonic Probe

A.1 Introduction

The ultrasonic probe system, consisting of 3 wt% solids sensor pairs, was used to monitor the weight percentage of a slurry. This probe is shown in Figure A.1. The proof-of-principle experiments have been published by Greenwood et al. (1993). The ultrasonic probe measures the attenuation of the ultrasound as it travels from a send transducer through a slurry to a receive transducer, where the two transducers are separated by a distance of 4 inches. A sinusoidal voltage of the desired frequency is applied to the send transducer to produce the ultrasound. The attenuated ultrasound produces a sinusoidal voltage in the receive transducer, and the maximum voltage or amplitude is recorded. When the density of the slurry increases, the amplitude decreases.

To measure the wt% of a given slurry, the probe must be calibrated. The first step is to place the probe in water, because the attenuation is very small, and measure the amplitude (V_0) of the received signal. This serves as a reference point. Add the particulate to the water and measure the amplitude, V. The same

Figure A.1. Ultrasonic Sensor Measures wt% Solids in Real Time formula for the slurry is used in the calibration experiments and for the 1/12-scale experiments. The wt% of the slurry is determined by weighing it. The measurements are repeated for various weight percentages. A graph of ln (V/V_0) versus the volume fraction at a given frequency is a straight line. Once the probe is calibrated in this way, a measurement of voltages V_0 and V will yield the volume fraction or the wt%.

A.2 Description of the Electronics

The tone burst, produced by the FG504 function generator and the transducer evaluation module, passes through the Matec attenuator box, as shown on the schematic diagram. This reduces the maximum voltage of the tone burst so that the voltage is less than 1 V peak-to-peak. This is an acceptable level for the ENI 2100L amplifier. The Matec attenuator box must be set no lower than 28 dB. The output from the ENI amplifier is sent to the three send transducers, A, C, and E. The ultrasound passes through the slurry and strikes the receive transducers, B, D, and F, producing a voltage. Each received signal is amplified by an MR101 receiver that has a gain of 100, which is reduced by pushing in the dB buttons. The amplified signal is obtained at the "Scope" output on the MR101.

Because the computer cannot digitize a signal of such a high frequency, the Scope output of the MR101 is fed into the MD702 peak detector (RF input). The MD702 detector analyzes at the RF signal within a certain window, finds the largest (or peak) voltage, and outputs a DC voltage. This DC voltage can be digitized by the computer and stored. The output of each MD702 peak detector is sent to the computer.

To set the window on the MD702 peak detector properly, the input RF signal and the window are viewed by sending the signal from the monitor output of the MD702 to an oscilloscope. The window is adjusted by the "delay" and "gate" of the MD702.

The dB buttons on the Matec attenuator box and the dB buttons on the three MR101's can be adjusted to make the signal on the computer screen less than 10 V. For water the Matec attenuator box is set to about 42 dB and the three MR101's to about 20 dB. The purpose of the HP8012B pulser is to shape the pulse sent to the MD702 detector and to eliminate high points at the beginning and end of the tone burst.

When recording data on the computer, the attenuation on the Matec attenuator box must be recorded and the attenuation buttons pushing in on the three MR101's must be recorded so that measurements are made by comparing with the signals obtained when the probes are immersed in water. Therefore, how the signal is amplified, compared with water, is very important.

A.3 Calculations to Determine the Weight Percentage

Measurements were carried out in the laboratory to determine the wt% of a given slurry when the voltage on the receive transducer was measured. We found a straight-line relationship for the quantity $\ln(V/V_0)$ versus wt%, where V_0 is the voltage measured for pure water. The equations are as follows:

Minusil-40 in water wt% = -7.851 ln (Vadj) + [7.851 ln V_0 - 2.575]
Minusil-10 in water wt% = -4.091 ln (Vadj) + [4.091 ln V_0 - 1.526]
Minusil-40 in sugar water wt% = -7.335 ln (Vadj) + [7.335 ln V_0 -1.697]
Minusil-10 in sugar water wt% = -5.215 ln (Vadj) + [5.215 ln V_0 - 3.373]

The voltage, V_0, must be determined by placing all three probes in water and determining the voltage for a given frequency, which is 2 MHz currently. The attenuator settings on the Matec attenuator box and on the three MR101 receivers must be recorded. There will be a different voltage for each probe, resulting in a slightly different equation for each one.

The voltage Vadj is an adjusted voltage because the attenuator settings may have one set of values for the water calibration and another set when data are being recorded. An adjusted voltage must be used to compensate for the different attenuator settings. That is, the voltage Vadj is the voltage that the receiver would have recorded if the dB settings had been the same as for water. Whenever the attenuator settings are changed, the constants called CP1, CP2, and CP3 must be changed in the computer. For example, for the low probe, Vadj = CP1 * (voltage recorded by probe 1).

The sample data sheet in Section A.4 shows how the constants CP1, CP2, and CP3 were obtained from the dB settings on the MR101s and the Matec attenuator box. After the water calibration has been carried out and the three values of the voltage V_0 determined, the quantity in the square bracket for a given slurry formula is calculated and entered into the computer.

A.4 Sample Data Sheet

Revision: April 20, 1994

THE dB BUTTONS ON THE MATEC ATTENUATOR BOX MUST NOT BE SET LESS THAN 25 dB. THE NORMAL RANGE IS BETWEEN 28 dB AND 42 dB, BUT FOR VERY DENSE SLURRIES THE MATEC ATTENUATOR BOX CAN BE SET TO VALUES BETWEEN 25 AND 28 DB.

To calculate the wt% we make calculations relative to water. The data for water (or sugar water) and the data that must be recorded for a slurry are shown in the following data table.

Data Table

Matec Atten.	Probe 1 Left MR101	Probe 2 Middle MR101	Probe 3 Right MR101	Voltage Probe 1 2 MHz	Voltage Probe 2 2 MHz	Voltage Probe 3 2 MHz	
	dB	dB	dB	dB	volts	volts	volts
water	42	15	16	16	7.425	6.2597	7.1672
slurry	H=	J=	K=	M=			

Whenever the dB buttons on MR101 and/or Matec attenuator box are changed, these values (H, J, K, and M) must be recorded. Also, the calculation of the wt% requires that three constants be entered into the computer program to determine the adjusted voltages. These three constants (CP1, CP2, and CP3) must be calculated and changed the computer code. The data is recorded as follows. Note that DBP1, DBP2, and DBP3 will be negative numbers. CP1, CP2, and CP3 will be less than 1.0 (usually).

Filename= ___________________________
DBP1 = H + J - 57 = ____________
DBP2 = H + K - 58 = ____________
DBP3 = H + M - 58 = ____________
ICON
Vadj1 a = CP1, CP1 = 10(DBP1/20) = _____________
Vadj2 a = CP2, CP2 = 10(DBP2/20) = _____________
Vadj3 a = CP3, CP3 = 10(DBP3/20) = _____________

The wt% was calculated using a frequency of 2 MHz, which corresponds to a ramp voltage of 4.91 V. The computer calculation must be checked to ensure that the limits are set so that values approximately equal to 4.91 V are obtained. The three voltages for water (or sugar water) have already been entered into the computer calculation. Examination of previous data for pure water and for sugar water shows that the value of V_0 is the same for water and for sugar water.

A.4 Computer Evaluation of the Weight Percentage

The frequency of the toneburst generator is swept between 0.4 and 3.6 MHz and produces a ramp voltage that is directly proportional to the frequency. The ramp voltage is recorded. The lowest value of the ramp voltage corresponds to a frequency of 0.4 MHz, and the highest to a frequency of 3.6 MHz. For example, the lowest voltage might be 0.086 V and the highest 9.655 V. Consider a graph of the ramp voltage versus frequency, plot these two points, and draw a straight line between them. The equation is given by: ramp voltage = 2.990 f - 1.109.

For a frequency of 2 MHz, the ramp voltage is 4.871 V in this example. The following is a summary of the steps for the computer calculation of the wt%:

1. Calculate the values of CP1, CP2, and CP3 based upon the attenuator setting on the MR101's and the Matec attenuator box using a hand-held calculator and enter into the computer.
2. Enter the voltage V_0 for each probe, which is obtained when the probe is immersed in water.
3. Obtained the voltages for each probe (VMEAS1, VMEAS2, and VMEAS3) for a frequency of 2 MHz by searching for the appropriate ramp voltage corresponding to 2 MHz and storing the three voltages.
4. Calculate the values of VADJ1, VADJ2, and VADJ3 using VADJ1 = CP1 * VMEAS1, and do the same for the other two probes.
5. Calculate the weight percentages based on the formulas obtained from the calibration experiments.

A.5 Transformation Equations

The transformation equations used by the data acquisition system (DAS) to convert the receiver voltage to wt% solids were determined via the calibration procedure discussed in Section A.3. The calibration procedure used Minusil-10 and Minusil-40 directly from the bags in which the material was shipped. Therefore, the particle distribution was unchanged for the various wt% mixtures used for the calibration of the probe.

During the uniformity tests, the larger, heavier particles settled first, resulting in the average particle diameter of the suspended mixture being reduced with each drop in the mixer pump flow rate. Therefore, the calibration mixtures had particle distributions that differed from those achieved at each equilibrium condition achieved during testing. This phenomenon resulted in the ultrasonic probe measuring concentrations that varied from those measured through bottle sampling.

Using the bottle samples taken during the uniformity tests, a post calibration analysis was performed. This post-calibration developed transfer functions for converting the measured wt% to a corrected wt%. However, because the particle distribution was constantly changing throughout the tests, more than one transfer function is required for each probe for a given simulant.

The transfer functions used for each simulant are presented in Sections A.5.1 to A.5.4. The original transfer functions refer to those determined during pretest calibrations that were employed by the DAS. The correction functions refer to those obtained from the post-test calibration analysis that converts the measured data to the final values. The correction functions include wt% ranges for which the functions are applicable.

In the following sections:

- Vadj is as defined in Section A.3.
- wt%DAS = wt% solids measured during testing using the transfer functions determined from the pretest calibration of the sensors.
- wt%CR = corrected wt% solids.

A.5.1 Simulant S1

Sensor Position	Original Transfer Function
Low	wt%DAS = -4.091 ln VADJ + 6.495
Middle	wt%DAS = -4.091 ln VADJ + 6.648
High	wt%DAS = -4.091 ln VADJ + 6.642

Correction Functions Low Probe:

wt% Range	Transfer Function
0-11.1	wt%CR = 0.774 wt%DAS + 1.7988
11.1 -16	wt%CR = -30.175 + 222.056 $(0.008047 + 0.0022\ \text{wt\%DAS})^{0.5}$
16-21	wt%CR = wt%DAS

Correction Functions Middle Probe:

wt% range	transfer function
0-11.1	wt%CR = 1.0 wt%DAS - 2.88e-6
11.1 -16	wt%CR = -64.442 + 43.9426 $(0.015918 + 0.271\ \text{wt\%DAS})^{0.5}$
16-21	wt%CR = 1.2372 wt%DAS - 1.77074

Correction Functions High Probe:

wt% range	transfer function
0-11.1	wt%CR = 0.7734 wt%DAS + 1.684
11.1 -16	wt%CR = -30.175 + 222.056 $(0.007719 + 0.0022\ \text{wt\%DAS})^{0.5}$
16-21	wt%CR = wt%DAS

A.5.2 Simulant S2

Sensor Position	Original Transfer Function
Low	wtDAS% = -7.851 ln (Vadj) + 14.2511
Middle	wtDAS% = -7.851 ln (Vadj) + 13.4493
High	wtDAS% = -7.851 ln (Vadj) + 12.0647

Correction Functions Low Probe:

wt% range	transfer function
0-9.3	wt%CR = 0.9189 wt%DAS - 1.841
9.3-10.5	wt%CR = 1.8630 wt%DAS - 10.64
10.5-12.6	wt%CR = 0.7713 wt%DAS + 0.8675
12.6-21	wt%CR = 2.0970 wt%DAS - 15.80

Correction Functions Middle Probe:

wt% range	transfer function
0-10	wt%CR = 0.9405 wt%DAS - 2.501
10-14	wt%CR = 0.6523 wt%DAS + 1.909
14-21	wt%CR = 1.5390 wt%DAS - 7.194

Correction Functions High Probe:

wt% range	transfer function
0-9.7	wt%CR = 0.9358 wt%DAS - 2.249
9.7-10.6	wt%CR = 2.4290 wt%DAS - 16.70
10.6-11.8	wt%CR = 1.1090 wt%DAS - 2.727
11.8-21	wt%CR = 1.1390 wt%DAS - 3.081

A.5.3 Simulant S3

Sensor Position	Original Transfer Function
Low	wtDAS% = -5.215 ln (Vadj)
Middle	wtDAS% = -5.215 ln (Vadj) + 6.1920
High	wtDAS% = -5.215 ln (Vadj) + 6.89802

Correction Functions Low Probe:

wt% range	transfer function
6-18	wt%CR = 5.989 - 0.05318 wt%DAS + 0.0403 wt%DAS^2

Correction Functions Middle Probe:

wt% range	transfer function
6-18	wt%CR = 3.360 + 0.5464 wt%DAS + 0.01703 wt%DAS^2

Correction Functions High Probe:

wt% range	transfer function
6-18	wt%CR = 3.0993 + 0.5644 wt%DAS + 0.01398 wt%DAS^2

A.5.4 Simulant S4

Sensor Position	Original Transfer Function
Low	wtDAS% = -7.335 ln (Vadj) + 14.0232
Middle	wtDAS% = -7.335 ln (Vadj) + 13.2741
High	wtDAS% = -7.335 ln (Vadj) + 11.9805

Correction Functions Low Probe:

wt% range	transfer function
0-12	wt%CR = 1.2245 + 0.3358 wt%DAS + 0.01692 wt%DAS^2
12-21	wt%CR = 0.7420 wt%DAS - 1.213

Correction Functions Middle Probe:

wt% range	transfer function
0-12	wt%CR = 1.1378 + 0.3169 wt%DAS + 0.01946 wt%DAS^2
12-21	wt%CR = 0.7840 wt%DAS - 1.665

Correction Functions High Probe:

wt% range	transfer function
0-12	wt%CR = 1.0762 + 0.3761 wt%DAS + 0.01260 wt%DAS^2
12-21	wt%CR = 0.6785 wt%DAS - 0.7383

A.6 Reference

Greenwood MS, J Mai, and MS Good. 1993. *J. Acoust. Soc. Am.*, Vol. 94, p. 908.

Appendix B

Data Summary Tables for Simulant S1

Appendix B – Data Summary Tables for Simulant S1

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
	2/2	13:55								5.18	5.85	3.19	B1M
												B1M	μ cP 1.50 ν mm^2/s 1.3559 Std. Dev. 0.0 ρ g/cm^3 1.1041
Mixing >100% U_0D_0													
			Probe at position 1, N										
			U1L	U1M	U1H								
S1-40	2/11	10:18											Mixing with air lance.
		10:27					B1M 15.3 15.44 14.7						B1M 1.1053 g/cm^3 1.1064 g/cm^3 1.1005 g/cm^3
		10:47											Completed air lancing
Mixing at 100% U_0D_0													
		11:55								20.9			Reduced flow.
		13:34											Stopped log.
S1-41		13:34											Started log. Data rate 1/min.
		14:09											Corrected setting for ultrasonic probe.
	2/11	14:20								5.39	6.18	3.73	B1M. Initial particle size measurement prior to start of tests.
												B1M	μ cP 1.61 ν mm^2/s 1.4602 Std. Dev. 0.0 ρ g/cm^3 1.1041
	2/13	10:25							17.8				Stopped log. Flow rate dropped.

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	**wt% mid**	**wt% high**	**wt% low**	**wt% mid**	**wt% high**		**Med-ian**	**Mean vol**	**S.D. vol**	
S1-42		10:25							17.5				Started log.
		11:12	14.82	15.33	15.50				17.7				Reset gate for ultrasonic signal.
	2/14	8:12	14.92	15.22	15.73				17.55				
		10:00	14.86	15.11	15.56				17.6 to 18.86				Stopped log.
S1-43		10:28											Started log.
		11:18							21				Turned pump off and on. Flow rate increased to 21 gal/min.
		11:25	14.79	15.06	15.76								
		14:35	14.92	15.21	15.68								
		15:14											Pump experienced auto shut off.
		15:49											Stopped log. Remixed stimulant.
Remix at >100% U_0D_0													
S1-44	2/15	11:24											Started log.
Mixing at 100% U_0D_0													
		11:54	16.17	16.66	17.32				20.88				
		12:00								5.03	5.34	2.59	B1M
													μ cP, ν mm^2/s, Std. Dev., ρ g/cm^3 1.55, 1.3907, 0.06, 1.117
		13:15											Stopped log.
S1-45		13:54											Started log.
		15:10			16.92			B1H 19.85					B1H 1.117 g/cm^3

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
	2/16	7:30											Pump knocking. Turned pump off and on and injected water for 2 s to back flush inlet line.
		10:30											Pump knocking. Turned pump off and on and injected water for 2 s to back flush inlet line.
		10:43											Stopped log.
		10:45								4.82	5.47	3.04	B1M
												B1M	μ cP: 1.53 ν mm^2/s: 1.3559 Std. Dev.: 0.0 ρ g/cm^3: 1.131
S1-46		10:48											Started log.
		11:30			16.11			B1H 18.59					B1H 1.131 g/cm^3
		23:15											Received call, pump automatic shut down.
		23:30											Reset power. Added water to flush inlet.
	2/17	0:05											Could not restart pump. Pump electrical problem later diagnosed and fixed.
Remix at >100% U_0D_0													
S1-47	2/19	14:47							34				Mix tank at 34 gal/min. Fluid level 32 in.
		15:19	16.5	17.1	17.6				21				
		16:42											Stopped log.

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
Mixing at 100% U_0D_0													
S1-48	2/19	17:04	15.96	16.27	16.79				21				Started log. $T_{ambient}$ questionable
		17:08								5.41	6.19	3.41	B1M
												B1M	μ cP, ν mm^2/s, Std. Dev., ρ g/cm^3 1.43, 1.2864, 0.06, 1.1152
		17:30			16.65			B1H 17.95 19.99					B1H 1.1044 g/cm^3 B1H 1.1260 g/cm^3
	2/20	9:57	15.61	15.71	16.27								Stopped log.
S1-49	2/20	10:04											Started log.
		10:22			16.32			B1H 19.50 19.78					B1H 1.1198 g/cm^3 B1H 1.1228 g/cm^3
		20:16							16-17				Pump low flow rate call, pump knocking.
		20:30							21				Turned pump off and restarted: flow rate rose to 21 gal/min.
	2/21	13:42	14.93	14.73	15.47				18.5				Pump knocking.
		13:46							20.7				Turned pump off and on. Flow rate rose to 20.7 gal/min.
		13:49											Stopped log.
S1-50		13:51											Started log.
	2/22	9:30	15.17	15.31	15.81								Turned pump off to clear air from line: S1-50-temp file not started.

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S1-51													Started log.
		14:07											Turned pump off and on.
		14:37			15.06			B1H 17.72					B1H 1.124 g/cm^3
	2/23	8:20	15.16	15.25	15.75				21				Stopped log. Turned pump off to clear air from line.
S1-52		9:11											Started log.
		13:25							20.8				
		15:17			15.66			B1H 17.72					B1H 1.124 g/cm^3
	2/24	15:05											Stopped log.
		16:21											Sporadic ultrasonic probe signals on computer; no sign of error in ultrasonic electronics by looking at HP scope signals. Pulled ultrasonic probes and cleaned surfaces. Found grease residue on tree and probes. One cable loose on middle probe; resealed with silicone vacuum grease and put back in tank.
													Determine elevation of maximum velocity. Locate EM velocity meter at W, R=23 in., height=2 in. Solids depth=1.5 in.
Equilibrium 100% U_0D_0													
			Probe at position, 1, N										
			U1L	U1M	U1H								
S1-53		17:05	15.27	15.74	16.25								Started log.
		17:22			16.23			B1H 14.86					B1H 1.0999 g/cm^3
		17:32											Stopped log

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S1-54		17:36	Probe at position 2, E										Started log.
			U2L	U2M	U2H								
		17:50			16.21			B1H 15.78					B1H 1.1069 g/cm^3
		18:02			16.22			B1H 18.26					B1H 1.1262 g/cm^3
		18:13											Stopped log.
S1-55		18:19	Probe at position 3, S										Started log.
			U3L	U3M	U3H								
		19:18											Stopped log.
S1-56		19:23	Probe at position 4, W										Started log.
			U4L	U4M	U4H								
		19:25	15.28	15.65	16.25								
		19:30								4.63	4.88	2.25	B1H
										4.95	5.37	2.66	B1M
												B1M	μ cP: 1.47 ν mm^2/s: 1.3211 Std. Dev.: 0.06 ρ g/cm^3 Av: 1.1162
										4.93	5.36	2.71	B1L
		19:50											Probed tank to determine topography, lab book p. 81.
		20:04											Stopped log.
S1-57		20:10	Probe at position 1, N										Started log.
			U1L	U1M	U1H								

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
		20:16			16.31			B1H 16.85					B1H 1.1151 g/cm^3
		20:30			16.29			B1H 17.19 16.86					B1H 1.1178 g/cm^3 B1H 1.1152 g/cm^3
50% U_0D_0 Test													
		20:39							10.4				Flow reduced to 50% U_0D_0.
		21:40	15.32	15.54	16.22								Stopped log.
S1-58		21:45											Started log.
	2/25	8:34	12.99	12.83	13.44				10.4				Stopped log. Turned pump off to clear air, it was not experiencing any problems.
S1-59		8:45	12.81	12.75	13.46								
		13.53			12.50			B1H 11.13					B1H 1.0745 g/cm^3
		14:45											Changed DB settings without creating a new file. The file has data with two differing DB settings on it! Data from 14:45 to 14:50 not valid because settings were being changed.
		20:55	10.27	9.86	10.46								
		20:56											Stopped log. Stopped and restarted pump to clear air from lines.
S1-60		21:11							10.5				
	2/26	9:38			10.43			B1H 9.41 9.58 9.74					B1H 1.0602 g/cm^3 B1H 1.0625 g/cm^3 B1H 1.0614 g/cm^3

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		13:55			10.09			B1H 9.80					B1H 1.0651 g/cm^3
		14:48											Changed db settings by 2 dbs and changed them back immediately within 1 min.
	2/27	7:44											Stopped log. Stopped and restarted pump to clear air from lines.
		7:55			9.09			B1H 8.78					B1H 1.0579 g/cm^3
S1-61		9:06											Started log.
	2/28	10:18											Stopped log.
S1-62		10:40	7.91	7.37	8.04								Started log.
		15:45			7.89			B1H 7.94 8.10					B1H 1.0500 g/cm^3 B1H 1.0511 g/cm^3
	3/1	9:43	7.40	6.77	7.47								Stopped log.
S1-63		9:53											Started log.
		10:30			7.45			B1H 7.48 7.59					B1H 1.0468 g/cm^3 B1H 1.0476 g/cm^3
		15:51											Ultrasonic amp turned off.
		15:56											Ultrasonic amp turned on.
													See note in log book regarding probe positions, p. 86-87.
	3/2	9:09	7.28	5.66	7.11								Stopped log. Added EM 2 to data acquisition, EM2=2 in out from wall, 15 in. above floor.
		9:40			7.26			B1H 7.33					B1H 1.0458 g/cm^3

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		9:45			7.26			B1H 7.31					B1H 1.0457 g/cm^3
S1-64		11:56											Started log.
	3/3	10:10	6.99	5.28	6.79								
		10:34			6.79			B1H 6.93 6.84					B1H 1.0451 g/cm^3 B1H 1.0445 g/cm^3
		10:54		5.31			B1M 7.04						B1M 1.0458 g/cm^3
		11:13											Stopped log.
		11:17		6.61			B1M 6.95						B1M 1.0452 g/cm^3 Removed ultrasonic probe to check face of middle probe. Nothing was observed on any probe face.
S1-65		11:53											
		15:30											Pump stopped and restarted several times while logging.
		17:15	6.83	6.56	6.76								
	3/4	6:48	6.74	6.42	6.68								Concentration essentially uniform since 3/3 10:10.
		6:57											Stopped log.
Equilibrium 50% U_0D_0													
S1-66		7:01											Steady-state data position 1.
													Profile of tank bottom, p. 92 log book.
		7:42											Stopped log.
S1-67		7:50	Probe at position 2, E U2L	U2M	U2H								
		10:25											Stopped log.

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	**wt% mid**	**wt% high**	**wt% low**	**wt% mid**	**wt% high**		**Med-ian**	**Mean vol**	**S.D. vol**	
			Probe at position 3, S										
			U3L	U3M	U3H								
S1-68		10:31	6.72	5.34	6.63								Started log.
		11:16		5.32	6.77		B1M 6.77	B1H 6.81					B1H 1.0443 g/cm^3 B1M 1.0440 g/cm^3
		11:30											Stopped log.
			Probe at position 4, W										
			U4L	U4M	U4H								
S1-69		11:39	6.79	5.69	6.61								Started log.
													Measured wt% slurry at pos 3, 15 and 22.5 in. above bottom.
										2.20	2.35	1.08	B1H
										2.62	2.64	1.16	B1M
												B1M	μ cP: 1.27 ν mm^2/s: 1.2168 Std. Dev.: 0.06 ρ g/cm^3: 1.0440
		12:15								2.92	2.92	1.31	B1L
		12:18											Stopped log.
25% U_0D_0													
			Probe at position 1, N										
			U1L	U1M	U1H								
S1-70		12:28	6.77	6.18	6.62								Started log. Reducing flow to 25% U_0D_0.
		12:43											Pump stopped momentarily and restarted. Rerouted Krone 4-20 mA through junction box on north wall.

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
		15:24											Stopped log; stopped 10 s data acquisition. Tried to move EM1 to search for maximum velocity. It was stuck in the sludge layer.
S1-71		15:57	6.50	6.14	6.44				5.22				Sample rate 1 reading per min.
	3/5	14:18											Flow steady past 24 hr. Concentration decreasing.
		14:20											Stopped log.
S1-72		14:22											Started log.
	3/6	13:11	5.24	4.83	5.10				5.21				Flow steady past 24 hr. Steady decrease in wt%.
		13:13											Stopped log.
S1-73		13:14											Started log.
	3/7	9:41	4.85	4.45	4.75								Stopped log.
S1-74		9:44											Started log.
		15:05		4.09	4.55		B1M 4.60	B1H 5.22					B1H 1.0335 g/cm^3 B1M 1.0295 g/cm^3
	3/8	~11:0											Stopped log.
S1-75		11:00											Started log.
		11:20			4.3			B1H 4.71 4.88					B1H 1.0282 g/cm^3 B1H 1.0293 g/cm^3
	3/9	9:30											Stopped log.
S1-76		10:48											Started log. Logs backed up.
		17:30		3.10	3.71		B1M 4.56	B1H 4.43					B1H 1.0263 g/cm^3 B1M 1.0272 g/cm^3
	3/10	10:07											Stopped log. Probe positions changed. See p. 97 lab book.

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S1-77		12:38	3.63	3.25	3.53								Started log.
		13:10		3.09	3.52		B1M 4.40	B1H 4.29					B1H 1.02544 g/cm^3 B1M 1.02617 g/cm^3
	3/11	16:03											Stopped log.
S1-78		16:07											Started log.
		16:35	3.40	2.73	3.20								
		16:50		2.77	3.22		B1M 4.25	B1H 4.20					B1H 1.02486 g/cm^3 B1M 1.02513 g/cm^3
	3/12	8:25	3.36	2.78	3.15								Stopped log.
S1-79		8:27											Started log.
	3/13	13:07	3.09	2.48	2.91								Stopped log.
S1-80		13:10											Started log.
	3/14	10:35		2.37	2.75		B1M 3.82	B1H 3.86					B1H 1.02261 g/cm^3 B1M 1.02235 g/cm^3
		11:22	2.94	2.34	2.73								Stopped log.
S1-81		11:49											Started log.
	3/15	9:22		2.18	2.58		B1M 3.85	B1H 3.70					B1H 1.02157 g/cm^3 B1M 1.02202 g/cm^3
		10:22	2.77	2.20	2.57								Stopped log.
S1-82		10:53	2.73	2.14	2.55								Started log.
	3/16	10:46		1.96	2.44		B1M 3.62	B1H 3.74					B1H 1.02184 g/cm^3 B1M 1.02107 g/cm^3
		13:02	2.60	2.01	2.43								Stopped log. Backed up files.
S1-83		13:31											Started log.
	3/17	8:36		1.93	2.37		B1M 3.49	B1H 3.54					B1H 1.02051 g/cm^3 B1M 1.02023 g/cm^3
		9:06	2.55	1.91	2.36								Stopped log. Changed date and S1-83 to S1-84 before stopped logging.

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S1-84		9:13											Started log.
		11:13											Pump switched to hand. Flow disruption occurred. Due to work on the current loop the reading may be negative and low. The actual flow was not changing.
		11:29											Pump switched back to Auto. Flow disruption occurred.
	3/18	9:06		1.84	2.25		B1M 3.45	B1H 3.51					B1H 1.02035 g/cm^3 B1M 1.01995 g/cm^3
		10:37	2.40	1.78	2.24								Stopped log.
S1-85		10:44											Started log.
	3/19	15:00	2.32	1.73	2.16				5.34				
		15:01											Stopped log.
S1-86		15:02											Started log.
	3/20	17:00	2.32	1.71	2.10				5.30				Stopped log.
S1-87		17:01											Started log.
	3/21	6:27	2.36	1.73	2.14				5.40				Stopped log.
Equilibrium 25% U_0D_0													
			Probe at position 1, N										
			U1L	U1M	U1H								
S1-88		6:32											Started log. Steady-state readings position 1, every 10 s. Breaker to computers turned off after 8:30. Data was lost.
S1-88 restart		11:26											Started log; 10-s readings for ultra-sonics, 1 min readings for flow rate.
		11:30	2.25	1.66	2.06								
		13:27											Stopped log.

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
			Probe at position 2, E										
			U2L	U2M	U2H								
S1-89		13:34	2.22	1.67	2.05								Started log. Steady state data at position 2, E.
		13:45		1.67	2.22		B4M 3.49 3.41 3.32	B4H 3.34 3.38 3.52					B4M B4H 1.01924 1.02022 g/cm^3 1.01951 1.01967 g/cm^3 1.02042 1.01908 g/cm^3
		14:15								1.05	1.03	0.26	Slurry sample for particle size analysis at north R=18 in. 22.5 in. above floor.
		14:50		1.67	2.21		B1M 3.34 3.30 3.37	B1H 3.27 3.33 3.39					B1M B1H 1.01875 1.01922 g/cm^3 1.01919 1.01899 g/cm^3 1.01958 1.01940 g/cm^3
		15:00								1.07	1.05	0.28	B1M
												B1M	μ cP / ν mm^2/s / Std. Dev. / ρ g/cm^3 1.28 1.2516 0.0 1.01917
		15:11											Stopped log.
			Probe at position 3, S										
			U3L	U3M	U3H								
S1-90		15:24	2.25	1.67	2.16								Started log. Steady-state data at position 3 S. Middle ultrasonic probe initial reading 0.80. Pulled probe, inspected face, checked for loose cables. When reinserted it read 1.67.
		15:30	2.24			B4L 3.36 3.29 3.32							B4L 1.01935 g/cm^3 B4L 1.01892 g/cm^3 B4L 1.01912 g/cm^3

Table B.1. Data Summary: Test S1, Low-Viscosity, Small-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		15:45											Profiled north settled solids p. 104 lab book.
		16:00											Profiled west settled solids p. 104 lab book.
		16:10											Profiled east settled solids p. 104 lab book.
		17:10	2.22			B1L 3.37 3.21 3.19							B1L 1.01943 g/cm^3 B1L 1.01840 g/cm^3 B1L 1.01825 g/cm^3
		17:26											Stopped log.
		17:30								1.12	1.12	0.29	B1L
			Probe at position 4, W										
			U4L	U4M	U4H								
S1-91		17:33	2.22	1.64	2.06								Started log. Steady-state data at position 4, W.
		18:30											South settled solids profile p. 104 lab book.
		19:00	2.19	1.62	2.04								
		19:28											Stopped log. Completed steady state data.
S1-92		19:32											Started log. Ultrasonic probe at position 4, at slow sampling rate.
		14:00	2.1	1.54	1.94								Stopped log. Started draining tank.
		14:45											Finished draining tank. See lab book p. 106 for drawing of settled solids' surface contour.
Test Complete													

Appendix C

Data Summary Tables for Simulant S2

Appendix C – Data Summary Tables for Simulant S2

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
Mixing >100% U_0D_0													
	5/25		Probe at position 1, N										
			U1L	U1M	U1H								
		4:08											Low flow call, abrupt pump shut off from 20.9 gal/min. System not restarted.
		13:25				B1L 17.83	B1M 17.61	B1H 17.58					Took north particulate and density samples after air lancing for 30 min.
		13:30								20.18 20.83 20.46	22.14 22.21 22.08	13.59 13.90 13.61	Sample Conf ID Count Run B1H 100.00% 65934 #1 B1M 99.99% 71011 #1 B1L 100.00% 63633 #1
		14:05				B3L 17.67	B3M 17.48	B3H 17.21					Took south particle size samples after air lancing for 15 min. Particulate seems to settle without air lancing.
										15.49 17.32 12.31	17.64 18.75 15.92	12.21 12.08 12.21	Sample Conf ID Count Run B3H 100.00% 72308 #1 B3M 99.99% 73498 #1 B3L 99.99% 98264 #1
		14:50											Took viscosity samples after air lancing for 15 min.
												B4M B4L B4L	μ cP, ν mm^2/s, Std. Dev., ρ g/cm^3 1.75 1.5645 0.0 1.1190 1.75 1.5645 0.06 #1 1.40 1.2516 0.22 #2 #1 and #2 1.1205
													Checked ultrasonic probe calibration in water. L 2.25, M 2.22, H 2.27

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		15:30	15.96	16.03	17.81								Placed ultrasonics in tank. Air lanced again.
S2-1		15:42											Data recorded every minute. Ultrasonic readings are increasing because of air lancing.
		16:30											Removed pump bypass line. Started air lancing to resuspend particles.
		17:00											Stopped air lancing. Readjusted flow.
Mixing at 100% U_0D_0 (93% U_0D_0 is the initial maximum sustainable flow)													
		17:20							19.5				19.5 gal/min is the maximum sustainable flow. This is 93% U_0D_0. Pump pressure at 50 psi.
		17:50	15.09	14.65	15.90				19.6 to 20.3				Flow increasing slightly as particulate settles.
		18:05	15.07	14.62	15.05				19.9 to 20.4				
		21:16	12.79	12.60	12.57				20.23				Sharp drop in concentration over past 3 hrs. Past two hrs constant between 12.5 and 13 wt%.
		21:20											Stopped log.
S2-2		21:27											Started log.
		21:29	13.14	12.33	12.74				21.13				
	5/26	8:03	12.59	11.35	11.83				20.60				
		10:49	12.40	11.20	11.54				20.6				
		10:55	12.44	11.19	11.55	B1L 10.44	B1M 10.03	B1H 10.31					
		15:00	12.41	11.07	11.46				20.6				

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		20:17	11.83	10.72	11.01				20.8				
S2-3		20:20											Started log. Data recorded every 10 min.
		20:21	11.88	10.68	11.09				20.40				
	5/27	7:07	12.50	12.71	11.55				20.72				Over the past 10 hrs the concentration has been rising slowly with the highest concentration in the Mid position for the last 3 hrs.
		16:00	11.05	10.82	10.69				20.45				Transient through Mid position lasted ~5 hrs. Steady for last 8 hrs.
	5/28	17:54	12.61	13.16	11.51				20.47				Flow rate steady for last 12 hrs (amount visible on chart). 17 hrs ago concentration at Low and High increased to values shown here. Concentration at Mid has fluctuated much higher during the past 15 hrs. settling to this value for past 2 hrs.
		18:05	12.48	13.13	11.72	B1L 10.61	B1M 10.38	B1H 10.37					
	5/29	16:00	12.68	12.56	11.81				20.81				Low and high positions constant over last 40 hrs. Mid fluctuated wildly remaining between ~11.5 and 12.8 wt% for last 7 hrs. Two low flow spikes observed in flow rate. 1 hr ago ~15:00 at 5 gal/min. ~5 hrs ago ~11:00 at 10 gal/min.
	5/30	7:36	12.74	13.92	11.89				20.61				Mid probe erratic over last 12 hrs
		7:39											Removed probes and wiped faces. They looked clean, but a small amount of black deposit came off.

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
Equilibrium at 100% U_0D_0													
S2-4		7:43	Probe at position 1, N U1L	U1M	U1H								Date recorded every minute.
		10:15	12.68	13.13	11.93	B1L 10.55	B1M 10.31	B1H 10.62					
		10:16											Stopped log. Moved probe to position 2 east.
S2-5		10:20	Probe at position 2, E U2L	U2M	U2H								Started log.
		10:41	12.69	13.08	11.92	B2L 10.66	B2M 10.68	B2H 10.07				B2H B2M B2L	μ cP / ν mm^2/s / Std. Dev. / ρ g/cm^3 1.48 / 1.3907 / 0.06 / 1.0643 1.52 / 1.4254 / 0.06 / 1.0686 1.48 / 1.3907 / 0.06 / 1.0685
													1
		12:56	11.33	11.68	10.50				20.68				Observed concentration at position 2 has decreased steadily since probe was inserted. Left probe in place longer.
		15:22	9.91	10.80	9.38								Observed that pump oscillation stopped. Probably as the concentration started to decrease at position 2.
	5/31												Mixer pump chain had bound and come off the sprocket. Several contribution factors 1) drive sprocket had slipped down out of adjustment. 2) Pump sprocket had become tilted (it was not horizontal) because collar screws had backed out. To rectify the problem the chain and sprocket were realigned and screws and set screws were threaded with threadlock compound.

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
Remix at >100% U_0D_0													
		14:15	6.41	6.83	6.53								Started remixing stimulant.
		15:08	14.82	13.54	14.15								
Restarted test at 100% U_0D_0													
S2-6		15:28	Probe at position 1, N U1L	U1M	U1H								Started log.
		15:30											Reduced flow rate to 20.8 gal/min.
		15:40	15.68	14.85	15.63				19.5				
		21:23	12.65	11.87	12.26				19.48				
	6/1	7:45	11.39	10.93	11.06				19.40				Turned pump off and on to stop light knock.
		13:20											Turned pump off and on to stop light knock.
		13:22	11.40	10.97	11.06				19.80				
	6/2	7:45	11.38	10.93	11.09				19.40				
		12:00	11.29	10.95	11.02				19.10				
		15:35	10.59	10.87	10.91				19.10				
	6/3	7:25	10.39	10.72	10.66				18.90				
		11:45	10.39	10.80	10.65				18.79				
		13:05	10.41	10.81	10.65								
		13:25	10.40	10.82	10.64	B2L 9.12	B2M 8.93	B2H 9.03					
		13:45											Stopped log.

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
Equilibrium at 100% U_0D_0													
S2-7		13:49											Started log.
		14:00	10.83	10.87	10.67	B3L 8.92	B3M 9.02	B3H 8.95		8.81 6.49 6.52	12.22 9.22 9.07	9.58 7.44 6.82	Sample Conf ID Count Run B3H 99.99% 94509 #1 B3M 100.00% 91250 #1 B3L 100.00% 84451 #1
		14:30										B4M B4L	μ cP, ν mm^2/s, Std. Dev., ρ g/cm^3 1.65 1.5645 0.0 1.0565 1.58 1.4950 0.06 1.0572
													1.
		14:40											Started measuring contours of settled solids layer.
		14:56											Stopped log.
S2-8		14:59	Probe at position 2, E U2L	U2M	U2H								Started log.
		15:44	10.66	10.82	10.38	B1L 8.93	B1M 8.90	B1H 9.05		7.06 6.31 5.98	9.11 8.08 7.49	6.06 5.37 4.88	Sample Conf ID Count Run B1H 99.99% 44607 #1 B1M 100.00% 55870 #1 B1L 99.99% 47839 #1
		17:03											Stopped log.
S2-9		17:07	Probe at position 3, S U3L	U3M	U3H								Started log.
		18:00	10.31	10.67	10.67	B4L 9.05	B4M 8.94	B4H 9.04					
		19:45											Stopped log.

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S2-10		19:49	Probe at position 4, W										Started log.
			U4L	U4M	U4H								
		21:51											Stopped log.
		21:52	10.31	10.65	10.59				18.5 to 19.4				
		22:02	10.16	10.47	10.58				19				
75% U_0D_0 Test													
			Probe at position 1, N										
			U1L	U1M	U1H								
S2-11		22:21	10.09	10.49	10.47				15.4 to 15.9				Turned down flow to 75% U_0D_0 fast sampling rate.
	6/6	7:30	9.42	9.66	9.50				15.6				
		8:35											Stopped log. Switch to slow sampling rate.
S2-12		8:40											Started log at slow sampling rate.
		15:10	9.51	9.73	9.52				15.6				
		15:30	9.40	9.70	9.45				15.8				
	6/7	6:21	9.40	9.80	9.55				15.8				
		6:22											Stopped log.
Equilibrium at 75% U_0D_0													
S2-13		6:24	9.42	9.80	9.70				15.46				Equilibrium sampling at Position 1.
		8:55	9.33	9.94	9.74	B2L 6.79	B2M 6.90	B2H 6.82					
		9:47	9.46	9.89	9.72	B3L 6.78	B3M 6.72	B3H 6.79		5.82 5.65 5.39	9.30 7.04 6.28	10.00 4.66 3.80	B3H 99.99% 155779 #1 B3M 99.99% 66940 #1 B3L 100.00% 78446 #1

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		10:45											Stopped log.
S2-14		10:51	Probe at position 2, E U2L	U2M	U2H								Started log.
		11:15	9.26	9.88	9.63	B4L 6.60	B4M 6.80	B4H 6.79				 B4H B4M B4L	μ cP / ν mm^2/s / Std. Dev. / ρ g/cm^3 1.52 1.4602 0.0 1.0418 1.41 1.3559 0.0 1.0419 1.63 1.5645 0.0 1.0405
		11:30											Contoured south, west, north tank quadrants.
		12:53											Stopped log.
S2-15		12:57	Probe at position 3, S U3L	U3M	U3H								Started log.
		13:00											Profile east quadrant.
		15:10	9.27	9.88	9.63	B1L 6.76	B1M 6.82	B1H 6.85		5.29 5.27 5.83	6.56 6.42 7.59	4.54 4.11 5.38	B1H 100.00% 91483 #1 B1M 100.00% 88152 #1 B1L 100.00% 89531 #1 Stopped log.
			Probe at position 4, W										
S2-16		15:28	9.23	9.88	9.61				15.6				Started log.
		20:30											Stopped log.
50% U_0D_0													
S2-17		20:38	Probe at position 1, N U1L	U1M	U1H								Reduced flow to 50% U_0D_0. Started log. Fast sampling rate.
		20:47	9.16	9.88	9.53								
		20:57							10.33 - 10.56				

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
	6/8	7:45	7.34	7.93	7.33				10.5				
		10:46	7.45	7.62	7.08				10.5				
		10:48											Stopped log.
S2-18		10:54	7.27	7.76	7.13				10.6				Started log. Sample every 10 min. See note on 6/12 18:04. Log probably not started.
		14:00	6.89	7.46	7.21				10.5				
		14:02	6.89	7.47	7.22	B1L 4.30	B1M 4.23	B1H 4.25					
	6/9	7:30	6.47	6.97	6.75				10.5				
		13:31	6.34	6.82	6.58	B1L 3.73	B1M 3.70	B1H 3.67					
	6/10	7:15	6.17	6.56	6.36				10.5				
		7:26	6.17	6.56	6.38	B1L 3.79	B1M 3.76	B1H 3.66					
	6/12	19:52	----	6.17	5.99				10.4				No signal observed on low transducer. Went to stop logs. Ultrasonic system said "Start Log." Probably do not have any data in file S2-18-ult. Checked depth of sludge. It was 27 in. below surface, near probe. Removed probe. Low transducer not stuck in sludge.
S2-18 re-start		18:04											Started log for S2-18.
	6/13												Low probe checked. Window on the MD 702 detector was not over signal from probe. Probe now working.
		11:02	5.59	6.15	5.91								Stopped log.
		13:35	5.53	6.14	5.91	B1L 3.27	B1M 3.25	B1H 3.41					

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S2-19		14:43											Started log.
		14:45	5.54	6.13	5.88								
	6/14	10:05	5.60	6.17	5.94				10.6	4.53 4.08 4.28	5.95 4.51 5.08	5.02 2.56 3.51	Sample Conf ID Count Run B1H 99.99% 71943 #1 B1M 99.99% 44085 #1 B1L 100.00% 78270 #1
		10:21	5.60	6.16	5.94	B1L 3.38	B1M 3.33	B1H 3.33					
		11:30											Stopped log.
Equilibrium 50% U_0D_0													
S2-20		11:34											Started fast log at Position 1; north
		11:35											
		11:48	5.61	6.20	5.98	B4L 3.29	B4M 3.30	B4H 3.25				B4M B4L	μ cP / ν mm^2/s / Std. Dev. / ρ g/cm^3 1.45 1.4254 0.06 1.0188 1.52 1.4950 0.06 1.0185
		13:00											Contoured east quadrant of tank floor.
		13:15 to 14:15											Profile of settled solids. North, east, south, west.
		13:22											Stopped log.
S2-21		13:24	Probe at position 2, E										Started log.
			U2L	U2M	U2H								
		13:28	5.53	6.20	5.91	B3L 3.17	B3M 3.43	B3H 3.46		4.23 4.27 4.14	4.82 4.84 4.52	3.02 2.94 2.39	Sample Conf ID Count Run B3H 100.00% 76212 #1 B3M 99.99% 44394 #1 B3L 100.00% 37526 #1

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
		15:00	5.53	6.14	5.89	B2L 3.35	B2M 3.22	B2H 3.22					
		15:09											Stopped log.
S2-22		15:18	Probe at position 3, S										Started log.
			U3L	U3M	U3H								
		17:31											Stopped log.
S2-23		17:35	Probe at position 4, W										Started log.
			U4L	U4M	U4H								
	6/15	7:30	6.25	6.52	5.81				10.5				Stopped log.
S2-24		15:40	6.16	6.42	5.99				10.5				Started log.
	6/16	14:10	6.40	6.30	5.98	B1L 3.30	B1M 3.38	B1H 3.30					
	6/17	14:10	6.75	6.66	6.42				11.7				
		14:40	6.42	6.66	6.75	B1L 3.41	B1M 3.07	B1H 3.19					
		15:49											Stopped log. Prepared to transfer supernate liquid to holding tank.
Test Complete													

Table C.1. Data Summary: Test S2, Low-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
Particle Size Distribution from Sludge Layer													
													Rad (in.) Ht. (in.) Conf. Interval Counts
										4.73	8.20	8.33	18 0.5 99.99% 196681
										6.36 25.17 36.30 36.34	9.08 26.28 36.01 39.78	7.90 12.99 11.72 20.09	28 3.125 99.99% 138944 28 1.125 100.00% 85559 28 0.25 99.99% 67080 #1 28 0.25 99.90% 112041 #2
										9.38 17.04 33.85 35.19	11.06 19.02 33.39 36.99	7.09 10.88 12.60 17.12	34 6.25 99.99% 207726 34 5.375 99.99% 70803 34 0.25 99.99% 41996 #1 34 0.26 99.99% 53701 #2
										14.22 16.79 33.10	16.58 18.55 35.35	10.47 10.55 17.29	37.5 6.75 99.99% 86630 37.5 5.00 99.99% 90469 37.5 0.25 100.00% 101719

Appendix D

Data Summary Tables for Simulant S3

Appendix D – Data Summary Tables for Simulant S3

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	**Date**	**Time**	**Ultrasonic**			**Bottle Samples**			**Flow Rate (gal/min)**	**Particle Size μm**			**Comments**
			wt% low	**wt% mid**	**wt% high**	**wt% low**	**wt% mid**	**wt% high**		**Med-ian**	**Mean vol**	**S.D. vol**	
Mixing >100% U_0D_0													
	4/22		Probe at position 1, N										Mobilized particulate with air lance. Entrained air increased ultrasonic reading.
			U1L	U1M	U1H								
												B4H B4M B4L	μ cP / ν mm^2/s / Std. Dev. / ρ g/cm^3 3.46 2.8509 0.06 1.2147 3.55 2.9204 0.06 1.2168 3.59 2.9552 0.06 1.2156
		15:00	~26	~26	~26	B1L 17.94	B1M 18.09	B1H 17.84		5.35 5.57 5.42	6.47 6.44 6.55	4.21 3.75 4.54	Sample / Conf ID / Count / Run B1H 100.00% 61349 #1 B1H 99.99% 42370 #2 B1H 99.99% 69439 #3
										4.83 5.05 5.02	5.32 5.51 5.73	2.63 2.82 3.16	B1M 100.00% 31719 #1 B1M 100.00% 37422 #2 B1M 99.99% 38346 #3
										5.68 5.61 5.42	7.36 6.35 6.22	5.43 3.62 3.53	B1L 99.99% 72394 #1 B1L 99.99% 42853 #2 B1L 99.99% 44260 #3
		15:41	25.00	25.21	27.75	B3L 18.08	B3M 18.32	B3H 18.49		5.63 5.86 6.89	6.55 7.37 8.21	3.85 4.98 6.93	B3H 99.99% 43812 #1 B3H 99.99% 71196 #2 B3H 99.99% 93543 #3
										5.55 5.71	6.89 8.77	4.83 9.30	B3M 99.99% 58153 #1 B3M 99.99% 131703 #2
										5.41 5.25 5.48	6.11 6.05 6.84	3.43 3.42 5.03	B3L 99.99% 41720 #1 B3L 99.99% 41489 #2 B3L 99.99% 74536 #3
S3-1		18:18											Ultrasonic transducers affected by entrained air from air lancing.
		18:22	18.54	18.31	19.48								

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		18:30											Tank air lanced from 18:30 to 19:00.
		19:00	23.95	23.61	30.59								
		19:02											Removed probe to wipe face.
		19:03	20.51	19.45	20.96								Wiped probe face before reading. Note wiping (removing the probe from the tank) could mix the fluid around the probe and therefore affect the reading.
		19:57	22.94	23.09	29.45								
		19:59	19.43	18.87	20.04								Wiped probe face prior to reading.
		20:01											Wiped probe face.
Mixing at 100% U_0D_0													
		20:02											Started to reduce flow rate to 100% U_0D_0.
		20:12							20.88				At 100% U_0D_0.
		20:16	28.25	25.63	31.02								Wiped probe face.
		20:18	20.66	20.25	22.23								Wiped probe face.
		20:22											Removed 2000 mL sample from top of tank to evaluate settling.
	4/23	16:02							17.5				Turned pump off and on.
		16:05	16.37	15.78	16.71								
		16:07	15.98	15.53	16.12								Wiped probe face prior to reading.
		16:14											Stopped log.
S3-2		16:22											Started log.
		16:55											Turned pump off and on.
		17:22	16.29	15.71	16.36								

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		17:24	16.12	15.70	16.59								Wiped probe face prior to reading.
		17:26	15.87	15.65	16.24	B1L 17.07	B1M 16.86	B1H 16.82					
		18:38											Turned pump off and on.
		20:08											Turned pump off and on.
		20:32	16.07	15.68	16.43								
		20:37	16.02	15.66	16.41								Wiped probe face prior to reading.
		20:38											Stopped log.
S3-3		20:43											Started log.
		22:22											Turned pump off and on.
		22:23	15.95	15.68	16.43				18.5				Pump knocking, flow rate decreased.
	4/25	8:30											
		8:31	15.98	5.49	16.10								
		8:32											Stopped log. Turned pump off and on twice.
S3-4		8:38							20.25				Turned pump off and on.
		8:42	16.30	15.85	16.42								
		9:46	16.00	15.54	16.38	B1L 16.79	B1M 16.75	B1H 16.65					
		10:10	16.04	15.51	16.36	B3L 17.02	B3M 16.84	B3H 17.05					
		11:28											Flow below 21 gal/min for majority of time since test start; therefore, restarted test.
S3-5		21:01											Note: Hadn't renamed file to S3-5-ult, it was S3-4-ult.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
Remix at >100% U_0D_0													
		13:18											Stopped log to verify ultrasonic readings via water insertion. Probes were okay.
S3-5		13:35											Really started S3-5 file.
		16:10	0.2	39.16	36.44	B1L 18.37	B1M 18.49	B1H 18.61		5.55 5.62 5.81	6.63 6.41 7.99	4.03 3.55 7.26	Sample Conf ID Count Run B1H 99.99% 39041 #1 B1H 99.99% 33915 #2 B1H 100.00% 143064 #3
										5.01 6.47 6.28	5.70 7.61 7.15	3.26 4.49 3.74	B1M 99.99% 115131 #! B1M 100.00% 61996 #2 B1M 100.00% 48469 #3
										6.20 5.68 5.77	9.34 6.57 6.62	8.94 3.74 3.84	B1L 99.99% 82945 #1 B1L 99.99% 28092 #2 B1L 100.00% 49562 #3
		16:22	1.00	39.07	36.38	B3L 18.49	B3M 18.49	B3H 18.47		5.28 5.11 5.46	6.59 5.86 6.18	5.02 3.46 3.50	B3H 99.99% 96265 #1 B3H 99.99% 45091 #2 B3H 99.99% 47135 #3
										5.41 5.25 5.10	6.41 5.83 5.80	4.09 3.00 3.26	B3M 100.00% 71955 #1 B3M 99.99% 38632 #2 B3M 99.99% 40337 #3
										5.14 5.25 5.28	5.96 5.98 6.35	3.59 3.35 4.28	B3L 100.00% 59234 #1 B3L 99.99% 39404 #2 B3L 99.98% 51810 #3

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
Restarted test at 100% U_0D_0													
		16:58											Data recorded every minute. Reduced flow to 100% U_0D_0.
		17:22							21				Added 500 mL chlorine and 2 mL algicide. Removed grease from top of liquid.
		17:25	23.20	23.03	24.11								Ultrasonic signals near normal; air removed.
		17:42	21.70	22.07	22.87								
		17:49	18.54	18.56	19.07								Wiped probes prior to reading.
		18:06	18.33	18.02	18.83								Ultrasonic signal above 10 V; stopped log.
S3-6		18:18											Turned pump off and on, restarted log.
		18:20	17.78	17.53	18.20								
		18:24	17.33	17.33	18.13								
		18:28											Corrected computer clock; it was 12 hr slow
		18:32											Turned pump off and on.
		18:58											Turned pump off and on.
		20:19											Turned pump off and on.
		20:20	17.46	16.90	17.48				20.78				
		22:06	17.15	16.63	17.23				20.40				
		22:07											Turned pump off and on.
		22:08	17.67	17.00	17.86				21.22				
	4/26	12:01	16.86	16.41	17.15	B1L 17.82	B1M 17.83	B1H 17.76					

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		12:09	16.79	16.37	17.12	B3L 17.91	B3M 18.03	B3H 17.91					
		1:49							20.50				
		1:50											Turned pump off and on.
		1:51	16.83	16.74	17.02				21.13				
		~2:30							~19.5				Data observed from chart history at 6:37.
		6:37	16.97	16.73	17.02				19.43				
		6:38											Turned pump off and on twice.
		6:39	17.06	16.26	17.04				20.77				
		8:53	16.73	16.53	17.29				20.21				
		8:53											Turned pump off and on.
		8:54	17.07	16.69	17.69				21.17				
		8:55											Turned pump off and on.
		11:08											Turned pump off and on.
		11:09	16.83	16.41	17.31				20.9				
		13:50											Turned pump off and on.
		13:51											Stopped log.
S3-7		14:02											Started log. Data recorded every 10 min.
		14:03	16.79	16.40	17.09								
		16:10	0.20	39.16	36.44	B1L 18.37	B1M 18.49	B1H 18.61					Entrained air from lance affected ultrasonic readings.
		16:22	1.00	39.07	36.38	B3L 18.49	B3M 18.49	B3H 18.47					Entrained air from lance affected ultrasonic readings.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
		16:45							20.3				Turned pump off and on.
		19.56							20.07				Turned pump off and on.
		19:56							21.3				
		19:58	16.77	16.26	17.03								
		23:41							20.08 to 20.50				Turned pump off and on several times.
		23:48							20.3 to 21.2				
	4/27	6:01	16.67	16.02	16.79				19.61				
		6:02											Turned pump off and on twice.
		6:04	16.85	16.46	17.16				20.64				
		9:57											Found both data acquisition computers off (later attributed to power tool being operated on the conditioned power supply outlet that also feeds this computer). Tagged to conditioned power to restrict unauthorized use.
		10:15											Both data acquisition computers back on.
		10:36							19.4				Turned pump off and on.
		10:36							20.4				
		10:53	16.31	17.96	18.76								Restarted log.
		10:53	18.49	18.01	18.77								
		11:45							20.00				
		11:45											Turned pump off and on.
		11:46	18.53	17.60	18.59				20.88				
		13:51	17.29	17.19	17.67				20.37				Adjusted window on ultrasonic probes. Now data should be okay.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size µm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		13:53											Turned pump off and on.
		13:55											Turned pump off and on.
		13:56	17.77	16.97	18.18				21.7				
		14:08	17.69	16.94	17.85	B1L 17.44	B1M 17.49	B1H 17.58					
		14:15	17.61	17.10	17.75	B3L 17.58	B3M 17.49	B3H 17.66					
		14:17											Turned pump off and on twice.
		14:40											Turned pump off and on.
		15:25							20.8				Turned pump off and on twice, reduced flow slightly.
		19:09	17.28	17.03	17.85				19.64				Turned pump off and on twice.
		19:14	17.63	17.00	17.76				20.88				
		21:51	17.69	17.35	17.83				20.83				Pump steady.
		21:53											Turned pump off and on.
	4/28	5:17	17.83	17.07	18.13				20.02				Turned pump off and on three times.
		5:24	17.48	16.88	17.83				20.74				Stopped logs, turned pump off and on.
Equilibrium at 100% U_0D_0													
S3-8		5:29	Probe at position 1, N										Data recorded every minute.
			U1L	U1M	U1H								
		5:30											Turned pump off and on.
		5:31	17.44	17.15	17.80				20.78				
		5:33											Turned pump off and on.
		7:30	17.71	17.12	17.87				19.5				Pump knocking hard.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
													To alleviate pump knocking injected two 2 s charges of water to pump inlet and opened 2 in. suction valve momentarily. Some air bubbles came up through the fluid.
		7:42	25.93	25.56	27.04								
		7:45	24.47	23.59	25.17								Wiped probes prior to reading.
		10:40	18.48	17.74	19.07	B3L 17.69	B3M 17.59	B3H 17.53					
		10:44	18.48	17.74	19.07	B1L 17.67	B1M 17.83	B1H 17.57					
		13:42	18.18	17.47	18.33	B2L 17.57	B2M 17.61	B2H 17.74					
		13:45	18.18	17.45	18.32				20.3				Pump knocking
		13:48							21.1				Turned pump off and on.
		14:00	17.98	17.25	18.10				20.4				
		14:02											Stopped log.
S3-9		14:11	Probe at position 2, E										
			U2L	U2M	U2H								
		14:12	17.72	16.85	17.81								
		14:17											Turned pump off and on.
		15:30	17.66	17.14	17.88								Stopped log. Turned pump off and on.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S3-10		15:47	Probe at position 3, S										Note: File heading said probe at position 1. This is incorrect. The probe was at position 3.
			U3L	U3M	U3H								
		18:08											Stopped log.
S3-11		18:12											Started log.
		18:13	17.44	16.66	17.57				20.66				
			Probe at position 4, W										
			U4L	U4M	U4H								
		18:45	17.57	16.86	17.64	B4L 17.62	B4M 17.69	B4H 17.75		5.07 4.92 5.05	5.88 5.55 5.84	3.49 3.07 3.39	Sample Conf ID Count Run B4H 99.99% 36599 #1 B4H 99.99% 33879 #2 B4H 99.99% 36987 #3
										5.16 5.19 5.10	5.95 5.98 5.79	3.49 3.41 3.17	B4M 99.99% 44330 #1 B4M 99.99% 49810 #2 B4M 99.99% 36463 #3
										5.28 5.14 5.12	6.03 5.84 6.48	3.54 3.31 6.11	B4L 100.00% 58560 #1 B4L 99.99% 44815 #2 B4L 99.99% 131940 #3
		18:57	17.49	17.14	17.83	B1L 17.67	B1M 17.79	B1H 17.49		5.19 5.17 5.17	6.09 5.82 5.84	3.69 3.15 3.29	B1H 99.97% 37919 #1 B1H 99.99% 37671 #2 B1H 99.99% 38683 #3
										4.98 4.95 5.12	5.51 5.64 6.03	2.91 3.16 3.72	B1M 100.00% 39033 #1 B1M 99.99% 39968 #2 B1M 99.99% 51475 #3
										4.95 4.70 4.97	5.65 5.25 5.69	3.34 2.80 3.32	B1L 99.99% 39874 #1 B1L 99.99% 33977 #2 B1L 99.99% 40598 #3

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
		19:53											μ cP, ν mm^2/s, Std. Dev., ρ g/cm^3
												B1H B1M B1L	3.12 2.5727 0.06 1.2120 3.42 2.8161 0.10 1.2144 3.37 2.7813 0.06 1.2134
		20:23	17.58	17.16	17.54				20.65				
		20:24											Stopped log.
75% U_0D_0 Test													
			Probe at position 1, N										
			U1L	U1M	U1H								
S3-12		20:29	17.58	16.85	17.61				20.53				Started log, decreased flow rate to 15.66 gal/min, 75% U_0D_0; data recorded every 10 s.
		20:29	17.34	16.39	17.28				15.81				Observed concentration decrease on chart.
	4/29	8:44	16.83	16.12	16.41				15.87				
		8:45											Stopped log.
S3-13		8:49											Data recorded every 10 min. Started log.
		10:20	16.56	16.07	16.71				16.5				
		10:30	16.59	16.07	16.70	B1L 16.53 B3L 16.43	B1M 16.39 B3M 16.52	B1H 16.45 B3H 16.53					
		16:43	16.49	15.73	16.12				16.76				Lowered pump speed slightly
	4/30	14:30	17.96	15.24	15.81				16.38				~12 hr ago wt% at low position began to increase. It leveled off at 18.5 wt% for the last 2 hr.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		14:48	18.12	15.03	15.83	B1L 15.41	B1M 15.60	B1H 15.40					
		14:56	15.69	15.09	18.45	B3L 15.79	B3M 15.82	B3H 15.60					
		15:15											Stopped log. Wiped probe faces.
		15:18											Restarted log.
		15:19	17.95	15.04	15.76				15.96				
		15:20											Reduced flow rate slightly to achieve 15.66 gal/min.
	5/1	16:35											Flow rate steady last 8 hr. Ultrasonic reading still decreasing slightly. Low in parallel with mid and high signals for past 6 hr.
		16:36	15.70	14.20	15.30				15.69				
		16:46	15.95	14.32	15.38	B1L 14.92	B1M 14.70	B1H 14.81					
		16:58	16.04	14.34	15.36				15.90				
	5/2	8:00	14.64	14.14	15.36				15.61				
		11:00	14.96	14.00	14.82				15.60				
		11:00	15.57	14.01	14.84	B1L 14.57	B1M 14.43	B1H 14.67					
		14:50	14.72	13.91	15.89								
		14:51							15.46				Stopped log.
S3-14		15:58											Started log.
		16:00	15.79	13.73	14.59				15.45				
		18:32											Raised flow rate slightly to 15.66 gal/min.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
		18:34	15.89	13.91	14.44				15.75				
	5/3	6:04	15.05	13.69	14.93				15.44				
		10:50	15.01	13.58	14.25				15.85				
		11:00	14.29	13.69	15.22	B1L 13.99	B1M 13.94	B1H 13.91					
		13:00	15.11	13.53	14.22								
		14:00	15.01	13.54	14.15								
		15:00	14.97	13.55	14.17								
		15:05	14.97	13.55	14.17	B1L 14.05	B1M 13.78	B1H 14.91					
	5/4	6:40	14.79	13.49	14.18				15.58				
		8:30	14.57	13.23	14.02				15.60				
		8:40	14.64	13.23	13.98	B1L 13.81	B1M 13.66	B1H 13.70					
		13:40	14.57	13.23	14.02				15.60				
		13:45	14.57	13.23	14.02	B1L 13.69	B1M 13.67	B1H 13.81					
		17:07	14.24	12.92	13.66				15.65				
		17:25	14.44	13.08	13.90								
	5/5	7:05	14.69	13.07	13.65				15.74				Readings from last 12 hr appear steady.
		7:10											Stopped log.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
Equilibrium at 75% U_0D_0													
			Probe at position 1, N										
			U1L	U1M	U1H								
S3-15		7:16	14.28	13.21	14.00				15.40				Record data every 10 s.
		8:15	14.61	13.06	13.75								
		8:45	14.53	13.01	13.72	B3L 13.61	B3M 13.53	B3H 13.59					
		9:15	14.55	12.99	13.69								
		9:17	14.54	12.99	13.97	B2L 13.56	B2M 13.45	B2H 13.61					
		9:35	Probe at position 2, E										Stopped logs.
			U2L	U2M	U2H								
		9:44	14.62	13.09	13.71				15.7				
S3-16		9:49											
		10:00											
		10:15	14.47	13.05	13.67					4.93 4.66 4.82	5.84 5.18 5.36	3.52 2.74 2.92	Sample Conf ID Count B3H 99.99% 45097 B3M 100.00% 29332 B3L 99.99% 26542
		10:46	14.48	13.05	13.73								
		11:15	14.43	13.02	13.71								
		11:47	14.41	13.04	13.73								
		12:16	14.43	13.03	13.75								
		13:00											Stopped log.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		13:20	14.39	13.03	13.17	B4L 13.56	B4M 13.41	B4H 13.65					
			Probe at position 3, S										
			U3L	U3M	U3H								
S3-17		13:25	14.39	13.13	13.95								Started log.
		14:00										B4H B4M B4L	μ cP / ν mm^2/s / Std. Dev. / ρ g/cm^3 3.20 2.7118 0.0 1.1821 3.16 2.6770 0.12 1.1803 3.49 2.9552 0.06 1.1814
		15:00	14.61	13.04	13.74				15.70				
		15:00											Probed tank to measure depth of settled solids layer.
		15:05											Stopped log.
S3-18		15:12	Probe at position 4, W										Started log.
			U4L	U4M	U4H								
		15:30	14.45	13.02	13.68	B1L 13.29	B1M 13.26	B1H 13.29					
		15:31	14.43	13.04	13.69				15.89				
		18:25	14.40	13.07	13.70				15.34				
		18:26											Stopped log.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size µm Med-ian	Particle Size µm Mean vol	Particle Size µm S.D. vol	Comments
50% U_0D_0													
			Probe at position 1, N										
			U1L	U1M	U1H								
S3-19		18:32	14.72	12.81	13.42				15.35				Started log. Decreased flow rate to 10.44 gal/min 50% U_0D_0. Sampling rate every 10 s.
		18:39	12.24	13.00	13.74				10.42				
		20:00	14.07	12.39	13.39				10.48				
	5/6	7:47	13.11	11.40	12.28				10.46				Decreased flow rate to 10.44 gal/min.
		7:52											Stopped log.
S3-20		7:54											Started log. Sampling rate every 10 min.
		7:55	13.06	11.90	12.33				10.40				
		8:45	12.29	11.59	12.13	B3L 12.02	B3M 12.01	B3H 12.06	10.5				
		10:05	12.93	11.57	12.06	B1L 11.94	B1M 11.76	B1H 11.83	10.5	4.42 4.55 4.31	4.77 6.06 4.62	2.45 5.37 2.26	Sample Conf ID Count B1H 100.00% 37421 B1M 99.99% 98774 B1L 100.00% 23166
		14:20											Added algicide and chlorine
		14:33											Stopped log.
S3-21		14:47											Started log.
		14:48	13.73	12.13	7.91				10.51				
		15:05	14.10	12.45	7.41	B1L 12.98	B1M 12.56	B1H 7.70					
		15:34	14.37	12.65	6.85				10.67				

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		16:08	14.48	12.72	6.55								
	5/7	8:52	11.82	10.46	11.09				10.60				
		9:09	11.46	10.46	10.93	B1L 11.17	B1M 11.02	B1H 11.03					
	5/8	8:34	10.08	9.06	9.53				10.67				Stopped log.
S3-22		8:45											Started log.
		8:46	10.59	9.13	9.58				10.36				
		8:53	10.58	9.03	9.56	B1L 9.86	B1M 9.89	B1H 10.03					
	5/9	7:20	9.56	8.24	8.78				10.37				For last 10 hr wt% at low position fluctuated sinusoidally through mid and high values.
		7:27	9.63	8.17	8.78	B1L 9.45	B1M 9.00	B1H 9.23					
	5/10	7:29	9.49	7.85	8.21				10.50				For last 10 hr constant values with low pos ~2 wt% higher than mid.
		7:37	9.32	7.79	8.14	B1L 8.45	B1M 8.60	B1H 6.67					
	5/11	7:50	8.02	7.43	7.59				10.39				
	5/12	6:52	7.56	6.81	7.20				10.64				Concentration appears constant for last 12 hr.
		7:00	7.53	6.91	7.18	B1L 8.09	B1M 7.68	B1H 7.95					
		17:20	7.30	6.80	6.88				10.64				
	5/13	7:49	6.93	6.75	7.01				10.77				
	5/14	7:59	6.66	6.57	6.80				10.64				
	5/15	6:56	6.70	6.52	6.67				10.76				
	5/16	7:48	6.70	6.37	6.52				10.50				Stopped log. Heading on ultrasonic file was incorrect; said S3-21-ult instead of S3-22-ult.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate (gal/min)	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
Equilibrium 50% U_0D_0													
			Probe at position 1, N										
			U1L	U1M	U1H								
S3-23		7:54											Sampling every 10 s.
		12:00	6.96	6.36	6.46								
		12:01											Stopped log.
			Probe at position 2, E										
			U2L	U2M	U2H								
S3-24		12:05											
		13:38	6.85	6.13	6.37	B3L 7.39	B3M 7.29	B3H 7.39		3.53 3.28 3.49	3.65 3.41 3.67	1.78 1.66 1.83	Sample Conf ID Count B3H 100.00% 36024 B3M 100.00% 40232 B3L 100.00% 35523
		14:05											Profiled settled solids on tank floor.
		14:15	6.86	6.10	6.36								Stopped log.
			Probe at position 3, S										
			U3L	U3M	U3H								
S3-25		14:17											
		14:45	6.35	6.12	6.83	B4L 7.42	B4M 7.35	B4H 7.09				B4H B4M B4L	μ cP, ν mm^2/s, Std. Dev., ρ g/cm^3 2.92 2.5727 0.06 1.1344 3.08 2.7118 0.10 1.1362 3.12 2.6770 0.12 1.1367
		15:15	6.86	6.10	6.35	B1L 7.35	B1M 7.42	B1H 7.31		3.13 3.56 3.28	3.28 3.68 3.39	1.67 1.75 1.60	Sample Conf ID Count B1H 99.99% 16733 B1M 100.00% 27533 B1L 100.00% 24243
		15:45	6.85	6.12	6.36	B2L 7.46	B2M 7.45	B2H 7.49					Stopped log.

Table D.1. Data Summary: Test S3, High-Viscosity, Small-Diameter Particulate

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate (gal/min)	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
			Probe at position 4, W										
			U4L	U4M	U4H								
S3-26		15:51											Started log.
	5/17	9:00	6.48	6.10	6.29				10.76				Stopped log.
Test Complete													
Particle Size Distribution from Sludge Layer													
													Rad in. / Ht. in. / Conf. Interval / Counts
										4.72 6.14	5.47 7.34	3.73 4.16	18 1.25 100.00% 71567 18 0.25 99.99% 54391
										5.39 5.78	5.92 6.58	2.82 3.38	28 2.00 99.99% 40720 28 1.00 100.00% 43932
										4.59 8.68	5.37 10.95	3.95 7.61	34 4.38 99.99% 101518 34 1.00 99.99% 101197
										4.27 7.75	4.47 8.90	1.88 4.86	37.5 4.25 100.00% 34739 37.5 1.00 99.99% 70520
Particle Size Distribution in Graduated Cylinder Static Test													
													in. from / Conf. Interval / Counts top
	5/6									10.99	10.45	8.59	2.75 99.86% 39070
										6.56 0.72	8.93 0.73	7.91 0.15	7.5 81.91% 6598 7.5 100.00% 1378
										0.77 0.82	0.79 1.12	0.19 0.99	10.5 100.00% 773 10.5 100.00% 7667
	5/17									0.99 1.17	1.04 2.09	0.33 1.76	7.0 100.00% 1347 7.0 99.31% 13793

Appendix E

Data Summary Tables for Simulant S4 Distribution

Appendix E – Data Summary Tables for Simulant S4 Distribution

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate gal/min	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
Mixing >100% U_0D_0													
	6/20		Probe at position 1, N						29				
			U1L	U1M	U1H								
S4-1	6/23	17:30											Started log.
		17:40	22.67	40.71	41.04	B1L 16.59	B1M 16.38	B1H 16.49		17.41 22.41 17.02	19.29 24.08 18.81	12.14 14.59 12.30	Sample Conf ID Count xRun B1H 100.00% 49208 #1 B1M 100.00% 164568 #1 B1L 99.99% 82539 #1
		18:00	23.06	29.83	33.40	B3L 16.68	B3M 16.50	B3H 16.51		19.60 18.41 14.33	20.78 20.46 17.33	12.44 13.82 12.74	B3H 99.99% 100875 #1 B3M 99.99% 86833 #1 B3L 100.00% 234949 #1
Mixing at >100% U_0D_0													
		18:15											Reduced flow rate to 20.88 gal/min.
		19:07											Stopped log.
S4-2		19:13											Started log.
		19:42							17.1				17.1 gal/min seems to be highest attainable flow rate.
	6/24	11:00	27.69	26.94	27.66				17.0				
		11:00	24.99	17.02	17.78	B1L 7.56	B1M 7.72	B1H 7.78				B1L B4L	μ cP, ν mm^2/s, Std. Dev., ρ g/cm^3 2.85 2.5032 0.10 1.1392 2.73 2.3989 0.10 1.1392

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate gal/min	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
		15:04											Stopped log.
S4-3		15:37											Started log. Ultrasonic readings are unexplainable. Cleaned probes and checked cables.
		15:40				B1L 7.19	B1M 7.38	B1H 7.23					
	6/25	9:38											Turned pump off and on. No change in flow rate. No air release.
		9:40	23.47	22.73	23.69	B1L 7.29	B1M 7.21	B1H 7.18					
		9:50											Stopped log. Cleaned off ultrasonic probes. After cleaning, readings were approximately 10 wt% lower.
S4-4		10:30											Started log.
	6/27	10:01	12.34	11.78	11.78				16.4				Stopped log.
S4-5		10:07											Started log.
		10:10	11.90	11.89	12.17	B1L 7.22	B1M 7.09	B1H 7.11					
Equilibrium at 100% U_0D_0													
			Probe at position 1, N										
			U1L	U1M	U1H								
	6/28	8:15	10.82	10.74	11.15	B1L 7.23	B1M 7.15	B1H 7.26	16.5	6.01 6.08 5.85	8.70 8.51 7.87	7.37 6.72 5.88	Sample Conf ID Count Run B1H 99.99% 119897 #1 B1M 99.99% 88106 #1 B1L 99.99% 97399 #1
		10:15	11.00	10.88	11.17	B2L 7.29	B2M 7.18	B2H 7.13					
		10:45	11.30	10.92	11.07				16.5	6.63 6.24 6.25	10.54 8.78 9.18	9.63 6.94 8.09	B3H 99.99% 112429 #1 B3M 100.00% 94358 #1 B3L 100.00% 152789 #1

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate gal/min	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
													Stopped log.
													Checked ultrasonic probes. They're reading 4-5% higher than bottle samples. Took water readings. See p 149 log book.
		11:27											Reinserted ultrasonic probes. Readings are still high with respect to density samples.
		11:30											Profile of settled solids at east position.
S4-6		11:31											Started log.
		11:45	11.25	11.09	11.48	B4L 7.05	B4M 7.15	B4H 7.11				B4H B4M B4L	μ cP / ν mm^2/s / Std. Dev. / ρ g/cm^3 2.96 2.6075 0.0 1.1345 3.27 2.8856 0.12 1.1348 3.08 2.7118 0.0 1.1342
		13:24											Stopped log.
S4-7		13:27	Probe at position 2, E U2L	U2M	U2H								Started log.
		13:50											Profiled settled solids at south, west, north positions.
		15:15											Stopped log.
			Probe at position 3, S U3L	U3M	U3H								Started log.
S4-8		15:25	11.93	12.71	11.66				16.5				Started log.
		17:09											Stopped log.

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate gal/min	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
S4-9		17:13	Probe at position 4, W										Started log.
			U4L	U4M	U4H								
	6/29	9:20											Stopped log.
75% U_0D_0 Test													
S4-10		9:26	Probe at position 1, N										Started log.
			U1L	U1M	U1H								
		9:27							15.66				Reduced flow to 75% U_0D_0
		9:37							15.47 – 15.81				Finished reducing flow to 75% U_0D_0
	6/30	8:08	11.51	11.06	11.08				15.7				Stopped log.
S4-11		8:15											Started log. 10 min sampling rate.
		8:20	11.08	11.04	11.52	B1L 6.78	B1M 6.67	B1H 6.59					
		14:50	11.23	11.11	11.56	B1L 6.71	B1M 6.92	B1H 6.76					
	7/1	8:55	11.36	11.04	8.32				15.6				
		9:00	7.86	11.04	11.36	6.80	6.69	6.73					B1L, B1M, B1H
		11:38											Stopped log.
Equilibrium at 75% U_0D_0													
S4-12		11:48	Probe at position 1, N										Started log.
			U1L	U1M	U1H								
		13:24											Stopped log.

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate gal/min	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S4-13		13:27	Probe at position 2, E U2L	U2M	U2H								Started log.
		14:20	11.08	10.90	11.25	B3L 7.11	B3M 7.05	B3H 6.99		5.52 5.67 5.78	7.49 7.59 7.49	5.89 5.64 5.19	Sample Conf ID Count Run B3H 100.00% 81523 #1 B3M 100.00% 86232 #1 B3L 100.00% 92128 #1
		14:55	11.14	10.94	11.30	B1L 6.88	B1M 6.87	B1H 6.99		6.17 5.87 5.97	8.19 7.96 7.84	5.77 5.91 5.57	B1H 99.99% 71846 #1 B1M 99.99% 100947 #1 B1L 99.99% 92104 #1
		15:20											Profiled settled solids at south position.
		15:32											Stopped log.
S4-14		15:36	Probe at position 3, S U3L	U3M	U3H								Started log.
		16:05	11.15	11.30	11.77	B4L 6.96	B4M 6.76	B4H 6.97				B4H B4M B4L	μ cP ν mm²/s Std. Dev. ρ g/cm³ 3.08 2.7118 0.10 1.1335 3.31 2.9204 0.10 1.1321 3.23 2.8509 0.06 1.1335
		17:00											Profiled settled solids at east, north, and west.
		17:20											Stopped log.
S4-15		17:24	Probe at position 4, W U4L	U4M	U4H								Started log.
		18:12	10.61	10.63	11.10	B2L 6.95	B2M 6.80	B2H 7.02					
		19:03											Stopped log.

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate gal/min	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
50% U_0D_0													
S4-16		19:08	Probe at position 1, N U1L	U1M	U1H								Started log.
		19:10							10.44				Reduced flow to 50% U_0D_0
		19:17							10.30 - 10.62				Adjusted flow rate.
	7/2	9:16											Stopped log.
		~9:20	7.38	7.44	7.67	B1L 4.98	B1M 5.00	B1H 4.99					Time estimated.
S4-17		9:27											Started log.
	7/6	9:17	3.87	5.20	4.15				10.6				
		9:20	4.15	5.18	3.87	B1L 2.68	B1M 2.83	B1H 2.65					
	7/7	7:50	3.64	3.82	3.82				10.6				
		8:02	3.82	3.82	3.64	B1L 2.56	B1M 2.39	B1H 2.57					
		11:10	3.59	3.66	3.78				10.6				
		11:20	3.78	3.66	3.59	B1L 2.54	B1M 2.34	B1H 2.42					
	7/8	9:00	3.46	3.69	3.69				10.6				
		9:15	3.69	3.69	3.45	B1L 2.45	B1M 2.33	B1H 2.41					
	7/10	8:36	3.44	3.32	3.33				10.48				
		8:42	3.53	3.35	3.37	B1L 2.51	B1M 2.44	B1H 2.44					

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate gal/min	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
	7/11	7:56	4.06	3.83	3.82				10.44				Rotation ~173 degrees.
		8:00											Stopped log.
Equilibrium 50% U_0D_0													
S4-18		8:03	Probe at position 1, N										Started log.
			U1L	U1M	U1H								
		8:30	3.78	3.81	4.04	B1L 2.48	B1M 2.53	B1H 2.60	10.6	3.27 2.94 3.17	3.37 3.14 3.26	1.63 1.65 1.58	Sample Conf ID Count Run B1H 100.00% 31853 #1 B1M 100.00% 53108 #1 B1L 100.00% 41729 #1
		10:23											Stopped log.
S4-19		10:30	Probe at position 2, E										Probes placed at R=13.5 in. instead of R=18 in.
			U2L	U2M	U2H								
		11:00											Profiled settled solids at north, south, east.
		13:01											Stopped log.
S4-20		13:13	Probe at position 3, S										Started log.
			U3L	U3M	U3H								
		13:29	3.25	3.26	3.39	B4L 2.60	B4M 2.42	B4H 2.50				B4H B4M B4L	μ cP; ν mm^2/s; Std. Dev.; ρ g/cm^3 2.91 2.6423 0.06 1.1032 2.99 2.7118 0.10 1.1027 3.11 2.8161 0.10 1.1039
		13:40	2.81	2.82	2.89	B2L 2.65	B2M 2.41	B2H 2.62					
		15:59	2.90	2.83	2.78				10.6				Stopped log.

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic			Bottle Samples			Flow Rate gal/min	Particle Size μm			Comments
			wt% low	wt% mid	wt% high	wt% low	wt% mid	wt% high		Med-ian	Mean vol	S.D. vol	
S4-21		16:07	Probe at position 4, W U4L	U4M	U4H								Started log.
		18:00	2.79	2.84	2.91	B3L 2.45	B3M 2.49	B3H 2.40		3.16 3.07 3.12	3.27 3.19 3.22	1.61 1.56 1.55	Sample Conf ID Count Run B3H 100.00% 40786 #1 B3M 100.00% 45294 #1 B3L 100.00% 51349 #1
		18:12											Stopped log.
25% U_0D_0													
S4-22		18:30	Probe at position 1, N U1L	U1M	U1H								Started log. Reduced flow to 25% U_0D_0
		19:34							5.03 - 5.46				Completed reducing flow to 25% U_0D_0. Used a bypass line to obtain desired flow rate.
		19:40											Appears that fresh water has come from above into tank. NW corner of tank, unistrut and edge are wet.
	7/12	11:00	2.44	2.31	2.60	B1L 2.24	B1M 2.10	B1H 2.31	5.8				
		17:49											Stopped log.
		17:53											Observed water coming into tank from zero level from leak in hose being used by other personnel. Stopped leak.
		19:29	2.38	2.05	2.19				5.08 - 6.26				Appears flow has increased with loss of particulate.
S4-23		19:34											Started log.
	7/13	10:05	1.95	1.87	2.16				6.1				

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate gal/min	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
		10:20	1.95	1.87	2.16	B1L 2.01	B1M 1.86	B1H 1.43					
	7/14	7:45	1.59	1.62	1.86				6.1				
		7:58	1.59	1.62	1.86	B1L 1.95	B1M 1.95	B1H 1.81					
	7/15	13:05	1.56	1.30	1.27				6.2				
		13:18	1.28	1.30	1.55	B1L 1.72	B1M 1.69	B1H 1.60					
S4-24		13:21											Started log.
	7/18	18:02	0.83	0.97	1.08	B1L 1.55	B1M 1.54	B1H 1.54					
		18:04											Stopped log.
S4-25		18:06	1.07	0.97	0.84				5.9 - 6.2				Started log.
	7/19	15:12	0.71	0.97	0.97	B1L 1.61	B1M 1.43	B1H 1.53					
	7/20	19:12		0.88	0.86	B1L 1.37	B1M 1.46	B1H 1.46					Observed low ultrasonic sensor not reading. Removed probe and cleaned sensor and tightened connections.
		19:40											Ultrasonic sensor back on line.
		19:44											Stopped log.
S4-26		19:47											Started log.
	7/22	16:40	0.21	0.35	0.43	B1L 1.14	B1M 1.00	B1H 1.11					
		17:51											Stopped log.
S4-27		17:52											Started log.
	7/25	16:55	0.48	0.60	0.67	1.24	1.19	1.22					

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate gal/min	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
Equilibrium 25% U_0D_0													
			Probe at position 1, N										
			U1L	U1M	U1H								
	7/26	11:05	0.20	0.25	0.40	B1L 1.28	B1M 1.21	B1H 1.29		1.27 1.14 1.23	1.38 1.14 1.41 2.15	0.53 0.30 0.68 2.54	Sample Conf ID Count Run B1H 100.00% 4360 #1 B1M 100.00% 1870 #1 B1M 100.00% 60103 #2 B1L 100.00% 187610 #1
		11:56											Stopped log.
S4-28		12:00											Started log.
		14:40											Profiled east settled solids.
		14:50 - 15:15											Stopped log. Profiled south, west, north settled solids.
S4-29		14:52	Probe at position 2, E										Started log.
			U2L	U2M	U2H								
		15:25	0.20	0.20	0.20	B3L 1.30	B3M 1.19	B3H 1.26		1.35 1.45 1.44	1.99 1.82 1.79	2.35 1.18 1.05	Sample Conf ID Count Run B3H 100.00% 265582 #1 B3M 100.00% 225422 #1 B3L 100.00% 166245 #1
		16:15	0.20	0.20	0.20	B4L 1.31	B4M 1.24	B4H 1.28				B4H B1H B4M	μ cP, ν mm^2/s, Std. Dev., ρ g/cm^3 2.51 2.2946 0.0 1.0952 2.36 2.1555 0.16 1.0950 2.89 2.6423 0.06 1.0954
		16:51											Stopped log.
S4-30		16:55	Probe at position 3, S										Started log.
			U3L	U3M	U3H								

Table E.1. Data Summary: Test S4, High-Viscosity, Large-Diameter Particulate Simulant

File	Date	Time	Ultrasonic wt% low	Ultrasonic wt% mid	Ultrasonic wt% high	Bottle Samples wt% low	Bottle Samples wt% mid	Bottle Samples wt% high	Flow Rate gal/min	Particle Size μm Med-ian	Particle Size μm Mean vol	Particle Size μm S.D. vol	Comments
		18:58											Stopped log.
			Probe at position 4, W U4L	U4M	U4H								Started log.
S4-31		19:01	0.20	0.20	0.20	B2L 1.33	B2M 1.25	B2H 1.30					Started log.
	7/27	9:42											Stopped log.
Test Complete													
													Decanted water. Took particle size samples from settled sludge.
Particle Size Distribution from Sludge Layer													
													Rad in. / Ht. in. / Conf. Interval / Counts
										5.92 16.84	7.57 20.48	5.20 14.28	18 1.00 100.00% 104314 18 0.25 99.99% 119821
										3.64 25.00 31.42	5.27 26.57 31.66	5.94 12.19 13.07	28 5.125 99.99% 148068 28 2.625 100.00% 76671 28 0.25 100.00% 58121
										5.22 6.20 13.10 16.46 34.22	6.14 7.83 15.78 19.69 34.35	3.59 5.19 10.69 12.62 12.72	34 8.75 100.00% 75108 34 8.125 100.00% 111752 34 7.25 100.00% 134982 34 6.75 99.99% 117865 34 0.25 100.00% 35112
										3.83 4.36 13.86 15.87 32.88	4.14 4.77 16.11 18.59 32.30	2.19 2.52 10.24 11.63 12.18	37.5 8.625 100.00% 37082 37.5 8.125 100.00% 50920 37.5 7.50 100.00% 133986 37.5 7.00 100.00% 274279 37.5 0.25 100.00% 49845