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Evaluation of Flygt Mixers for Application in Savannah River Site Tank 19

Test Results from Phase A: Small-Scale Testing at ITT Flygt

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Summary

This report provides the results of the small-scale (0.45-m-diameter tank) Flygt mixer tests conducted at the ITT Flygt Corporation (Trumbull, Connecticut) laboratory in March 1998. Staff from Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory, the Savannah River Site, and ITT Flygt Corporation are conducting a joint mixer testing program to evaluate the applicability of Flygt mixers to Savannah River Site Tank 19 waste retrieval and waste retrieval in other U.S. Department of Energy waste tanks.

Stationary submerged jet mixers manufactured by ITT Flygt Corporation were tested in a 0.45-m- (1.5-ft-) diameter tank to evaluate their ability to mobilize cohesive sludge and maintain rapidly settling solids in suspension. The data gathered in these small-scale tests will be compared with similar tests conducted in 1.8-m- and 5.7-m-diameter tanks at PNNL (Powell et al. 1999). This comparison will allow inferences to be drawn regarding the scale-up of Flygt mixers over the range of configurations and waste simulants tested.

The principal objectives of the small-scale Flygt mixer tests were to measure the critical fluid velocities required for sludge mobilization and particle suspension, to evaluate the applicability of the Gladki (1997) method for predicting required mixer thrust, and to provide small-scale test results for comparison with larger-scale tests to observe the effects of scale-up.

The following key observations resulted from the analysis of the small-scale (Phase A) data presented in this report.

- The average fluid velocities near the tank floor required to maintain 20x50-mesh zeolite particles in motion on the tank floor are between 25 and 40 cm/s. Tank 19 at the Savannah River Site is known to contain a significant quantity of 20x50-mesh zeolite.

- The zeolite suspension test results are consistent with the predictions of the Gladki (1997) particle suspension model, which was developed by ITT Flygt staff using the same mixers and tank that were used for the present study.

- The average wall shear stress required to mobilize about 80% of a cohesive sludge layer in the 0.45-m tank was observed to be about 5% of the undisturbed sludge shear strength. It is presently unknown whether a similar relationship holds in larger tanks.

The small-scale tests were not designed to be geometrically, dynamically, or kinematically similar to the planned mixing in Tank 19, so these results cannot be used to directly make predictions for Tank 19 mixing. The effects of scale-up on the mixing requirements will be evaluated as part of the Phase B Flygt mixer testing (Powell et al. 1999).

Acknowledgments

The authors gratefully acknowledge the support of ITT Flygt staff, in addition to Hanna Gladki, who participated in this test program. The authors of this report thank Harry Langford, Mike Dillard, and David Robinson, all of whom are affiliated with ITT Flygt Corporation. Their assistance during the Phase A tests is greatly appreciated.

Funding for this work was provided by the Tanks Focus Area, a program established by the U.S. Department of Energy's Environmental Management Office of Science and Technology to provide technical solutions for remediation and closure of radioactive waste storage tanks.

Acronyms and Nomenclature

D	propeller diameter, m
D_n	nozzle diameter for submerged fluid jet, m
DOE	U.S. Department of Energy
F	axial mixer thrust, N
h_{liq}	liquid level, m
k	mixer performance coefficient, 1/revolution
LDA	laser Doppler anemometer
$M_{supernate}$	mass of supernate before sludge mobilization commences, kg
N	mixer speed, s^{-1}
P	axial hydraulic mixing power, W
PNNL	Pacific Northwest National Laboratory
P/V	power per unit volume
Q	total axial fluid flow rate from propeller exit, m^3/s
r	radial distance from centerline of submerged fluid jet, m
SRS	Savannah River Site
TNX	full tank test facility at SRS
U_o	fluid exit velocity from nozzle, m/s
$U(r,z)$	local jet velocity, m/s
V	total fluid volume in tank, m^3
V_{sludge}	volume of sludge before sludge mobilization commences, m^3
V_{tank}	total volume of sludge and supernate, m^3
v_{avg}	average fluid velocity, m/s
v_{peak}	peak fluid velocity, m/s
x	fraction of sludge suspended in Equation (4.5), dimensionless
z	axial distance in Equation (4.4), m
ρ	fluid density, kg/m^3
ρ_{final}	density of slurry when all sludge is mixed with supernate, kg/m^3
ρ_{slurry}	density of slurry formed by mixing sludge with supernate, kg/m^3
τ_0	average wall shear stress, Pa
τ_s	shear strength of sludge, Pa
τ_y	dynamic yield stress of sludge, Pa

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1.0 Introduction

In the early 1980s two jet mixer pumps were used to dissolve and retrieve the saltcake in Tank 19 at the Savannah River Site (SRS). Not all of the waste was removed during this retrieval campaign, however, and roughly 125 m^3 (33 kgal) of waste solids remain. The solids are composed of sludge, zeolite, and salt. Based on the topography of the solids heel in Tank 19, it is suspected that the mixer pumps did not have sufficient power to maintain the faster settling solids in suspension or that the mixer pump jets pushed the larger, settled solids out beyond the reach of the jets.

Efforts are now being made to identify and design alternative waste retrieval techniques for the Tank 19 waste. Shrouded axial propeller mixers manufactured by ITT Flygt Corporation are one of the suggested alternatives. Staff from Pacific Northwest National Laboratory (PNNL),[a] Oak Ridge National Laboratory, SRS, and ITT Flygt Corporation are conducting a joint mixer testing program to evaluate the applicability of Flygt mixers to Tank 19 waste retrieval and waste retrieval in other U.S. Department of Energy (DOE) tanks. This test program consists of three phases. The first phase involves small-scale mixer testing at the ITT Flygt laboratory in Trumbull, Connecticut. The second phase involves larger-scale (about 1/4-geometrical scale) tests of Flygt mixers at PNNL. The third and final phase involves full-scale mixer testing at SRS. Testing in different tank sizes is needed to evaluate and validate scaling methods so that the results of the relatively inexpensive small-scale tests can be used to make full-scale mixer performance predictions more cost effective.

Flygt mixers consist of an electrically powered propeller surrounded by a close-fitting shroud. Figure 1.1 shows a Flygt mixer mounted to a vertical mast (Flygt 1997). The 37-kW (50-hp) mixers being considered for use in Tank 19 have a propeller diameter of approximately 51 cm (20 in.) and operate at 860 rpm. The rapidly spinning propeller creates a turbulent fluid jet with an average exit velocity approaching 6 m/s (see Figure 1.2) (Flygt 1997). Several of these 37-kW mixers may be required to mix the waste in Tank 19.

This report is focused on the first phase of testing (Phase A tests conducted at ITT Flygt). Phase A tests were performed in a 0.45-m- (1.5-ft-) diameter tank using small Flygt mixers (7.8-cm propeller diameter) positioned near the floor. The ability of these small Flygt mixers to suspend rapidly settling particles and to mobilize simulated tank sludge was evaluated through testing. The data from these tests are described in this report.

Section 2.0 of this report provides the key findings of the small-scale Flygt mixer tests. Modifications to the tests outlined in the original test plan for this work are described in

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[a]PNNL is operated by Battelle for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

Section 3.0. Section 4.0 presents the results from the small-scale Flygt mixer tests. Publications referenced in this report are listed in Section 5.0. The Phase A Test Plan is provided in Appendix A. Appendix B provides the mixer thrust data from all the tests. The sludge mobilization test results are provided in Appendix C.

Figure 1.1. Flygt Mixer

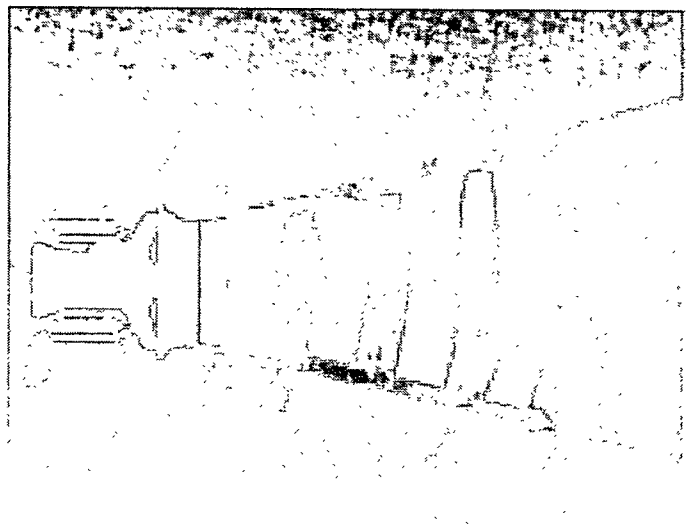

Figure 1.2. Flygt Mixer Jet Flow as Described by ITT Flygt

2.0 Conclusions

The key findings of the small-scale Flygt mixer tests are provided in this section. Some of these findings may not apply in larger tanks, so these data must be applied carefully when making predictions for large tanks. Flygt mixer testing in larger tanks at PNNL and in a full-scale tank at the SRS will be used to determine the applicability of these findings.

The principal objectives of the small-scale Flygt mixer tests were to measure the critical fluid velocities required for sludge mobilization and particle suspension, to evaluate the applicability of the Gladki (1997) method for predicting required mixer thrust, and to provide small-scale test results for comparison with larger-scale tests to observe the effects of scale-up.

The tank profile and mixer orientation (i.e., stationary, horizontal mixers) were in the same configuration as the prototype system, however, available resources did not allow geometric, kinematic, and dynamic similitude to be achieved.

The results of these tests will be used in conjunction with the results from similar tests using larger tanks and mixers (tank diameters of 1.8 and 5.7 m [Powell et al. 1999]) to evaluate the effects of scaling and to aid in developing a methodology for predicting performance at full scale.

2.1 Key Findings from Small-Scale Testing

The key findings from the small-scale tests are listed below. Until the results of the larger-scale tests are known, the conclusions drawn from the small-scale tests should be viewed as preliminary.

- The average fluid velocities near the tank floor (1 cm above) required to maintain 20x50-mesh zeolite particles in motion are between 25 and 40 cm/s. Measurements indicated that slightly lower velocities are required to maintain 50x100-mesh zeolite in motion.

- The zeolite suspension test results are consistent with previous particle suspension work (Gladki 1990, 1997) in a 0.45-m tank using the same Flygt mixers with the exception that at higher particle concentrations less mixer thrust was required than is predicted by Gladki (1997). This difference is likely due in part to the fact that Gladki used the somewhat more demanding just-suspended criterion rather than the all-particles-in-motion criterion, which was used for most of the Phase A testing.

- Sludge mobilization experiments revealed that, for the mixer configuration tested, the average wall shear stress required to achieve roughly 80% of the sludge mobilized was

approximately 5 ± 1.5%[a] of the undisturbed sludge shear strength when the shear strength was greater than or equal to 100 Pa. If more time is allowed for the erosion of sludge, then the required shear stress will likely be less than about 5% of the undisturbed shear strength, but the amount of potential decrease is unknown.

- The sludge mobilization data are consistent with the hypothesis that undisturbed shear strength provides a more appropriate measure of sludge erosion resistance than does the yield stress of the disrupted sample.

- The *axial* hydraulic power per unit slurry volume required to reach the all-particles-in-motion criterion was typically between 150 and 200 W/m^3 for the 20x50-mesh zeolite and between about 80 and 140 W/m^3 for the 50x100-mesh zeolite. Some uncertainty exists in the basis for these power estimates. The actual axial power densities may have been higher based on measurements made by Fahlgren and Tammelin (1992). If the total hydraulic power (i.e., shaft power) is used in the calculations, the 20x50-mesh zeolite required approximately 500 W/m^3 to reach the all-particles-in-motion condition.

- At the end of the zeolite suspension tests, slurry was pumped from the tank while mixing continued until the propeller blade was exposed. The suction tube was located 1 cm above the tank floor. Between 45% and 70% of the zeolite was removed from the tank using this technique. The applicability of these numbers to the retrieval of similar solids from much larger tanks is currently unknown but will be evaluated as part of the testing in larger tanks.

2.2 Predictions for Larger-Scale Mixing

The predictions provided below for mixing requirements in larger tanks are based on the findings of the small-scale Flygt mixer tests. Significant differences exist between the predicted numbers of mixers for zeolite suspension when different scale-up relationships are used. Further, it is unknown whether the constant-wall-shear-stress approach is appropriate for predicting sludge mobilization. These uncertainties will be addressed through testing in larger tanks at PNNL and SRS. The predictions should all be viewed as preliminary until they are validated or refuted by the larger-scale tests. The predictions for larger-scale Flygt mixing are as follows:

- The constant wall stress method for mixer sizing predicts that the 3-kW (4-hp) Model 4640 mixer, which is planned for use in PNNL's 1.8-m tank, will need to produce 110 ± 25 N of thrust to meet the all-particles-in-motion criterion for a 1.5 vol% slurry of 20x50-mesh zeolite. This thrust corresponds to a mixer speed of roughly 315 ± 30 rpm.

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[a]Unless otherwise noted, all uncertainty values in this report refer to the 95% confidence interval for the mean value, which is computed based on the assumed Gaussian data scatter from replicate measurements.

- The constant power-per-unit-volume (P/V) method predicts that the Model 4640 mixer will need to run at 530 ± 25 rpm in the 1.8-m tank to achieve the predicted power density of 150 to 200 W/m^3, which is the power density range found to be required for the 1.5 vol% slurry of 20x50-mesh zeolite in Test 1. The power densities observed in the small-scale tests might actually have been up to twice as high as those estimated based on the mixer thrust data (see Section 4.1). Using mixer shaft power instead of just hydraulic axial power leads to a predicted Model 4640 mixer speed of 625 rpm for 20x50-mesh zeolite in the 1.8-m tank.

- Constant-wall-shear-stress scaling predicts that two (1.9 ± 0.4) modified 37-kW (50-hp) Model 4680 Flygt mixers will be required to maintain all 20x50-mesh zeolite particles in motion inside SRS Tank 19. Based on this estimate and an allowance for experimental and scale-up uncertainties, Flygt recommends that three Model 4680 mixers be used in Tank 19.

- Constant-P/V scaling predicts that, in Tank 19, seven (6.4 ± 0.9) Model 4680 mixers will be required to achieve 175 ± 25 W/m^3, which is approximately the power density found to be required to suspend the 20x50-mesh zeolite. The lack of geometric similarity between the small-scale tests and the planned Tank 19 operation may lead to different (higher or lower) power densities required at full-scale than were measured in the small-scale tank, assuming that constant P/V scaling applies here.

- Assuming that constant average wall shear stress is the appropriate scale-up parameter for sludge mobilization, and assuming that the required average wall shear stress is roughly 5% of the sludge shear strength, the number of 37-kW (50-hp) Model 4680 mixers required to mobilize 80% of sludge with shear strengths of 100, 1000, and 2000 Pa shear strengths is 1, 6, and 12 (calculated values of 0.6, 5.6, and 11.2) mixers, respectively. Note that the small-scale test conducted using 2000 Pa sludge required less thrust than predicted by the 5%-of-shear-strength relationship. These test data predict that only 69 Pa is required, which leads to a prediction of 7.5 mixers for mobilization of sludge at full scale.

2.3 Issues for Larger-Scale Tests

Solids suspension and sludge mobilization tests will be conducted in larger-scale tanks during Phase B (1.8- and 5.7-m tanks) and Phase C (25.9-m tank) of the Flygt mixer test program. During these larger-scale tests, data will be collected that will ultimately lead to a better understanding of the design requirements for Flygt mixer systems in SRS Tank 19 and other DOE waste tanks.

The larger-scale tests will be designed to address specific issues related to both Flygt mixer system scale-up and operation in large tanks like Tank 19. The key issues to be addressed in later testing are briefly described below:

- Scaling relationships will be evaluated to determine how best to predict the mixing requirements in large tanks, such as SRS Tank 19. In particular, the accuracy of the constant-wall-shear-stress scaling method developed by Gladki (1997) will be evaluated. The tests planned for Phase B should allow an assessment of Gladki's scaling method as well as other methods such as constant-power-per-unit-volume scaling.

- The effects of multiple mixers in the tank as well as the orientations of those mixers will be examined in the larger-scale tests. Tests in a full-scale tank at SRS (Phase C) will be used to evaluate mixer placement methods as well as the fluid velocities produced for a given set of mixing conditions.

- Tests will also be performed to determine the fraction of solids that can be pumped from the different size tanks during mixer operation. The goal is to determine how to best maximize the quantity of solids recovered from the tank.

3.0 Modifications Made to Test Plan

The experimental apparatus and procedures used to conduct the small-scale tests are described in the test plan for this work provided in Appendix A. Modifications made to the tests outlined in the original test plan are discussed in this section. Refer to Appendix A for a complete description of the tests performed.

3.1 Zeolite Suspension Tests

The zeolite suspension tests (Tests 1A through 1F and 2A through 2F) were conducted as described in Appendix A with one exception. The test plan states that the mixer speed and thrust would be recorded when all the particles met the just suspended criterion (i.e., when no particles remain on the tank floor for more than one second). Early in the testing, it was decided that the all-particles-in-motion criterion would be more appropriate because it is only necessary to move the solids around the tank to eventually retrieve them; all the particles do not need to be lifted above the tank floor. This revised criterion is slightly less demanding because it allows particles to remain on the tank floor provided they are visibly moving or sliding on the tank floor or remain motionless for less than one second.

Mixer thrust data were collected during these tests, but not all of these measured thrusts were used in the data analysis because some of the data were suspect. A small screw on the mixer support structure was found to have been biasing some of the thrust measurements low in Test 2F and possibly in some of the earlier tests. See Section 4.1 for a complete discussion of how the mixer thrust data were analyzed. All the thrust data collected are given in Appendix B.

Particle size analysis of the zeolite used for the zeolite suspension tests verified that there was no significant change in the zeolite particle size distribution during the tests. As testing continued, some increasing cloudiness in the supernate was noted and attributed to degradation of the zeolite particles from repeated collisions with the mixer blades. The particle size analyses demonstrates that the size reduction of zeolite particles was not significant. The pre-test and post-test particle size data for both the 20x50-mesh and 50x100-mesh zeolites are shown in Figures 3.1 and 3.2, respectively. Two sieve analyses were performed for both the pre-test and post-test samples.

3.2 Fluid Velocity Tests

Fluid velocities were measured, as planned, using a hot-film anemometer with clean water in the tank (the anemometer will not operate with particles in the fluid). Hot-film probe calibration measurements were performed both before and after the small-scale testing and no significant differences were found. Figure 3.3 shows the probe calibration data.

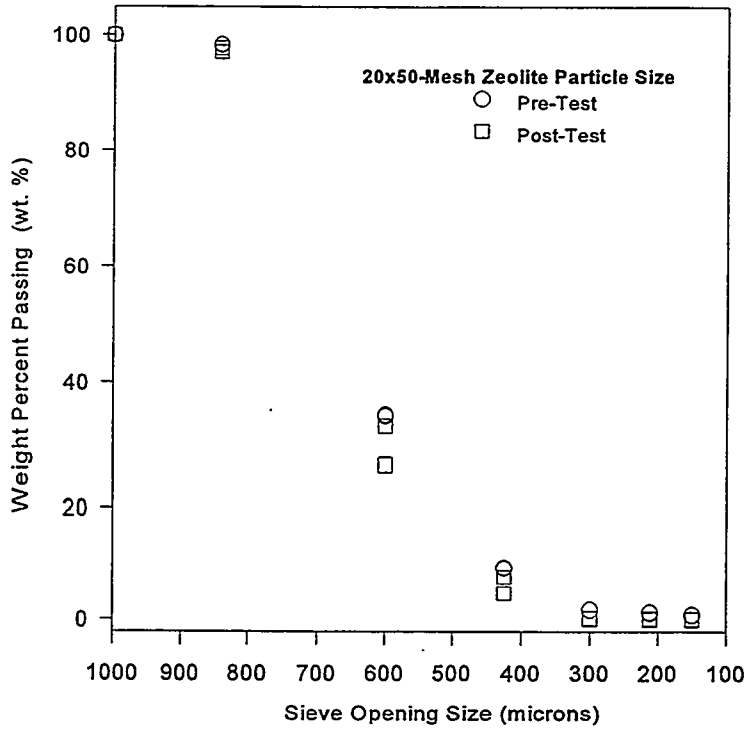

Figure 3.1. 20x50-Mesh Zeolite Particle Size Data

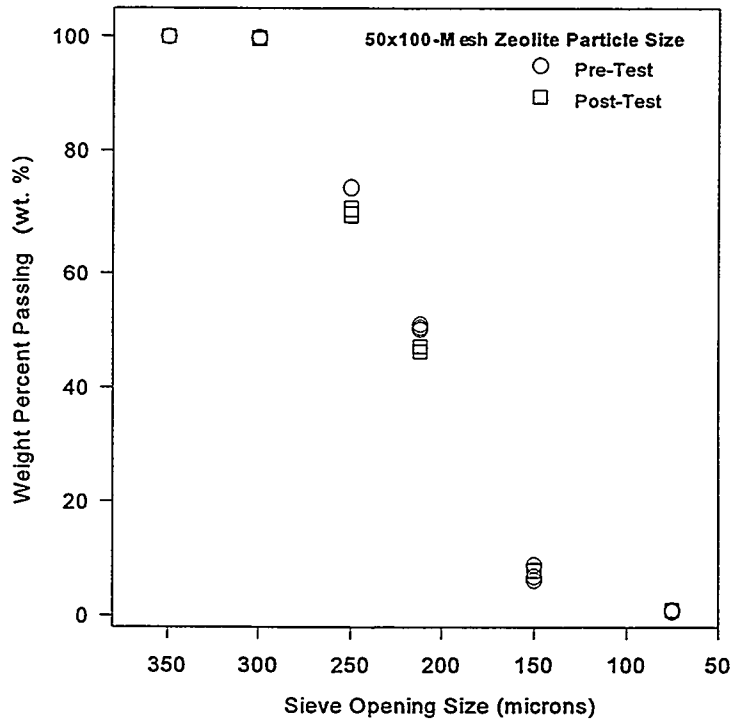

Figure 3.2. 50x100-Mesh Zeolite Particle Size Data

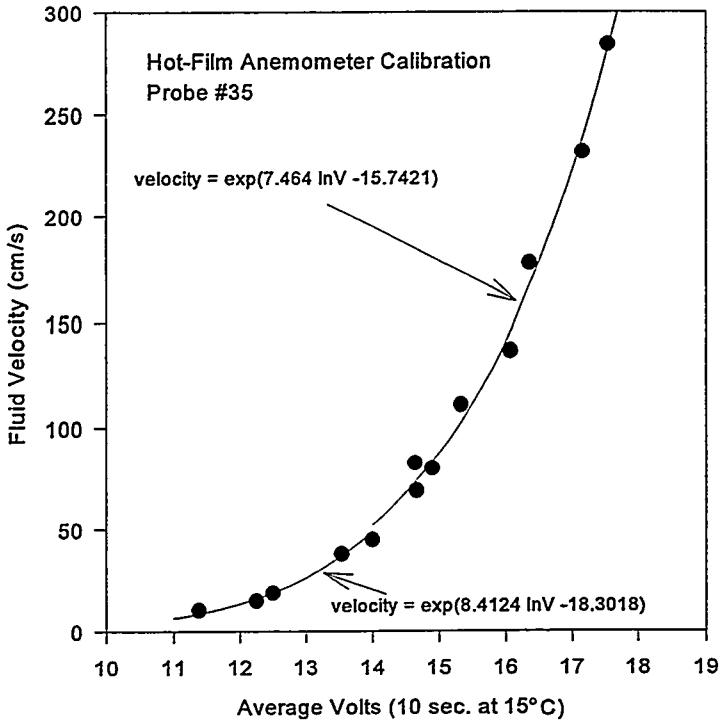

Figure 3.3. Hot-Film Anemometer Calibration

The hot-film probe calibration was separated into two regions for the purpose of the fluid velocity data analysis. The data below 14 volts were fit with one set of parameters and the data above 14 volts were fit with a second set. Fitting the data with a single set of parameters did not result in a good fit of the data in the low velocity range. All voltages were corrected to a water temperature of 15°C. The same temperature correction was applied to all of the Test 3 data gathered in the small-scale tank.

The voltage output from the hot-film anemometer controller was sampled and recorded at 100 Hz by a computer-based data acquisition system. At each probe location and mixer speed tested, between 3 and 5 scans of the temporal voltage data, each 10 seconds long, were recorded at 100 Hz. These data were used to compute the average and peak fluid velocities for each scan.

Efforts were made to ensure that the probe was aligned with the predominant fluid flow direction at each probe location in the tank. This task was difficult, however, in locations where the flow direction varied significantly because of turbulence.

Velocity measurements were not made at all the probe locations specified in the test plan. These measurements were quite time-consuming so a smaller set of probe locations was selected for testing. The probe locations tested are described in Table 3.1 and Figure 3.4. The test plan stated that velocity measurements would be performed only at the mixer speeds observed to be required for selected zeolite suspension tests. Because the mixer speed could be adjusted without difficulty and the fluid velocities reached steady-state quickly, fluid velocity measurements were made at 1000, 1250, 1500, 1750, and, when possible, 2000 rpm. Liquid levels of 17.5 and 25.7 cm were tested using a single mixer positioned parallel to the 0-to-180-degree tank diameter but shifted to the left by 6.4 cm, as shown in Figure 3.4. The mixer propeller was located 18.4 cm from the 0-degree edge of the tank, and the propeller axis was 5 cm above the tank floor. This is the same mixer position that was used for all the tests where one mixer was used. When the second mixer was employed, it was positioned so that the center of the propeller was located 10 cm radially from the tank center at 225 degrees. The propeller was angled so that it formed an 18-degree angle with the axis of the first mixer. When not in use, the second mixer was removed

Table 3.1. Hot-Film Anemometer Probe Locations

Test No.	Probe Location	Probe Height (cm)	Probe Direction (deg.)
3A	90 degrees, 7.6 cm from tank wall, h_{liq} = 17.5 cm	1.0	various
3B	Aligned w/mixer axis, 6.4 cm from tank wall, h_{liq} = 17.5 cm	1.0	0, 90
3C	270 degrees, 6.4 cm from tank wall, h_{liq} = 17.5 cm	1.0	0
3E*	Aligned w/mixer axis, 17.5 cm from tank wall measured along mixer axis, 8.6 cm from mixer propeller, h_{liq} = 17.5 cm	5.0	0
3F	135 degrees, 2 cm from tank wall, h_{liq} = 17.5 cm	1.0	45
3G	135 degrees, 2 cm from tank wall, h_{liq} = 25.7 cm	1.0	45
3H	90 degrees, 7.6 cm from tank wall, h_{liq} = 25.7 cm	1.0	0
3I	270 degrees, 6.4 cm from tank wall, h_{liq} = 25.7 cm	1.0	0
3J	Aligned w/mixer axis, 3.5 cm from tank wall, h_{liq} = 25.7 cm	1.0	0
3K	Aligned w/mixer axis, 17.5 cm from tank wall measured along mixer axis, 8.6 cm from mixer propeller, h_{liq} = 25.7 cm	5.0	0

*Test 3D was not performed

from the tank. All of the water velocity measurements made in Test 3 were made using only a single mixer. The second mixer, which is shown in Figure 3.4, was removed from the tank during Test 3. The second mixer was used in some of the other tests and, when used, it was positioned as shown in Figure 3.4.

3.3 Sludge Mobilization Tests

The sludge mobilization tests (Tests 4 through 8) were conducted as described in the test plan except that not all of the tests were repeated because of time constraints. The tests performed are described in Section 4.4. The only other deviation from the test plan for these tests involved the target sludge properties for Test 4. The sludge simulants tested in Tests 4A and 4B were likely weaker than the target of 50 Pa. This issue is discussed further in Section 4.4. The data collected during Tests 4 through 8 are provided in Appendix C.

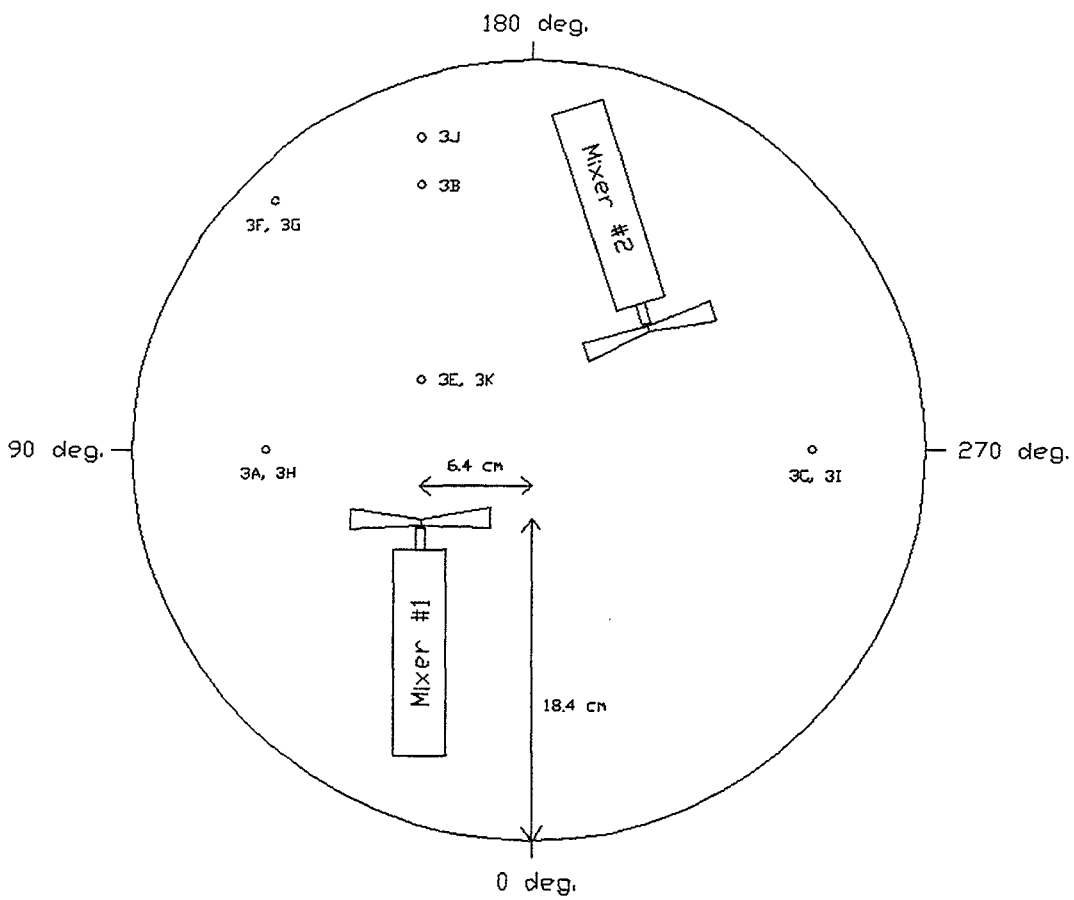

Figure 3.4. Velocity Measurement and Mixer Locations (Mixer #2 not used in velocity measurement tests, but it was used in the position shown for some of the other tests.)

3.4 Test Apparatus Photographs

Figures 3.5 through 3.8 are photographs taken during the small-scale testing. These pictures are included to provide a more complete description of the test apparatus than that provided in the test plan in Appendix A.

Figure 3.5 is a close-up picture of the small-scale Flygt mixer. This mixer is a 1/10-scale model of a Flygt Model 4501 mixer. It has a 3-blade propeller with a diameter of 7.8 cm and a pitch of 5.2 cm, which implies a blade angle of about 12 degrees.

No jet ring shroud was used on the small-scale mixer during the Phase A testing. The full-scale mixers planned for Tank 19 have jet rings surrounding their propellers. The jet rings improve the thrust and efficiency of the Flygt mixers. However, because the mixer thrust was measured directly in the Phase A testing, the lack of a jet ring on the small-scale mixer is of little consequence according to the mixer sizing approach described by Gladki (1997). Only the mixer thrust data are used to make predictions using Gladki's constant-wall-shear-stress method. The mixer efficiency does not enter into the calculations.

Figure 3.6 shows the small-scale mixer operating in the 0.45-m tank. The tank contained water and small plastic beads, which were used to observe the liquid flow patterns.

Figure 3.7 shows a zeolite suspension test in progress. It is evident in the photograph that the concentration of zeolite particles was significantly higher near the tank floor than near the liquid surface. The picture in Figure 3.8 was taken a couple of seconds after the mixer was activated for a sludge mobilization test. The mobilized solids are forming a slurry downstream of the mixer propeller.

3.5. Tank Volume Measurements

All the tests were performed with the liquid level inside the tank adjusted to either 17.5 cm or 25.7 cm. With the mixer assembly removed, the mass of water required to fill the tank to each of these two levels was measured. To reach the 17.5-cm liquid level, a total of 28.14 kg of water at 15°C was required. This mass corresponds to a volume of 28.17 L, which implies an average tank diameter of 45.32 cm. To reach the 25.7-cm liquid level, a total of 41.30 kg of 15°C water was required. This mass, which has a volume of 41.34 L, implies an average tank diameter of 45.26 cm. An average tank diameter of 45.3 cm was used for data analysis.

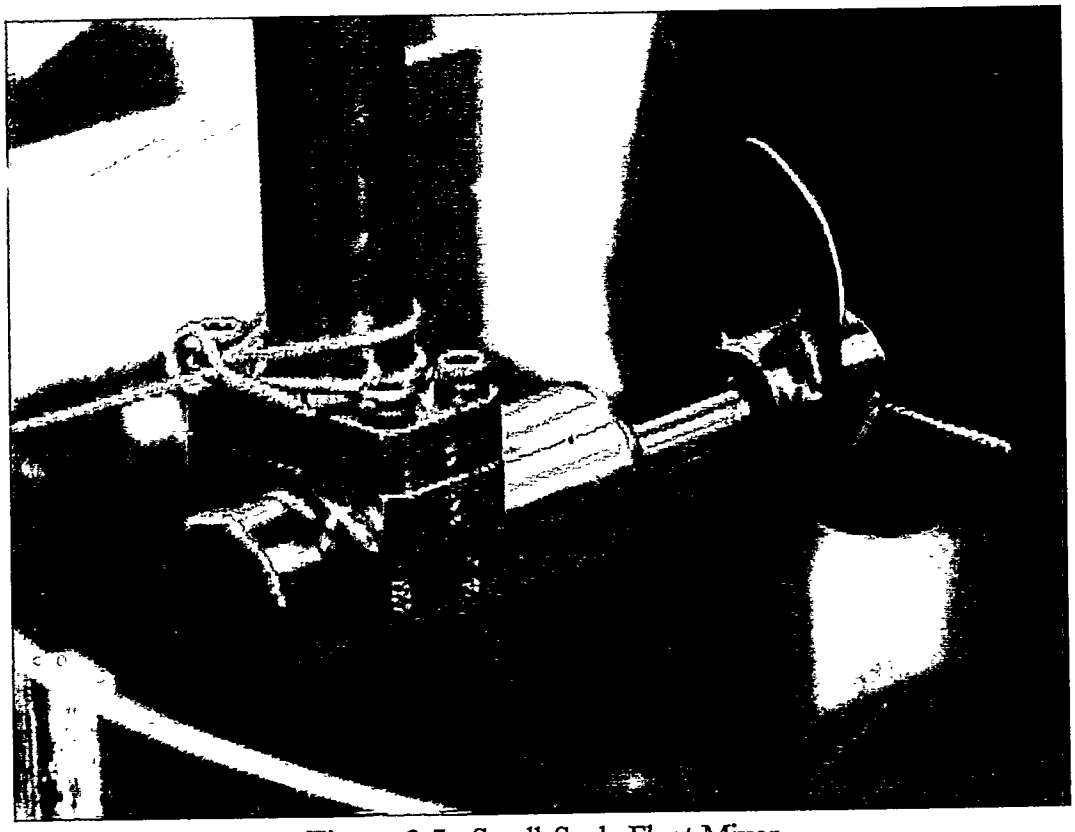

Figure 3.5. Small-Scale Flygt Mixer

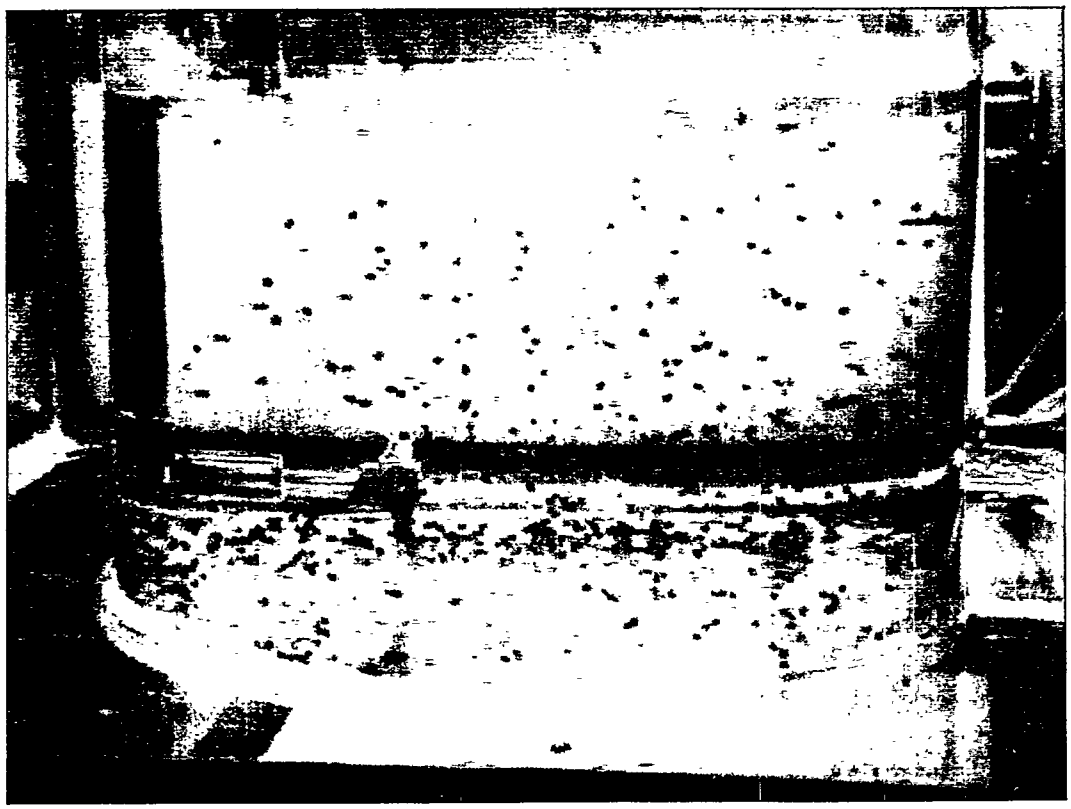

Figure 3.6. Small-Scale Mixer in 0.45-m Tank with Tracer Beads in Water

Figure 3.7. Zeolite Suspension Test in Progress

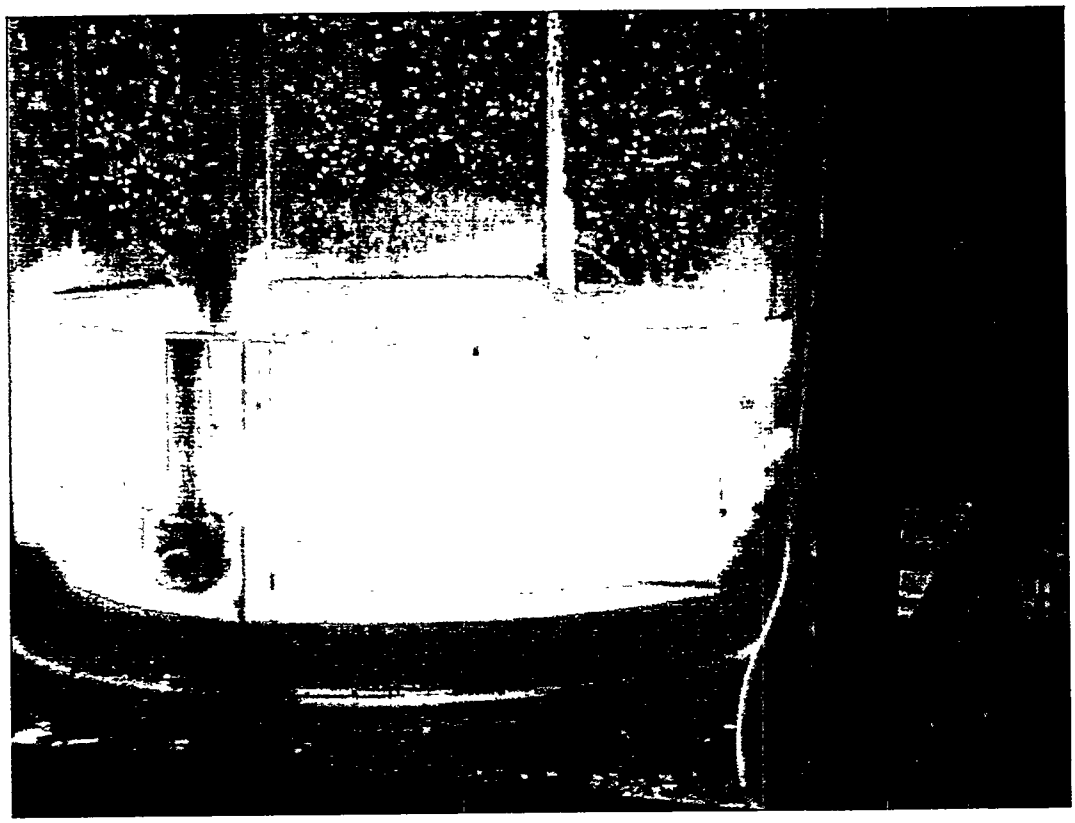

Figure 3.8. Beginning of Sludge Mobilization Test

4.0 Results and Analysis

The results from the small-scale Flygt mixer tests are presented in this section. It must be stressed that the data given in this section do not necessarily imply that similar performance will be attained in larger-scale tanks. The question of scale-up will be addressed through testing in larger tanks.

In general, the small-scale test results were consistent with expectations. The zeolite suspension tests, for example, demonstrated that Gladki's (1997) correlation for solids suspension applies well to zeolite solids in a 0.45-m-diameter tank. While this result is encouraging, it is not surprising given that the correlation was developed using identical mixers in tanks of equal and smaller sizes. The fluid velocities required to maintain zeolite particles in suspension (or in motion) were also found to be consistent with expectations based on correlations that predict erosion velocities for cohesionless solids.

4.1 Mixer Thrust Data

A load cell was used to measure the axial thrust produced by the small-scale Flygt mixer. Thrust data were gathered during all tests. Mixer thrust is a key mixer performance parameter used by Flygt to predict the mixing requirements for solids suspension in larger tanks (see Section 4.6).

For the data analysis, a subset of the mixer thrust vs. rotations per minute (rpm) data were fit to the mixer thrust affinity law. A subset of the data rather than all the data was used because some of the mixer thrust data gathered on the first day of testing were likely erroneous. This assertion is based on the fact that many of the thrust measurements taken on the first day of testing were significantly lower than those observed during later tests at the same mixer speeds. During the last zeolite suspension test conducted on the first day of testing (Test 2F), it was noticed that an adjustment screw on the mixer support structure was restricting the movement of the mixer against the load cell. The mixer was operating at 2000 rpm and thrust readings of 6.10 N and 6.15 N were recorded. The adjustment screw was then removed to ensure the screw no longer interfered with the thrust measurements. Subsequent thrust measurements made immediately after the screw was removed yielded 9.1 N, 9.0 N, and 9.1 N at 2000 rpm. Clearly the adjustment screw was biasing the thrust measurements low during part of Test 2F. This screw may also have affected some of the earlier tests as well, but it is unknown to what extent they were affected.

Some of the thrust measurements made on the first day of testing might also have been biased low due to misalignment of the load cell with the steel rod transmitting the force from the mixer assembly to the load cell. The steel rod became misaligned whenever the mixer assembly was lifted vertically out of the tank. In some cases, the misalignment was noticed and corrected

before testing resumed, but it is not certain that this correction was made in all cases on the first day of testing. After the first day, care was taken to ensure good alignment of the load cell and to periodically verify the calibration of the load cell. Further, the adjustment screw mentioned above was no longer present after the first day of testing. Therefore, none of the thrust data collected during the first day of testing were used. Instead, the thrust data collected on subsequent test days were used to form a correlation between thrust and mixer speed. This correlation was used for all data analyses.

The thrust vs. mixer speed data used for data analysis are shown in Figure 4.1. Data from Test 3 (water only) through Test 8 (kaolin sludge mobilization) are included in Figure 4.1. Thrust data from tests where two mixers were used are not included in Figure 4.1 because the second mixer was positioned to induce a recirculating flow inside the tank and the drag from this swirling flow biased the mixer thrust measurements low. Thrust data for the repeat zeolite suspension tests conducted on the second day of testing (i.e., Tests 1A, 1B, and 1C) are also included in Figure 4.1. The good agreement between the correlation and the zeolite data from the second day of testing provides further evidence that the relatively low thrust measurements observed on the first day of testing were in error. All the mixer thrust data collected during the tests are provided in Appendix B.

The mixer thrust data were fit to the thrust affinity law equation, which is derived based on an assumed average velocity distribution exiting the propeller blades.[a] The equations for the mixer flow (Q), thrust (F), and power (P) affinity laws derived in this manner are

$$Q = \frac{\pi}{12} kND^3 \tag{4.1}$$

$$F = \frac{\pi}{32} \rho k^2 N^2 D^4 \tag{4.2}$$

$$P = \frac{\pi}{160} \rho k^3 N^3 D^5 \tag{4.3}$$

where ρ = fluid density, kg/m^3
k = empirical constant, 1/revolution
N = mixer rotation speed, 1/second
D = propeller diameter, m

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[a]The fluid velocity is assumed to vary linearly from zero at the propeller centerline to kND at the propeller tip.

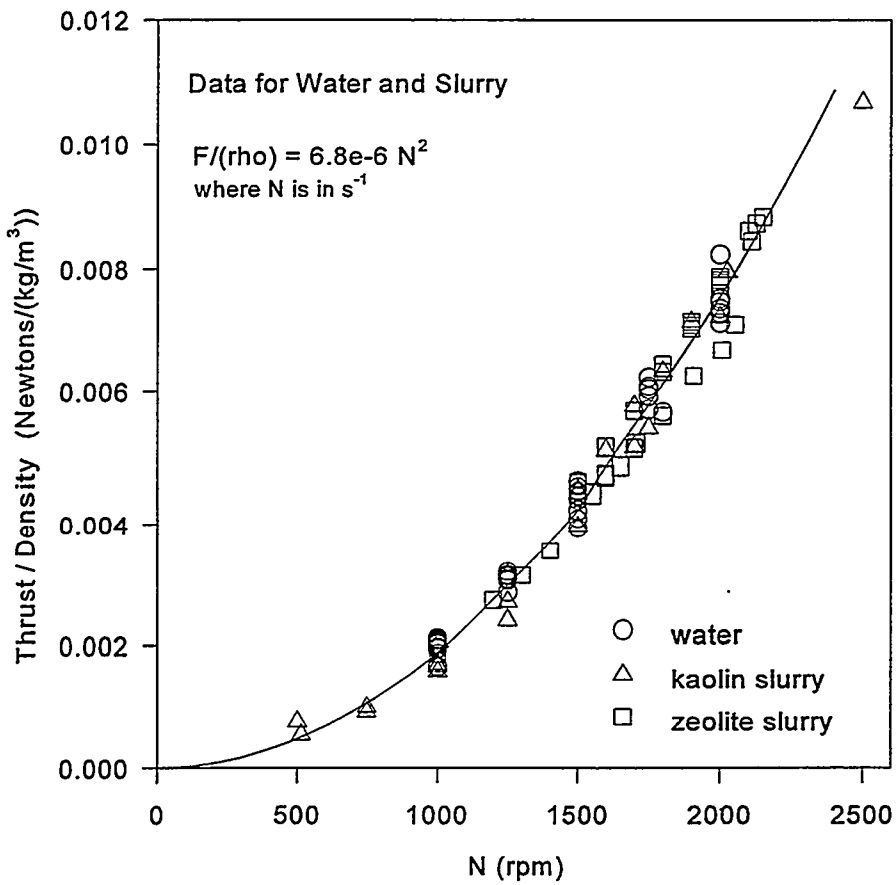

Figure 4.1. Mixer Thrust Data and Correlation Used for Data Analysis

Using the thrust affinity law [Equation (4.2)], the data in Figure 4.1 are used to determine a value for k. For the Figure 4.1 data, k is found to be 1.37. If the assumed velocity distribution is reasonable,.this same k can be used to predict the flow (Q) and axial hydraulic power (P) from the small-scale mixer. It is worth noting that a k of 2.42 is consistent with the flow, thrust, and power affinity law constants given in the 37-kW (50-hp) Model 4680 mixer test report (Flygt 1998).

Fahlgren and Tammelin (1992) used a laser Doppler anemometer (LDA) system to measure the fluid velocity distributions produced by a small Flygt mixer impeller identical to the one used in the present study. The average velocity very near the mixer discharge was found to be near zero at the propeller centerline, but between about 25% to 80% of the propeller radius the fluid velocity was nearly constant. Beyond 80% of the propeller radius, the velocity drops rapidly to zero. This velocity distribution is quite different from the one assumed in the derivation of Equations (4.1) through (4.3).

To evaluate whether the LDA-determined velocity distribution gives results consistent with Equations (4.1) through (4.3), the thrust data given by Fahlgren and Tammelin were fit to Equation (4.2) and k for their mixer was found to be 1.55.[a] Using this value for k, Equations (4.1) and (4.3) were used to estimate the axial volumetric flow rate (Q) and axial hydraulic power (P) at 1200 rpm, which is the mixer speed used for the LDA measurements. The flow rate was estimated to be 3850 cm^3/s and the axial power was estimated to be 1.7 W.

These predictions were then compared with the data given by Fahlgren and Tammelin. The actual value of Q at 1200 rpm was found by integrating the LDA velocity data immediately downstream of the propeller. This calculation gave a flow rate of 3760 cm^3/s, which is in excellent agreement with the Q estimate based on Equation (4.1) using $k = 1.55$, that was, as noted previously, determined from the mixer thrust data at 1200 rpm.

Fahlgren and Tammelin (1992) computed the kinetic energy flux (power) across the mixer discharge surface by integrating the temporal fluid velocity data in both the axial and angular directions. The mixer power was estimated to be 3.1 W based on root-mean-square velocities and 3.5 W based on the integrated temporal data, which likely provides a better measure of the true time-averaged kinetic energy flux. These values are roughly two times greater than that predicted by Equation (4.3) using $k = 1.55$. Part of this difference is that Equation (4.3) addresses only the axial power and not the angular power. Fahlgren and

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[a]The k for the Fahlgren and Tammelin mixer (1.55) is higher than that found for the mixer used in the present study (1.37). This discrepancy is attributed to the Fahlgren and Tammelin mixer being positioned well away from the tank floor whereas our mixer was positioned with the blade tips about 1 cm above the tank floor. The presence of the floor restricts the flow of fluid into the propeller intake region.

Tammelin (1992) do not report the relative fractions of axial and angular power found by their computations, but when the reported average velocities in the axial direction are integrated, the axial hydraulic power is estimated to be 2.6 W at 1200 rpm. The mixer shaft power at 1200 rpm was reported to be 3.8 W.

The 2.6-W estimate is roughly 1.5 times the 1.7 W estimated based on the mixer power affinity law [Equation (4.3)] using $k = 1.55$. This difference implies that the axial hydraulic power in the tests described in this report may actually be greater than those estimated by Equation (4.3) using $k = 1.37$, which was determined by the thrust vs. mixer speed curve (Figure 4.1). For the mixer power calculations presented in this report, it has been assumed that the power predicted by Equation (4.3) (and $k = 1.37$) is accurate. It should be noted, however, that the actual mixer power may have been larger, perhaps by a factor of 1.5 to 2.0. This issue will be investigated further in Phases B and C of this test program.

4.2 Fluid Velocity Measurements

The hot-film anemometer was used to make fluid velocity measurements at the probe locations shown in Table 3.1 and Figure 3.4. For each probe location, several (3 to 5) 10-second-long scans of the probe voltage were taken at 100 Hz and recorded using the computer-based data acquisition system.

The average velocity (v_{avg}) during each 10-second scan was computed. The v_{avg} values from each scan were then averaged and the sample standard deviation and Student's t-Distribution was used to estimate the 95% confidence interval for the mean v_{avg}.

The peak velocities during each 10-second scan were also averaged to provide a measure of the highest velocities experienced by each point. Because interest exists in the fluid velocities required to keep solids from remaining motionless on the tank floor for more than one second, the peak velocities for each second of data collected were also computed. The ten 1-second peak velocities from each scan were averaged and their respective 95% confidence intervals computed.

The v_{avg}, 10-second peak, and 1-second peak velocity data are presented in Table 4.1 and Figures 4.2 though 4.21.

Section 4.3 describes the use of fluid velocity data to predict the critical suspension velocities for zeolite particles.

Fahlgren and Tammelin (1992) measured the centerline fluid velocities of an identical small-scale Flygt mixer roughly 8.5 cm downstream from the propeller, which is the same distance used for Tests 3E and 3K. They report a centerline average velocity of 90 cm/s at a mixer speed of 1200 rpm. This value falls within the range of velocities measured at 1250 rpm

Table 4.1. Hot-Film Anemometer Velocity Data

Test No.	Mixer Speed (rpm)	V_{avg} (cm/s)	95% CI (cm/s)	10-sec. V peak (cm/s)	95% CI (cm/s)	1-sec. V peak a (cm/s)	95% CI (cm/s)	1-sec. V peak b (cm/s)	95% CI (cm/s)	1-sec. V peak c (cm/s)	95% CI (cm/s)	1-sec. V peak d (cm/s)	95% CI (cm/s)
3A	1000	13.4	2.1	23.8	2.7	20	2.3	19.7	1.7	19.1	1.3		
	1250	14.3	2.7	34.4	12	23.4	3.4	28	3.8	23.6	3.2		
	1500	16.1	2.1	42.3	4.2	31.1	4.1	29.1	4.5	30.3	4	31.9	4.5
	1750	20.3	15.3	52.6	12.2	45.1	6.7	42.8	5	30.7	7.7		
	2000	20.0	0.7	59.1	8.5	45	7	45.7	9.5	44.2	5.6	43.2	7.5
3B	1000	9.8	3.8	62.2	31.8	26.1	9.2	42	15.4	30.4	12.6		
	1250	17.9	2.8	66.8	10	47.5	9.6	46.8	8.5	38.5	9.4	46	11.6
	1500	20.8	4.1	72.4	25	52.6	9.5	47.2	8.7	54.9	14		
	1750	25.6	6.5	107.6	19.8	65	19.5	68.8	10.2	70	12	78.4	14.7
	2000												
3C	1000	16.6	2.5	38.4	1.7	29.9	6	32.7	2.7	32.7	3.5		
	1250	23.3	4.5	63.2	8.9	42.5	5.6	47.7	8.1	51.5	6.8	44.8	7
	1500	32.2	3.3	73.9	2.4	61.5	6	62.6	4.6	59.8	5.2	62.5	5.5
	1750	15.0	3.4	88	5.9	77.2	7.1	72.4	6	70	6.8	71	9.9
	2000												
3E	1000	54.9	6.9	140	25	129	11.9	126	7.9	120	5.6		
	1250	82	12	191	40	162	10.4	170	13.4				
	1500	114	13.3	235.6	26	205	12	220	14	220	12		
	1750	130	24	278	59.5	254	10	240	11.1	266	14		
	2000												
3F	1000	8.3	2.8	15	5.1	13.4	1.9	13.4	1.4	10.8	1.14		
	1250	12.5	1.5	24.3	4.4	20.2	2.35	17.8	1.7	20.4	2.7		
	1500	20.6	3.4	35.9	3.2	28.1	3.3	31.1	2.8	27	3.5		
	1750	21.7	11	45.5	24.2	26	6.4	40.5	4.6	33.3	3.9		
	2000												
3G	1000	9.1	2.3	58	18.6	26.9	11	24.6	13.5	31.4	9.6	22.5	8.8
	1250	11.9	3.6	73.1	10.8	42.3	13	45	14	38	15		
	1500	23.2	3.7	100.2	23.5	70.5	9.4	71.1	10.1	63.4	13.4	83	13.6
	1750	29.2	4.5	126	21	98	15	88	13	88	12	85.5	10.5
	2000	37.6	2.1	151.5	16	114	12.9	108	19	109	20	107	13
3H	1000	14.7	2.3	40	22	29	3.6	36	7.2	28	3		
	1250	19.0	1.7	75.8	51	41.6	8	53	12.3	65	20.4	39	5.7
	1500	30.2	4.4	125	63	98	25	87	20	51	6.4	101	28
	1750	34.2	3.5	168	51	84	16	96	25	139	32	94	30
	2000	44	18	197	41	156	27	167	26	112	36	105	24
3I	1000	12.8	2.6	28	10.6	18.8	3	22.9	3.3	22.1	3.7		
	1250	10.3	1.8	34.8	4.4	18.8	4.6	23	3.9	21	5	23	6.6
	1500	16.0	3.0	45.7	14	30	4.5	31	5.8	35	7.4	27	4.6
	1750	18.0	4.5	54	17	43	8.5	32	8.7	37	6.6	33	6.4
	2000	31.8	17	89.4	18	42	12.5	72	11	74	14	61	12
3J	1000	20.9	2.2	74	22	48	8	47.6	6	52	14		
	1250	26.9	3.1	90	16	66.5	9	61	7.9	65	10	61	15
	1500	35.2	2.0	107	20	83	7.9	89	6	87	13	87	14
	1750	30.9	5.7	117	13	82	14	95	11	96	13.5	89	14
	2000	39.3	2.4	140	22	98	11	103	13	113	22	111	12
3K	1000	46.6	8.4	158	15	120	19	114	21	121	21	116	24
	1250	61	19	193	28	174	28	154	13	165	20	133	33
	1500	60	24	244	25	172	34	168	33	203	17	180	32
	1750	125	2.6	290	30	243	17	241	22	253	15	263	22
	2000	123	61	337	19	300	26	221	55	290	5	291	20

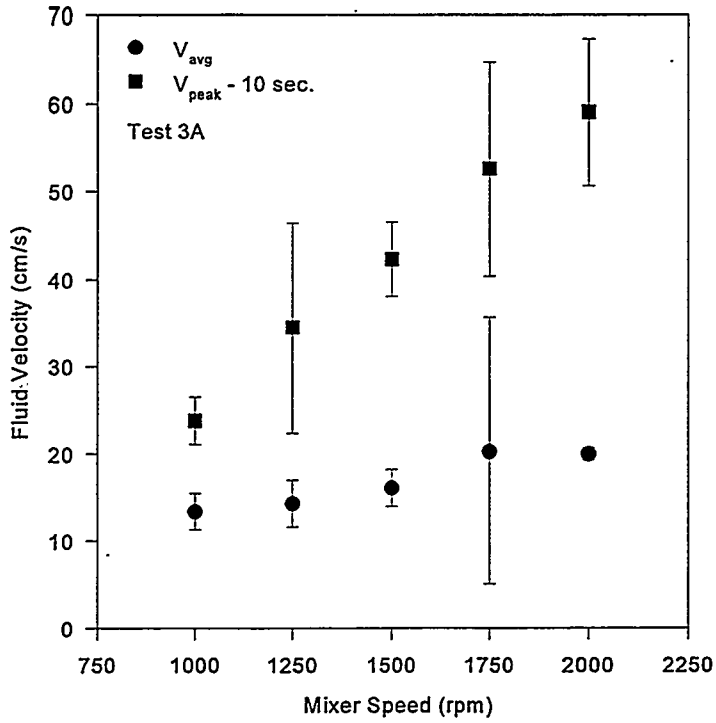

Figure 4.2. Test 3A Fluid Velocity Data

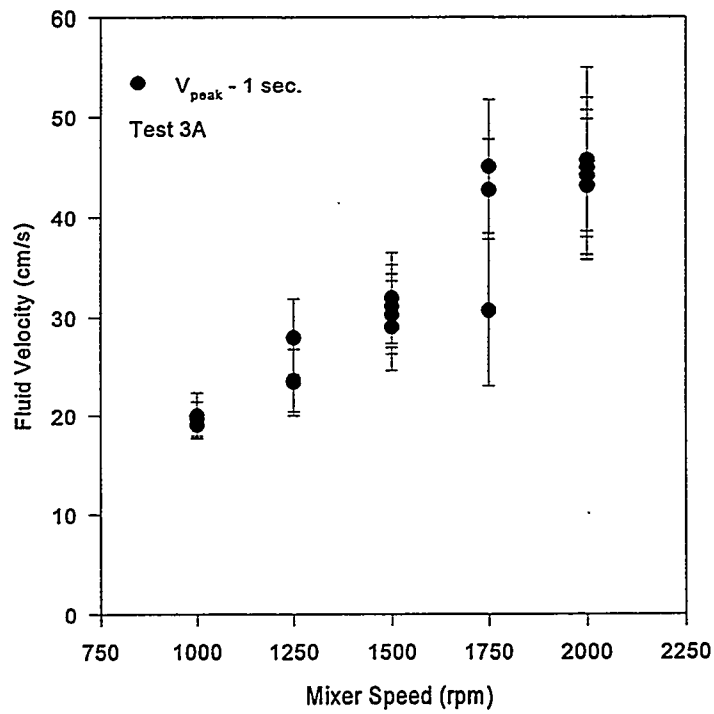

Figure 4.3. Test 3A 1-Second Peak Velocity Data

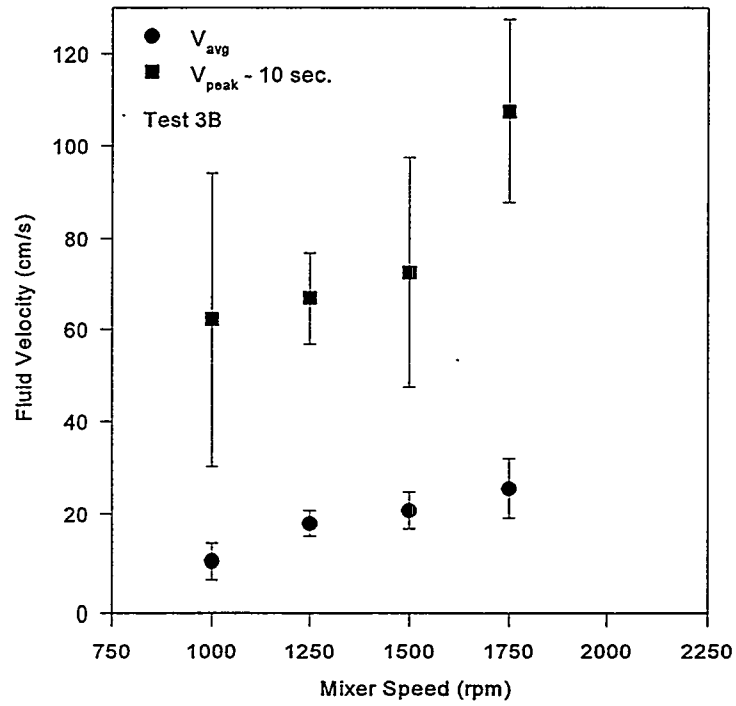

Figure 4.4. Test 3B Fluid Velocity Data

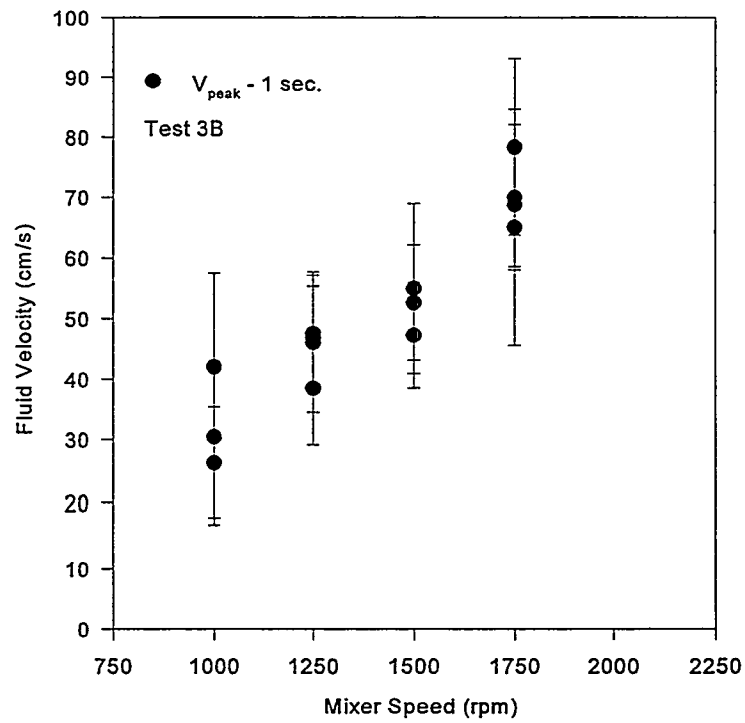

Figure 4.5. Test 3B 1-Second Peak Velocity Data

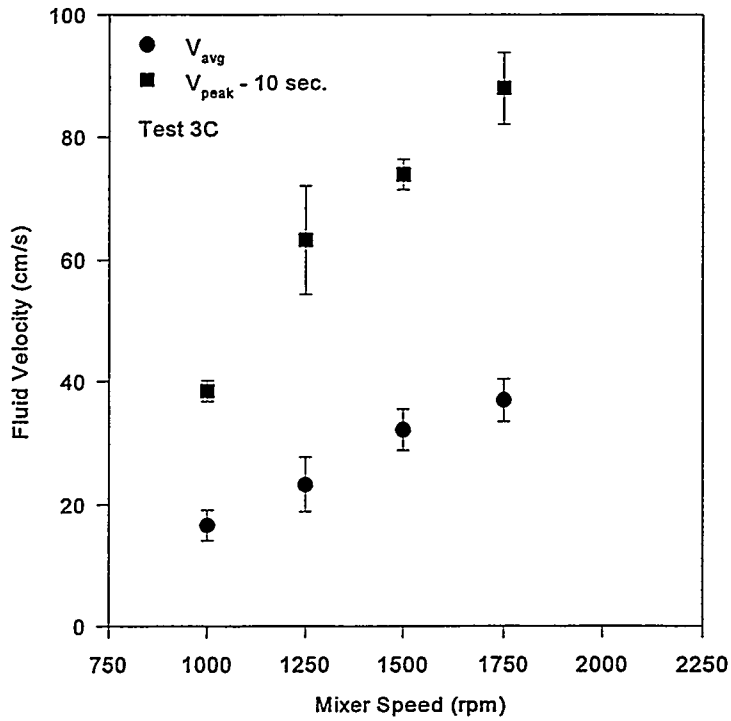

Figure 4.6. Test 3C Fluid Velocity Data

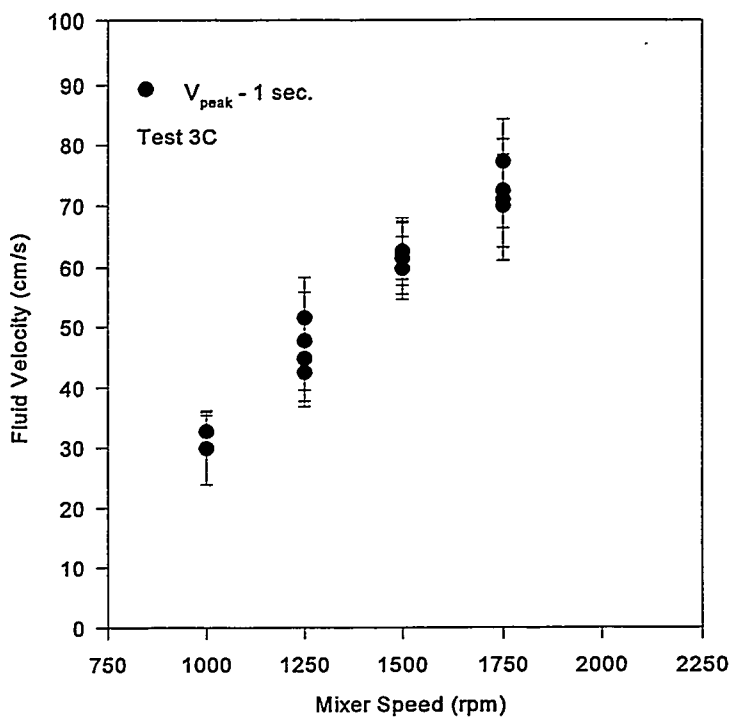

Figure 4.7. Test 3C 1-Second Peak Velocity Data

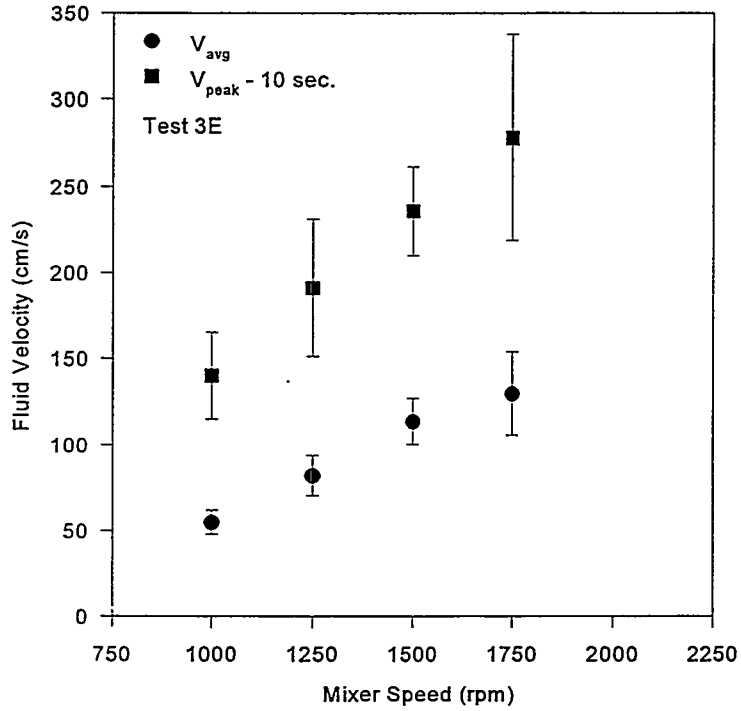

Figure 4.8. Test 3E Fluid Velocity Data

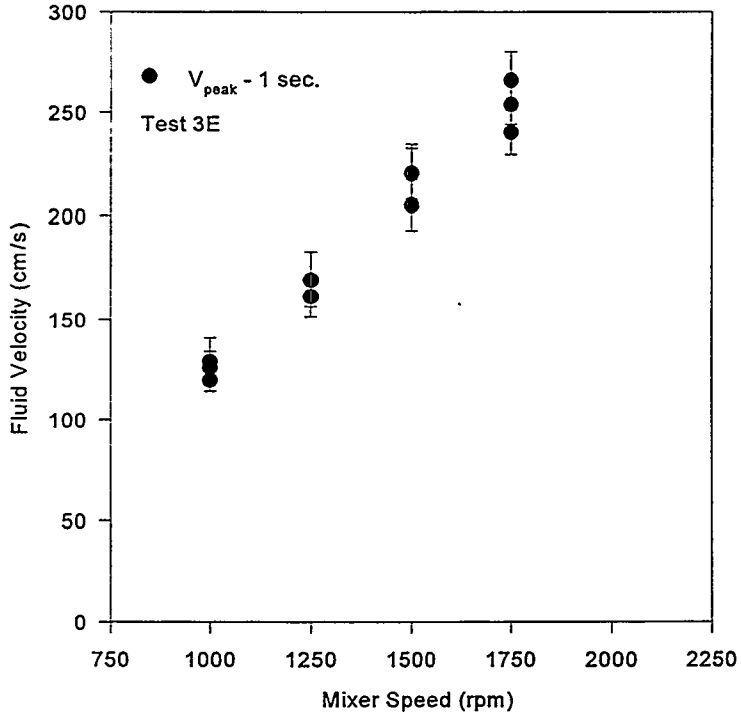

Figure 4.9. Test 3E 1-Second Peak Velocity Data

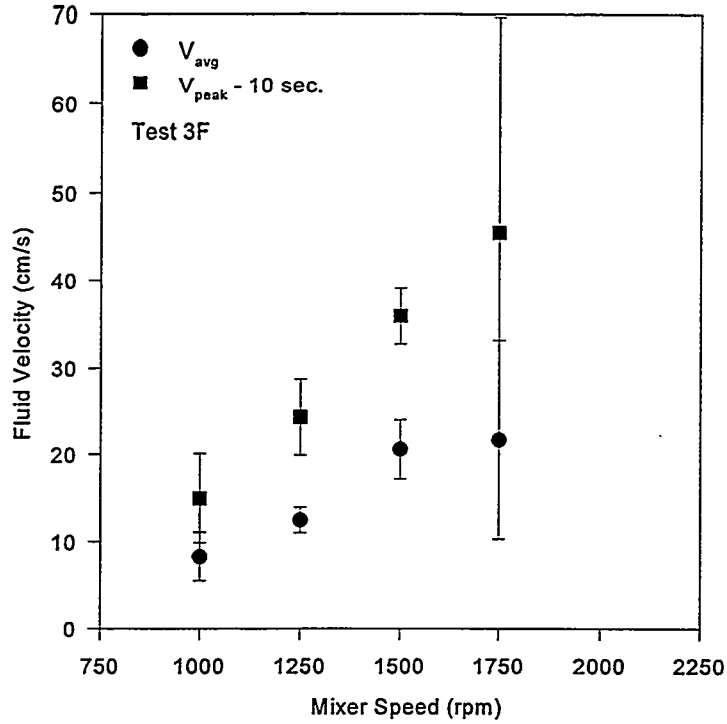

Figure 4.10. Test 3F Fluid Velocity Data

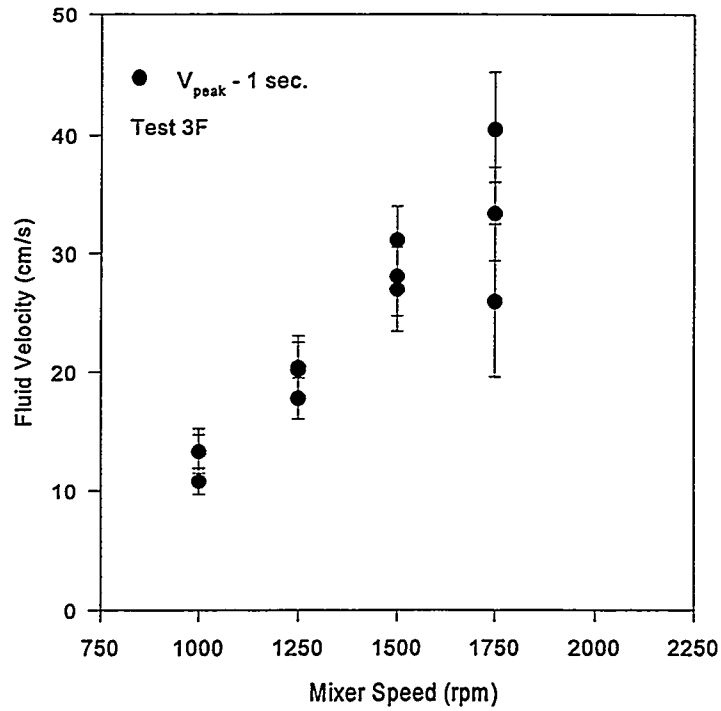

Figure 4.11. Test 3F 1-Second Peak Velocity Data

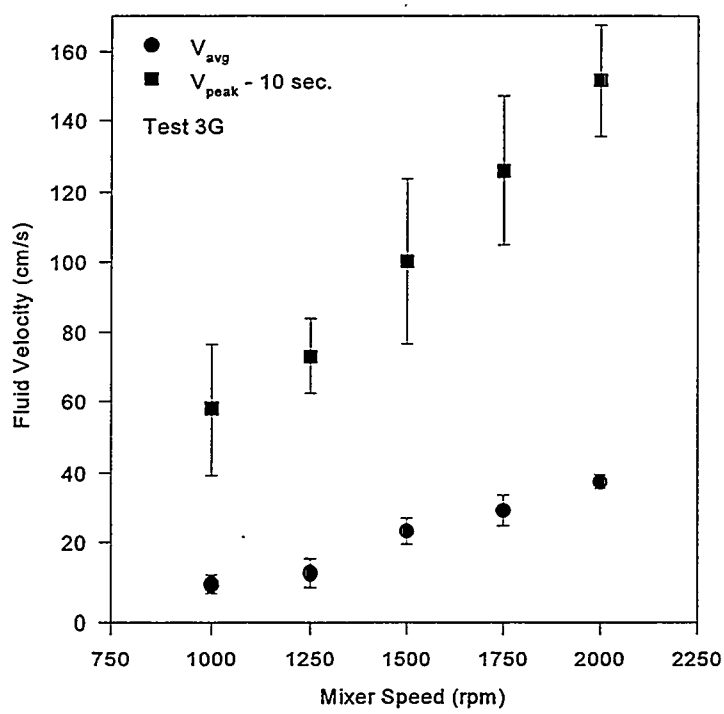

Figure 4.12. Test 3G Fluid Velocity Data

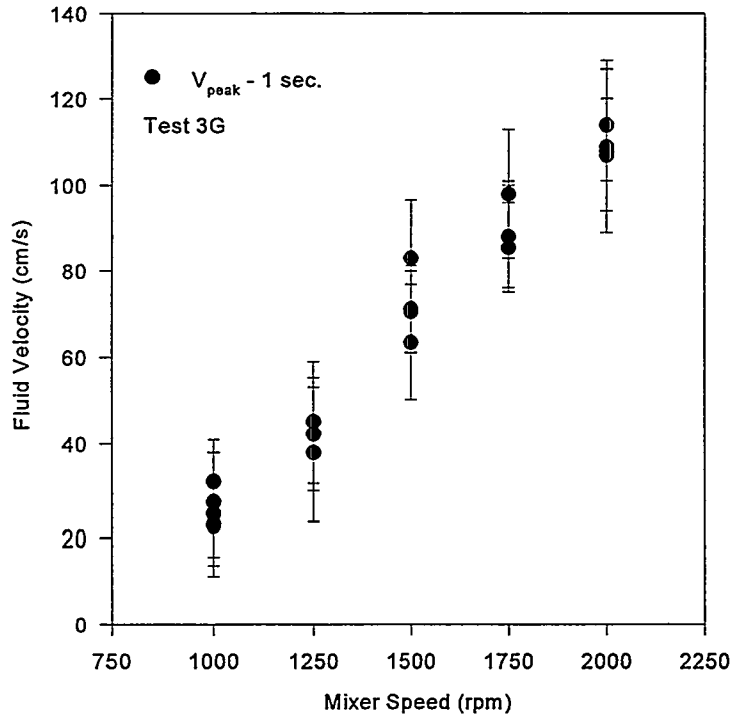

Figure 4.13. Test 3G 1-Second Peak Velocity Data

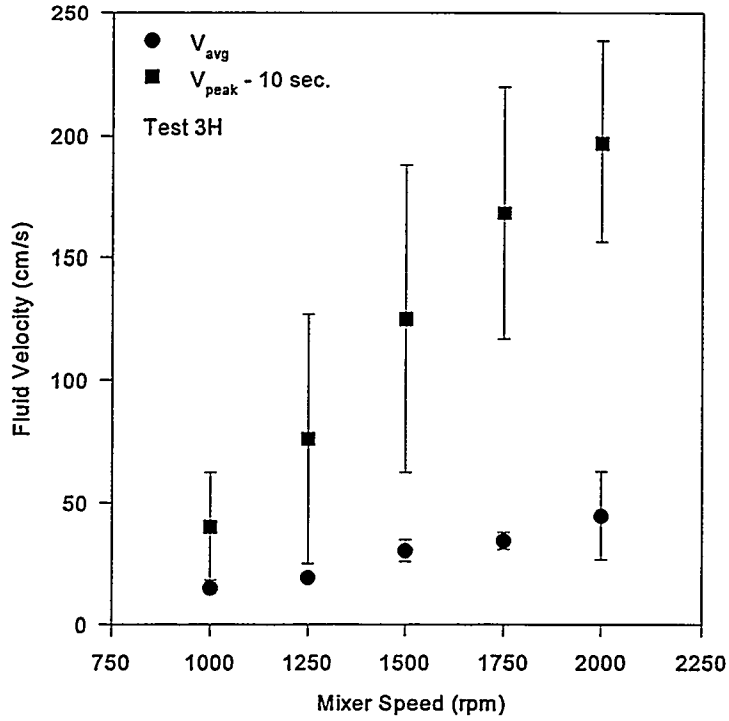

Figure 4.14. Test 3H Fluid Velocity Data

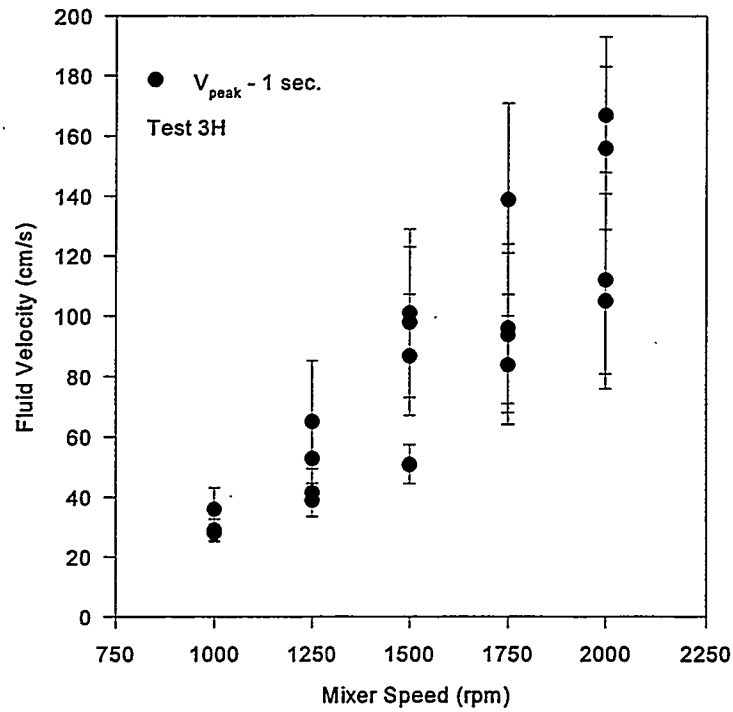

Figure 4.15. Test 3H 1-Second Peak Velocity Data

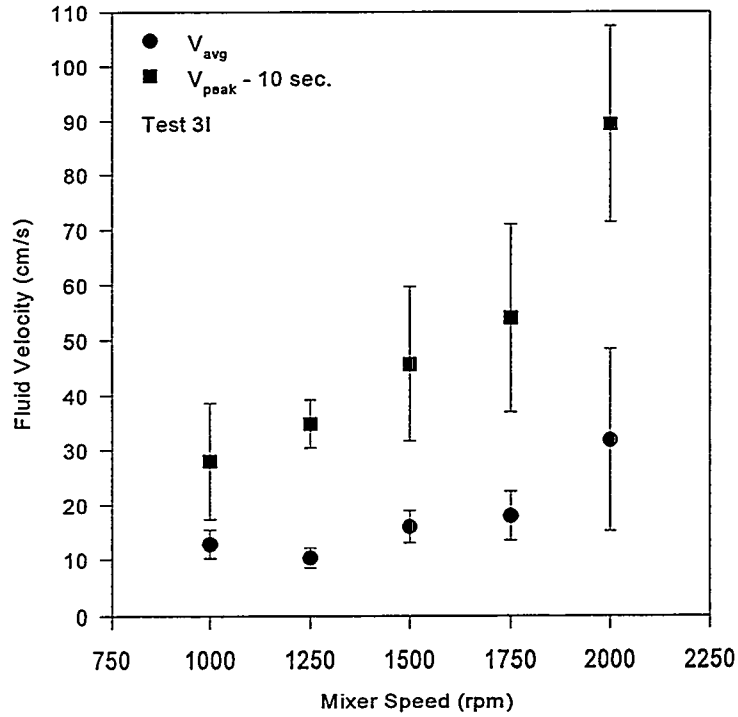

Figure 4.16. Test 3I Fluid Velocity Data

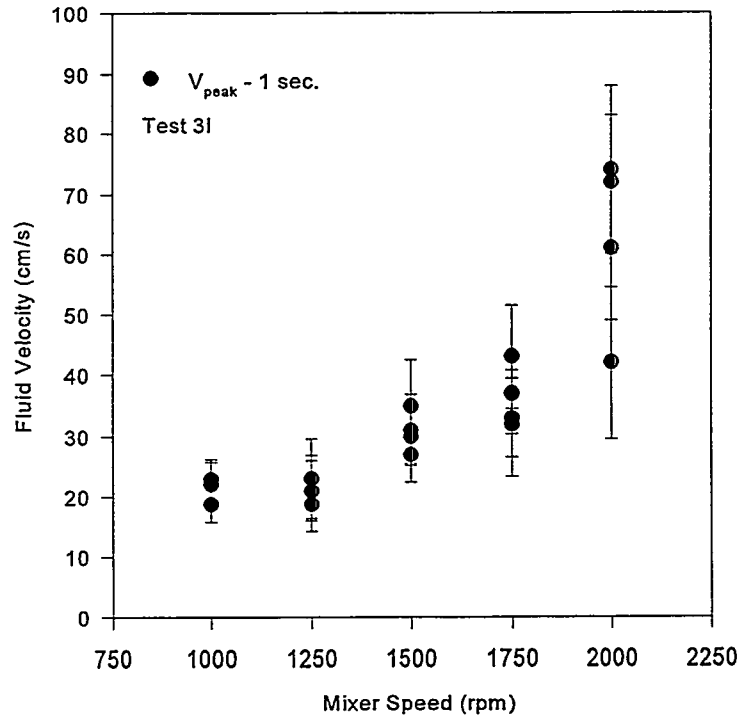

Figure 4.17. Test 3I 1-Second Peak Velocity Data

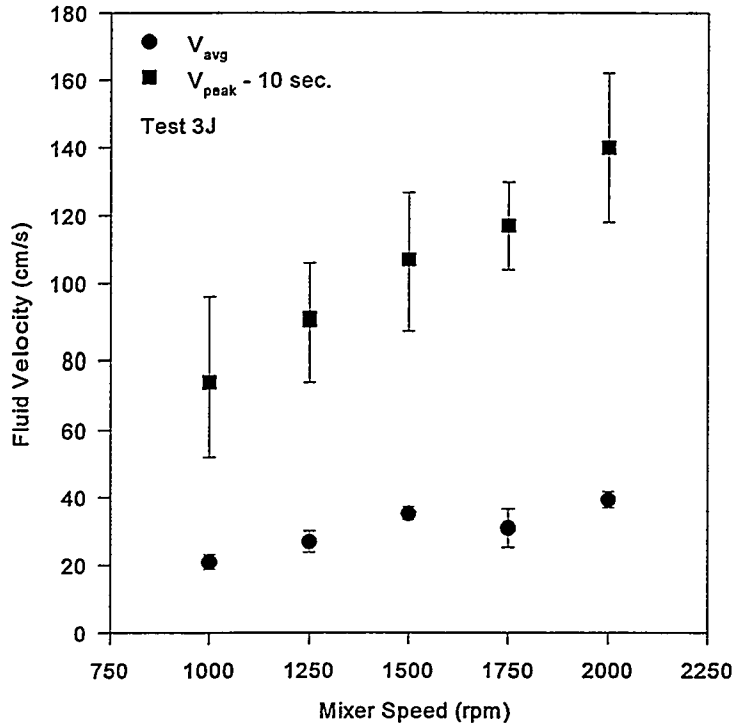

Figure 4.18. Test 3J Fluid Velocity Data

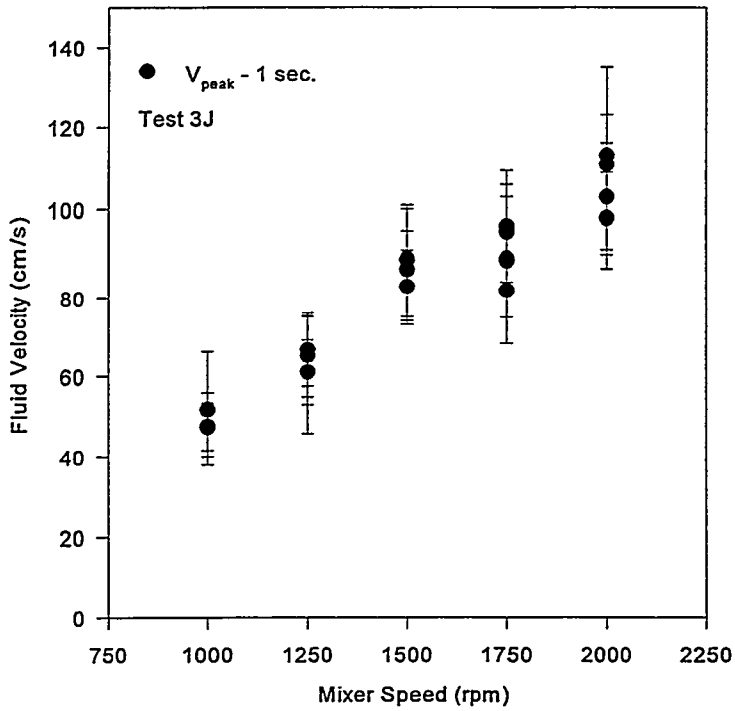

Figure 4.19. Test 3J 1-Second Peak Velocity Data

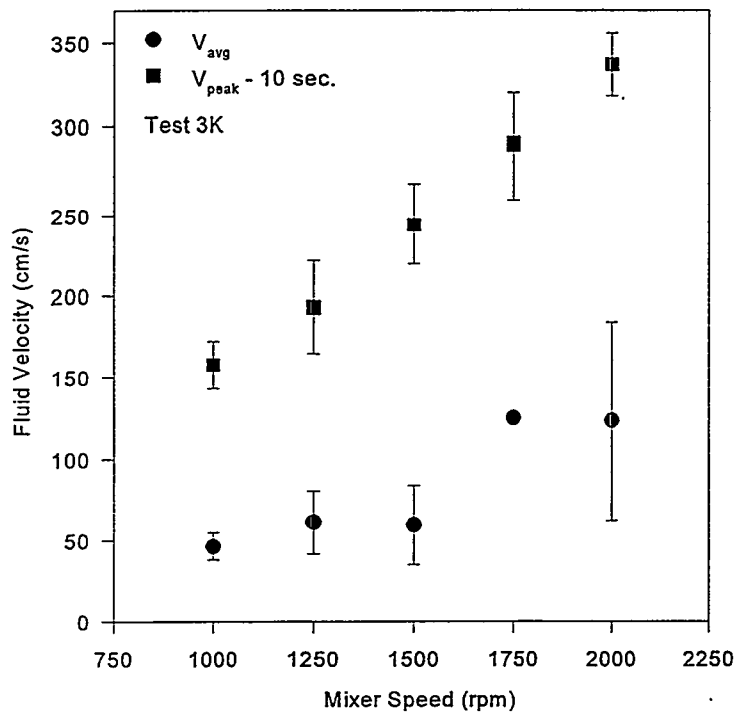

Figure 4.20. Test 3K Fluid Velocity Data

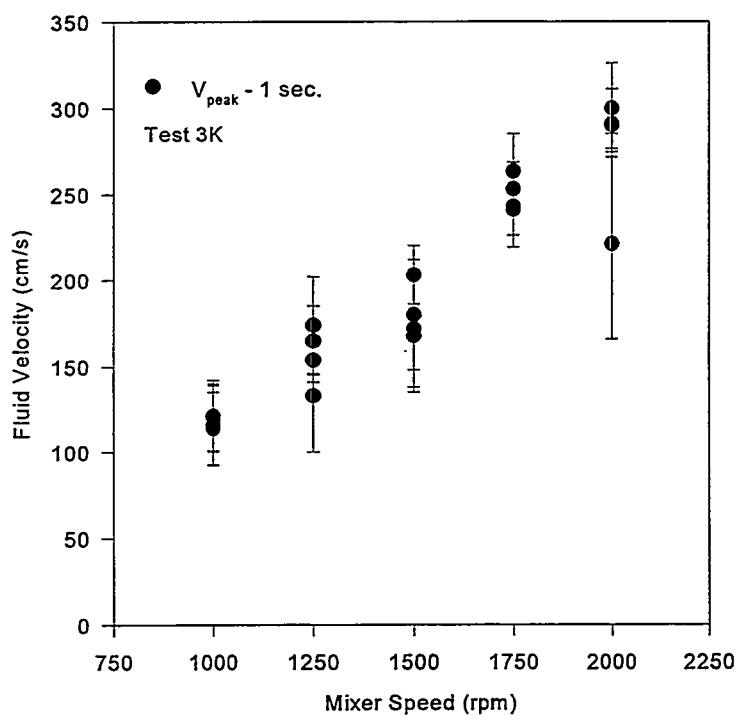

Figure 4.21. Test 3K 1-Second Peak Velocity Data

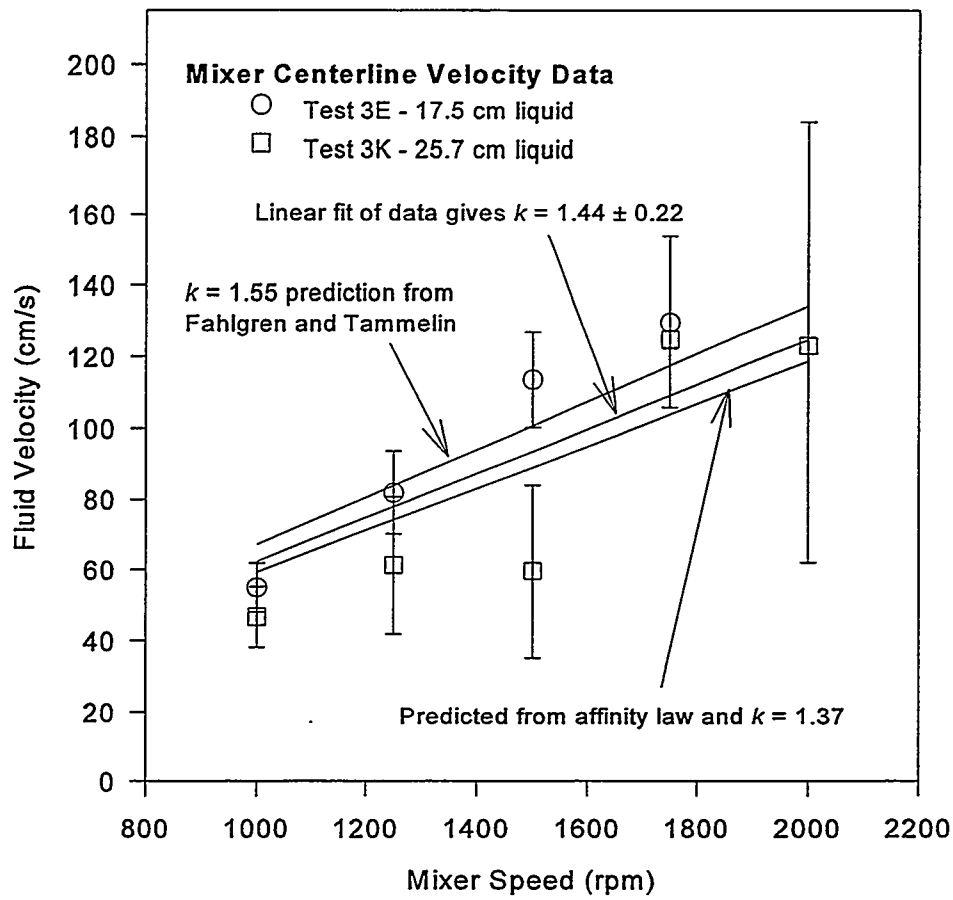

Figure 4.22. Comparison of Centerline Velocities with Flow Affinity Law

in Tests 3E and 3K. The centerline fluid velocity predictions for $k = 1.55$ are also shown in Figure 4.22. The $k = 1.55$ line compares well with the centerline fluid velocity data collected in the present test program.

The v_{avg} data agree reasonably well with expectations based on the mixer flow affinity law [Equation (4.1)] and on measurements made by Fahlgren and Tammelin (1992). Using $k = 1.37$ in Equation (4.1) and then dividing the computed flow by the mixer jet cross-sectional area ($\pi D^2/4$) gives an estimate of the average fluid velocity downstream of the propeller. As shown in Figure 4.22, these estimates compare well with the fluid velocity measurements made at the mixer centerline (i.e., Tests 3E and 3K). A linear fit of the velocity data gives $k = 1.44 \pm 0.22$.

4.3 Zeolite Suspension Tests

As discussed earlier, the mixer thrust data from selected tests were correlated with mixer speed (units of revolutions per second are used for mixer speed in all correlations). This

correlation, given in Figure 4.1, was used to quantify the thrust needed to maintain zeolite solids in suspension. A small adjustment, described below, was made for the increased density of the slurry.

It was assumed that the zeolite solids were well mixed with the tank supernate and the density of this mixture was used when making the mixer thrust estimates. It is known, however, that the zeolite concentration was greater near the tank floor than near the liquid surface, so the actual slurry densities were likely higher. The density effect, however, is unlikely to be significant. For the highest zeolite concentration tested (6 vol.%), the average bulk density is estimated at 1040 kg/m^3. Assuming that all of the zeolite were concentrated in the lower half of the tank, the estimated density only increases by about 4% to 1080 kg/m^3. This increase is relatively small compared with the other experimental uncertainties. Because a defensible basis for selecting a density correction was not apparent, it was decided that the average bulk density would be used. Thus, the actual mixer thrust values may have been slightly higher than those used for data analysis.

For each set of experimental conditions (i.e., particle size, particle concentration, and liquid level), Gladki's (1997) solids suspension prediction model was used to estimate the mixer thrust required to reach the just-suspended criterion. Predictions were made using the low, midpoint (50 wt% passing), and high zeolite particle sizes (see Figures 3.1 and 3.2). Thus, three mixer thrust and average wall shear stress predictions were made for each test. The mixer thrust affinity law [(Equation (4.2)] with $k = 1.37$ was used to relate mixer speed to mixer thrust in the calculations required for Gladki's model.

In general, the required mixer thrusts and average wall shear stresses fell within the predictions from Gladki's model. In many cases, the actual mixer thrust required was somewhat lower than expected from Gladki's model, but this result is likely due to the fact that a less demanding all-particles-in-motion criterion was used for this testing. Gladki's previous work used a slightly more demanding just-suspended mixing criterion. This difference may also account for the small effect of solids concentration observed in the present testing while Gladki's model implies that the required wall stress should increase with the square root of solids concentration.

The predictions from Gladki's model and the actual mixer speed, thrust, and average wall shear stress data are given in Tables 4.2 and 4.3.

Equation (4.3) was used (with $k = 1.37$) to estimate the axial hydraulic P/V at each of the mixer speeds listed in Tables 4.2 and 4.3. As noted in Section 4.1, there is some concern that Equation (4.3) might underpredict the axial mixer power by a factor of 1.5 to 2.0. Thus, the P/V values given in Tables 4.2 and 4.3 should be taken as lower-bound estimates. Whether the P/V estimates can be improved is being investigated. If mixer shaft power (rather than axial hydraulic power) is used, then all the P/V values given in Tables 4.2 and 4.3 must be multiplied by a factor of approximately three.

Table 4.2. Results from 20x50-Mesh Zeolite Suspension Tests

Measured Quantities							Predicted/Calculated Quantities			
Test No.	Solids Conc. (vol.%)	Liquid Level (cm)	Number of Mixers	Required Mixer Speed (rpm)	Total Mixer Thrust (N)	Avg. Wall Stress (Pa)	Predicted Wall Stress for Three Particle Sizes (Pa) 0.3 mm	0.7 mm	0.85 mm	Estimated P/V Ratio (W/m^3)
1A	0.015	17.5	1 1 1	2410* 1700 2052	11.1 5.5 8.0	27.0 13.4 19.6	11.0	21.5	25.3	338 119 210
1B	0.011	25.7	1 1 1	2450* 2150 2100	11.4 8.8 8.4	21.6 16.7 15.9	10.8	21.3	25.0	241 162 152
1C	0.015	25.7	1 1 1 1 1 1	2230 2000 2000 2180 2110 2126	9.5 7.6 7.6 9.1 8.5 8.6	18.0 14.5 14.5 17.2 16.1 16.3	11.8	22.6	26.5	183 132 132 170 154 154
1D	0.060	17.5	2 2 1 1	1500 1500 2170 2000	8.8 8.8 9.2 7.8	21.5 21.5 22.5 19.0	15.3 17.9	26.9 29.7	31.0 34.0	168 168 254 199
1E	0.043	25.7	2 2	1650 1650	10.6 10.6	20.0 20.0	14.9	26.4	30.6	151 151
1F	0.060	25.7	2 2	1700 1700	11.3 11.3	21.5 21.5	17.2	29.0	33.2	165 165

* Note that these readings correspond to the mixer speed needed to maintain all particles off the tank floor rather than just ensuring that all particles are in motion on the tank floor as was used for all other tests.

Table 4.3. Results from 50x100-Mesh Zeolite Suspension Tests

Measured Quantities							Predicted/Calculated Quantities			
Test No.	Solids Conc. (vol.%)	Liquid Level (cm)	Number of Mixers	Required Mixer Speed (rpm)	Total Mixer Thrust (N)	Avg. Wall Stress (Pa)	Predicted Wall Stress for 3 Particle Sizes (Pa) 0.15 mm	0.25 mm	0.3 mm	Estimated P/V Ratio (W/m^3)
2A	0.015	17.5	1 1 1	1500 1510 1600	4.3 4.3 4.9	10.5 10.6 11.9	6.7	8.5	11.0	83 83 99
2B	0.011	25.7	1 1	1800 1800	6.2 6.2	11.8 11.8	6.6	8.3	10.8	96 96
2C	0.015	25.7	1 1	1700 1750	5.5 5.8	10.5 11.1	7.4	9.2	11.8	81 88
2D	0.060	17.5	1 1	1750 1750	6.0 6.0	14.7 14.7	13.7	15.3	17.9	133 133
2E	0.043	25.7	1 1	1942 1925	7.3 7.2	13.9 13.6	13.1	14.7	17.4	122 119
2F	0.060	25.7	1 1	2000 2000	7.8 7.8	14.9 14.9	17.0	18.2	20.6	135 135

Comparing the mixer speeds required to meet the all-particles-in-motion criterion with the fluid velocity vs. mixer speed data given in Section 4.2 leads to the conclusion that average fluid velocities of approximately 25 to 40 cm/s are required to maintain 20x50-mesh zeolite particles in motion everywhere on the tank floor. In most cases, mixer speeds of about 2000 to 2200 rpm were required to effect 20x50-mesh zeolite suspension. Fluid velocity tests 3A and 3H were conducted with the hot-film anemometer probe positioned 1 cm above the tank floor in the region where the last particles to be suspended were observed in Tests 1 and 2. Figures 4.2 and 4.14 show that in the circa 2100 rpm range, the v_{avg} values range from about 25 to 40 cm/s.

Data from Tests 3F and 3G are also consistent with these estimates. In Tests 3F and 3G, the hot-film probe was positioned in the other region of the tank where solids tended to remain settled. Figure 4.12 shows fluid velocities in the 30 to 40 cm/s range for a mixer speed in the 2100 rpm range. Extrapolating the Figure 4.10 data also implies velocities in this range.

A similar comparison of mixer speeds and fluid velocities for the 50x100-mesh zeolite reveals that the required velocities range from about 17 to 50 cm/s. Because the 50x100-mesh zeolite particles are smaller than the 20x50-mesh particles, the required velocities are expected to be somewhat lower, but the data do not permit an accurate determination of how much lower the suspension velocities are for the 50x100-mesh zeolite.

The range of fluid velocities found necessary for suspending the 20x50-mesh zeolite is consistent with those expected based on a simplified analysis of mixer pump effectiveness in SRS Tank 19. In 1980 and 1981 two Bingham-Willamette 112-kW (150-hp) mixer pumps were operated in Tank 19. Following salt retrieval operations, an hourglass-shaped pile of remaining salt, sludge, and zeolite particles was observed to span the tank. Each mixer pump had effectively cleaned the tank floor out to a distance of about 9 m (30 ft) from the pump nozzles. The mixer pump nozzles were 3.8 cm (1.5 in.) in diameter and produced submerged fluid jets with exit velocities of about 30.5 m/s (100 ft/s). Turbulent submerged fluid jets decay according to a relationship of the form (Tuve 1953):

$$U(r,z) = 6\,\frac{U_o D_n}{z}\exp\left[-22.5\left(\frac{r}{z}\right)^2\right] \tag{4.4}$$

where $U(r,z)$ = local jet velocity, m/s
U_o = nozzle exit velocity, m/s
D_n = nozzle diameter, m
r = radial position measured from the jet centerline, m
z = downstream distance measured from the nozzle exit, m

Using Equation (4.4), the mixer pump jet velocities in the region near the residual Tank 19 solids are estimated to have been approximately 25 cm/s (0.8 ft/s).[a] The actual velocities near the Tank 19 solids were possibly somewhat higher than this estimate due to the tendency of the mixer pump jets to attach to the tank floor because of the Coanda effect. The effects of the tank floor and the sludge bank on the jet flow pattern make this simplified velocity estimate highly uncertain. This estimated velocity, however, is in reasonable agreement with the results of this study (i.e., required velocities are 25 to 40 cm/s) considering the uncertainties in the Tank 19 waste properties and in the applicability of Equation (4.4) to a jet confined within a tank impinging on a sludge bank.

4.4 Sludge Mobilization Tests

The results for the sludge mobilization tests are shown in Table 4.4. For each test, the measured slurry density was used to compute the weight fraction of sludge mobilized as a function of time and applied average wall shear stress.[b] The equation used for this calculation is

$$\rho_{slurry} = \frac{M_{supernate} + x\,(\rho_{final} V_{tank} - M_{supernate})}{V_{tank} - (1-x)\,V_{sludge}} \tag{4.5}$$

where ρ_{slurry} = measured slurry density, kg/m^3
$M_{supernate}$ = mass of initial supernate (water), kg
x = weight fraction of sludge suspended, dimensionless
ρ_{final} = slurry density at 100% sludge suspension, kg/m^3
V_{tank} = total volume of sludge and supernate, m^3
V_{sludge} = initial sludge volume, m^3

The average wall shear stress (τ_0) required to result in 80% and 95% of the sludge mobilized was estimated from a plot of wt% sludge mobilized vs. applied average wall shear stress for each test. These data are given in Table 4.4. Copies of the spreadsheets used to produce Table 4.4 and Figures 4.23 and 4.24 are given in Appendix C.

Some uncertainty exists in the sludge simulant properties for Tests 4A and 4B. In Tests 4A and 4B, the target shear strength (τ_s) and yield stress (τ_y) were both 50 Pa. A 43.5 wt%

---

[a]In Tank 19, the nozzle centerline was located 1.37 m (54 in.) above the tank floor. A jet expansion angle of 20 degrees was assumed when using the correlation in Tuve (1953). The estimated jet velocity applies to a downstream distance (x) of 9 m (30 ft) and a radial position of 1.37 m. The effects of the tank floor, walls, and the sludge bank were ignored in this calculation.

[b]For definitions of sludge, supernate, slurry, average wall shear stress, yield stress, and shear strength, refer to Section 3.1 in Appendix A.

Table 4.4. Sludge Mobilization Test Results

Test No.	τ_0 for 80% Mobilized (Pa)	τ_0 for 95% Mobilized (Pa)	Yield Stress τ_y (Pa)	Shear Strength τ_s (Pa)	$(\tau_0\ 80\%)/\tau_s$
4A	4.8	12.2	$7 < \tau_y < 50$	$7 < \tau_s < 50$	0.1 to 0.7
4B	< 9.5	< 9.5	≈ 2.4	≈ 2.4	< 4.0
5A	9.5 to 15	15	100	100	0.095 to 0.15
5B	4.7	≤ 7.5	100	100	0.047
6	50	> 50	100	800	0.063
7	69	>69	150	2000	0.035
8	< 4.7	4.7 to 7.4	10	10	< 0.47

Notes: τ_0 is the average wall shear stress, which equals total mixer thrust divided by wetted area. τ_y is the sludge dynamic yield stress and τ_s is the vane shear strength (see Appendix A)

kaolin clay slurry was prepared for these tests. Previous testing showed that this concentration of kaolin has a shear strength and disturbed yield stress of 50 Pa. In Test 4A, the kaolin slurry was poured into the tank with the layer of water supernate already in place. This procedure resulted in some unknown degree of mixing between the sludge simulant and the water. The sludge strength was likely decreased to some unknown extent. Judging by the thickness of the sludge layer just prior to testing (3 cm), the average weight percent solids throughout the layer is estimated to have been 31.7 wt%. Previous testing has shown that a kaolin slurry with this concentration has a yield stress of about 7 Pa. It is likely, however, that the fraction of sludge nearest the tank floor had a concentration greater than 31.7 wt% but less than or equal to 43.5 wt%.

Test 4B was performed by letting the fully mixed slurry from Test 4A settle to form a layer roughly 3.8 cm thick. The average kaolin concentration in this slurry layer is estimated at 26 wt%. The yield stress of a 26 wt% kaolin slurry is approximately 2.4 Pa. Again, there may have been a significant vertical concentration gradient through the slurry layer, so the yield stress of the simulant nearest the floor was probably higher than 2.4 Pa.

Some of the data given in Table 4.4 are plotted in Figures 4.23 and 4.24. Figure 4.23 shows the effect of simulant shear strength (undisturbed) on the average wall shear stress required to reach roughly 80% of the sludge mobilized. It appears that the required wall shear stress is *roughly* 5% of the sludge simulant shear strength (see the right-most column in Table 4.4). This estimate is very rough, however, because so few data points are present. It is also not

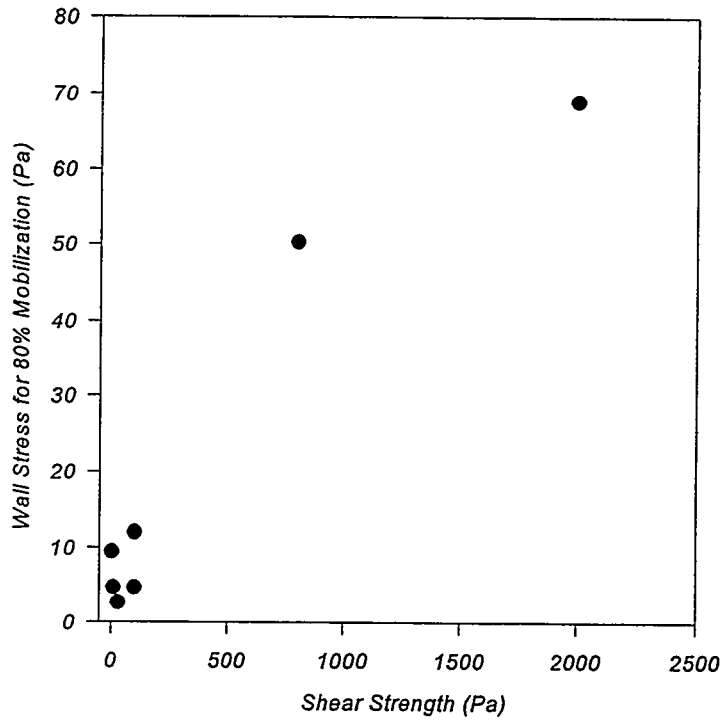

Figure 4.23. Effect of Shear Strength on Sludge Mobilization

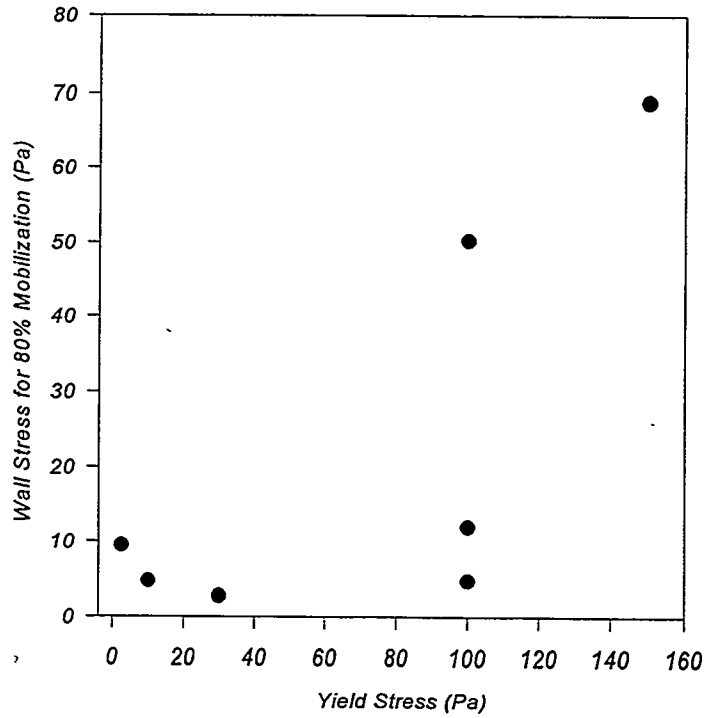

Figure 4.24. Effect of Yield Stress on Sludge Mobilization

clear that the ratio of wall shear stress to shear strength will be constant as tank size is increased. The relationship between applied wall shear stress and sludge simulant strength will be investigated further through testing in larger tanks.

Figure 4.24 shows the effect of disturbed simulant yield stress on the average wall shear stress required to mobilize 80% of the sludge. A comparison of the data points from Tests 5A and 5B with Test 6 (all tests were at 100 Pa yield stress) shows that the disturbed simulant yield stress does not provide as good a measure of sludge mobilization resistance as does the undisturbed strength (i.e., shear strength). This conclusion is consistent with previous sludge mobilization testing at PNNL (Powell et al. 1995) and the soil science literature pertaining to cohesive soil erosion (Graf 1971).

It is worth noting that the mixer speed required to reach a specified fraction of mobilized sludge is likely somewhat slower than that measured in our testing. By allowing more time at a given mixer speed it would be expected that a larger amount of sludge would be mobilized than was measured. The magnitude of this increase, however, is not known.

4.5 Pump-Down Tests

At the end of several of the zeolite suspension tests, the zeolite slurry was pumped from the tank through a piece of 1.5-cm-inside-diameter tubing oriented vertically with the suction end located roughly 1 cm from the tank floor. At the conclusion of Test 1F, slurry was pumped from the tank at approximately 170 cm^3/s while mixer operation continued at 1500 rpm (until the liquid level dropped below about 15 cm). In this test, roughly half the zeolite solids were removed from the tank. At the conclusion of Test 2F a similar test was performed, although in this test mixer operation was continued at a reduced speed until the propeller became exposed. In this test, roughly two-thirds of the zeolite solids were pumped from the tank.

It is not yet clear whether similar solids fractions might be pumped from the tank in tests at larger scales. The potential similarity of these pump-down tests to the full-scale operation has not yet been assessed.

4.6 Predictions for Mid-Scale and Full-Scale Mixing

Based on the small-scale test results, it is possible to make several predictions for mixer performance in the mid-scale tanks at PNNL and the full-scale tanks (both the TNX test tank and Tank 19) at SRS. The reader is cautioned, however, to not place much credence in these predictions at this time, especially since the Phase A test tank was so small. Tests in a single tank size cannot usually be used to assess various scale-up methodologies. Therefore, it is currently unclear how to best scale up the data from the small tank tests to make predictions at larger scale. Further, the small-scale mixer propeller is considerably larger than that needed to ensure geometric similarity of the small-scale mixing system with those at larger scale. The

small-scale mixer propeller diameter was 7.8 cm whereas a geometrically scaled mixer similar to that planned for full-scale use would have a propeller diameter of only 0.9 cm. Geometric similarity of mixing systems is usually maintained when developing scaling relationships. This approach was not practical for the current test program.

One further complication is the ratio of liquid level to tank diameter. In the Tank 19 application, the ratio of liquid level to tank diameter is about 0.076. To avoid vortex formation and to keep the small-scale mixer propeller fully submerged, it was necessary to run the tests at liquid level to tank diameter ratios of 0.39 and higher.

Using the data from Test 1 (20x50 mesh zeolite suspension) and the constant-wall-shear-stress scaling method recommended by Flygt, it is possible to predict the mixing intensity that will be required to meet the all-particles-in-motion criterion in PNNL's 1.8-m-diameter tank. In Test 1A (i.e., 1.5-vol% solids, 17.5-cm liquid level), a wall shear stress of about 16.5 ± 3.5 Pa was found to effect particle suspension. To obtain this same wall shear stress in the 1.8-m tank (at scaled liquid level and the same particle concentration), a total mixer thrust of 110 ± 25 N will be required. According to data provided by Flygt, the Model 4640 mixer planned for use in the 1.8-m tank produces 810 N of thrust at 860 rpm. This thrust implies a k in Equation (4.2) of 1.49. Using this value in Equation (4.2), it is found that a mixer speed of 315 ± 30 rpm will be required to maintain the solids in motion in the 1.8-m tank. Thus, constant-wall-shear-stress scaling predicts that the required mixer speed will be between 285 and 345 rpm.

For comparison, consider the predictions of constant-P/V scaling. The power densities required to meet the particle motion criterion for Test 1 were in the range of 150 to 200 W/m^3, or perhaps higher. Using $k = 1.49$ in Equation (4.3) to predict the Model 4640 mixer power, it is found that mixer speeds between 550 and 600 rpm are required to reach these power densities. At 330 rpm, P/V is only about 35 W/m^3, so the results of the tests in the 1.8-m tank should allow us to assess whether constant-wall-shear-stress, constant-P/V, or some other scaling methodology is most appropriate for scaling between the 0.45-m and the 1.8-m tanks. Testing in the 1.8-m tank will be advantageous because the mixer propeller diameter and liquid level can be set to be almost geometrically similar to small-scale Tests 1A, 1B, and 1C.

Similar predictions can be made for full-scale implementation of Flygt mixers, but these predictions are even less reliable than those made above for the 1.8-m tank. These predictions are provided below for information only. Future testing will be used to refine these predictions and improve their defensibility.

Constant-wall-shear-stress scaling for zeolite suspension similar to Test 1 implies that an average wall shear stress of 16.5 ± 3.5 Pa will be needed in Tank 19. The wetted surface area inside Tank 19 is approximately 690 m^2, so the total thrust required is 11,400 ± 2400 N. Each modified Model 4680 mixer with inlet screen produces roughly 6160 N of thrust (Flygt 1998), so the required number of mixers is two (1.9 ± 0.4).

Constant-P/V scaling implies a greater number of mixers are required at full scale.[a] Fitting the Model 4680 mixer thrust data reported by Flygt (1998) gives $k = 2.42$. Using this value in Equation (4.3), it is predicted that each of the Model 4680 mixers produces 28 kW of axial hydraulic power at full speed. To reach the power density range measured in Test 1 (i.e., 150 to 200 W/m^3), a total power input of 180 ± 25 kW is required. This power implies that seven (6.4 ± 0.9) Model 4680 mixers will be required in Tank 19 to achieve the same level of particle suspension as was observed during the small-scale tests. Again, this prediction is only true if constant-P/V scaling applies. It should be noted that these estimates are uncertain in that the axial power of the small-scale mixer may have been a factor of 1.5 to 2.0 higher than given in Table 4.2. If so, the number of mixers required increases proportionally to something between 8 and 15 mixers. Also, the Tank 19 liquid-level-to-tank-diameter ratio is significantly lower than that tested in the small-scale tank. The required P/V will likely increase as this ratio decreases (Myers et al. 1994), so the mixing power required at full scale may be higher yet.

The significant differences in predictions between different scaling methods demonstrates the importance of determining the correct scaling relationships so that the full-scale mixing system can be defensibly designed. These scaling issues will be addressed through testing in larger-scale tanks at PNNL and SRS.

An additional set of predictions can be made if it is assumed, as discussed in Section 4.4, that the average wall shear stress required to mobilize 80% of the tank sludge is *roughly* 5% of the undisturbed sludge strength. Sludge strengths in the range of 100, 1000, and 2000 Pa are not unreasonable estimates for typical tank sludge strengths. These values imply required average wall shear stresses of 5, 50, and 100 Pa. For SRS Tank 19, the wetted surface area inside the tank is about 690 m^2. To attain these target wall shear stresses, total mixer thrusts of about 3,450, 34,500, and 69,000 N are required. Because each Model 4680 mixer produces roughly 6160 N of thrust, the number of mixers required in these three cases are predicted to be 1, 6, and 12 (calculated values are 0.6, 5.6, and 11.2). The assumption that the required average wall shear stress is 5% of the undisturbed sludge strength is speculative at this point and will be investigated further in larger-scale tests. It should be noted that the test data showed that only 69 Pa was required to reach 80% mobilized for the 2000 Pa shear strength sludge, rather than 100 Pa as predicted by the 5% assumption. If these data are used instead of the 5% assumption, then the predicted number of mixers for a 2000 Pa sludge is reduced to 7.5.

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[a]Constant-P/V scaling, when strictly applied, presumes the same number of geometrically scaled mixers in both the scaled test and the prototype. Using constant-P/V scaling to predict the number of mixers required for the prototype (full scale) is an extension of what is usually meant by constant-P/V scaling. A detailed discussion of the application of constant-P/V scaling to the Flygt mixer test data is provided in Section 5.0 of Powell et al. (1999).

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Appendix A

Phase A Test Plan

Appendix A
Phase A Test Plan

Before the small-scale tests commenced, a test plan was prepared to document the planned tests and to provide procedural guidance during testing. The document describing the test plan is provided in this appendix. The tests were performed as described except for the modifications discussed in Section 3.0 of this report.

Evaluation of Flygt Mixers for Application in Savannah River Site Tank 19

Test Plan

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B. K. Hatchell

March 1998

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
Richland, Washington 99352

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1.0 Introduction

In the early 1980s two jet mixer pumps were used to dissolve and retrieve the saltcake in Tank 19 at the Savannah River Site (SRS). Not all of the waste was removed during this retrieval campaign, however, and roughly 125 m^3 (33 kgal) of waste solids remain. The solids are composed of sludge, zeolite, and salt. Based on the topography of the solids heel in Tank 19, it is suspected that the mixer pumps did not have sufficient power to maintain the faster settling solids in suspension or that the mixer pump jets pushed the larger, settled solids out beyond the reach of the jets.

Efforts are now being made to identify and design alternative waste retrieval techniques for the Tank 19 waste. Shrouded axial propeller mixers manufactured by ITT Flygt Corporation are one of the suggested alternatives. Staff from Pacific Northwest National Laboratory (PNNL),[a] Oak Ridge National Laboratory, SRS, and ITT Flygt Corporation are conducting a joint mixer testing program to evaluate the applicability of Flygt mixers to Tank 19 waste retrieval and waste retrieval in other U.S. Department of Energy (DOE) tanks. This test program consists of three phases. The first phase involves small-scale mixer testing at the ITT Flygt laboratory in Trumbull, Connecticut. The second phase involves larger-scale (about 1/4-geometrical scale) tests of Flygt mixers by PNNL. The third and final phase involves full-scale mixer testing at SRS. Testing in different tank sizes is needed to evaluate and validate scaling methods so that the results of the relatively inexpensive small-scale tests can be used to make full-scale mixer performance predictions more cost effective.

Flygt mixers consist of an electrically powered propeller surrounded by a close-fitting shroud. Figure 1.1 shows a Flygt mixer mounted to a vertical mast (ITT Flygt Corporation 1997). The 37-kW (50-hp) mixer being considered for use in Tank 19 has a propeller diameter of approximately 51 cm (20 in.) and operates at 860 rpm. The rapidly spinning propeller creates a turbulent fluid jet with an average exit velocity approaching 6 m/s (see Figure 1.2) (ITT Flygt Corporation 1997). Several of these 37 kW mixers may be required to mix the waste in Tank 19.

This test plan is focused on the first phase of testing (i.e., that conducted at Flygt), though general descriptions of the second and third phases are also given. Phase one tests will be performed in a 0.46-m- (1.5-ft-) diameter (or smaller, if necessary) tank using small Flygt mixers positioned near the floor. The mixers will discharge a horizontal fluid jet of supernate into a layer of simulated sludge. Effectiveness of the Flygt mixer for sludge mobilization will be measured by the extent to which the sludge simulant is mobilized. Particle suspension tests will be performed to determine the mixing intensity needed to suspend zeolite particles and to compare the data with previous testing of Flygt mixers for solids suspension (Gladki 1997).

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[a]PNNL is operated by Battelle for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

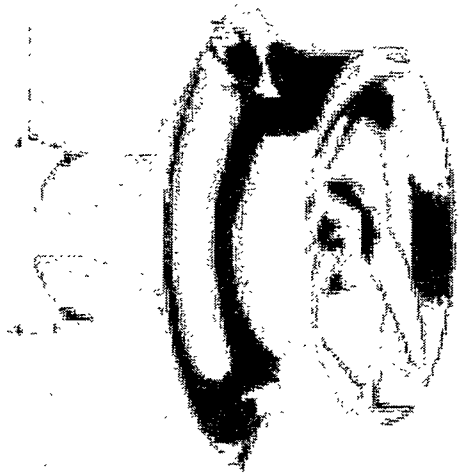

Figure 1.1. Flygt Mixer

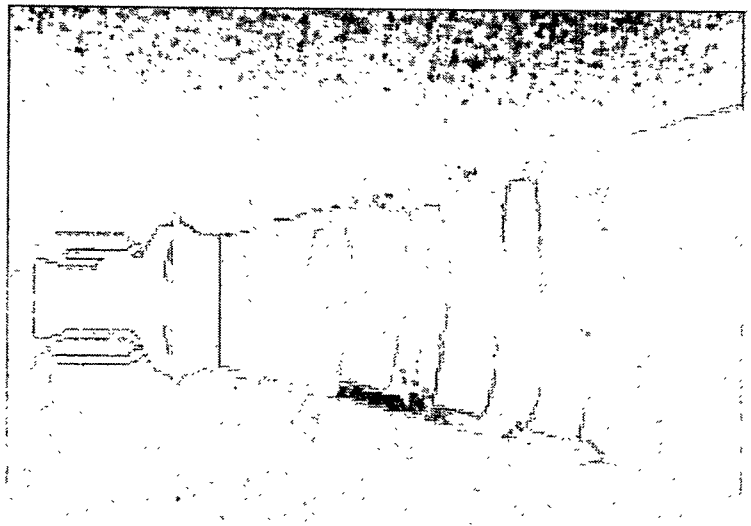

Figure 1.2. Flygt Mixer Jet Flow as Described by ITT Flygt Corporation

2.0 Scope and Objectives

Testing of Flygt mixers will proceed in three sequential phases. The principal objective of the tests is to determine whether Flygt mixers can be used to successfully mix the waste heel in SRS Tank 19. Another objective of this work is the development of predictive capabilities for Flygt mixers in U.S. Department of Energy (DOE) waste tanks so their effectiveness can be predicted for future applications. To answer these questions, several issues must be addressed using a combination of small-scale testing, analysis, and then larger- and full-scale tests. The scope and objectives of each phase of this test program are discussed in this section. Emphasis is placed on the Phase A tests because future test plans will be prepared to describe the Phase B and C tests.

2.1 Phase A Tests at ITT Flygt Corporation

One or more small Flygt mixers (7.8-cm propeller diameter) will be used inside a 0.46-cm-diameter tank[a] to mobilize and mix several different waste simulants. Each simulant will be tested two times and the results averaged. Simulants for cohesive tank sludge and for the less cohesive zeolite particles will be tested in addition to a single test using only water. Sludge simulant compositions are chosen to yield a range of sludge strengths that reflect those of the Savannah River Site (SRS) and other tank wastes. The zeolite particles that will be tested are similar to the particles known to be inside SRS Tank 19.

The zeolite slurry tests will be used to determine whether resuspension of zeolite particles follows the solids suspension prediction methodology outlined by Gladki (1997) and described in Section 3.2 of this appendix. The cohesive sludge resuspension tests will indicate the relationship between average wall stress and the stress required to induce sludge mobilization (i.e., critical shear stress). Finally, the water-only test will be used to determine the fluid velocities near the tank floor under the flow conditions used for the zeolite suspension tests.

The small-scale Flygt mixer test results will be used to help interpret and analyze the data collected in the larger-scale tests. In particular, the applicability of different scaling relationships (e.g., constant-wall-shear-stress scaling) will be evaluated by comparing the performance of Flygt mixers in the small-scale tanks with that observed in larger tanks.

Seven different waste simulants will be tested at small scale. Two sets of tests will be performed using mixtures of zeolite particles with water. One zeolite simulant will be in the 20- to 50-mesh size range (0.3 to 0.85 mm), which reportedly is the size range of the Linde AW-500 (also called IE95) zeolite originally placed in Tank 19. The second zeolite simulant will be in the

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[a]For some tests, a smaller tank may be used if the 7.8-cm Flygt mixers provide insufficient mixing intensity in the 0.46-cm-diameter tank.

50- to 100-mesh size range (0.15 to 0.3 mm) to determine the effect of the smaller particle size on the required mixing intensity. It is speculated that the Tank 19 zeolite particles may have broken down to a size range smaller than 20- to 50-mesh as a result of long-term exposure to caustic liquid.[a]

In addition to the two zeolite simulants, five cohesive sludge simulants will be tested. The yield stresses and shear strengths of these simulants were selected to cover a wide range so the test results can potentially be applied to a wide range of DOE waste tanks.

The scope and objectives for the small-scale Flygt mixer tests are summarized in Table 2.1. The tests will not necessarily be performed in the order shown.

Table 2.1. Phase 1 Scope and Objectives

Test No.	Scope Description	Test Objective
1	2 tests using 20x50 zeolite particles of varying concentration in 0.46-cm tank	Determine average wall stress required to mix and maintain solids in suspension
2	2 tests using 50x100 zeolite particles of varying concentration in 0.46-cm tank	Determine average wall stress required to mix and maintain solids in suspension
3	Test using water under same mixer conditions as found in Tests 1 and 2	Determine sedimentation and erosion velocities present in Tests 1 and 2
4	2 tests using kaolin clay sludge $\tau_s = 50$ Pa, $\tau_y = 50$ Pa	Determine relationship between critical shear stress and average wall stress
5	2 tests using kaolin clay sludge $\tau_s = 100$ Pa, $\tau_y = 100$ Pa	Determine relationship between critical shear stress and average wall stress
6	2 tests using kaolin/plaster sludge $\tau_s = 800$ Pa, $\tau_y = 100$ Pa	Determine relationship between critical shear stress and average wall stress
7	2 tests using kaolin/plaster sludge $\tau_s = 2000$ Pa, $\tau_y = 150$ Pa	Determine relationship between critical shear stress and average wall stress
8	2 tests using kaolin clay sludge $\tau_s = 10$ Pa, $\tau_y = 10$ Pa	Determine relationship between critical shear stress and average wall stress

[a]Fowler, J.R., and R.M. Wallace. December 2, 1980. *CRC Zeolite in SRP Waste.* DPST-80-488, Memorandum to M.J. Plodinec.

2.2 Phase B Tests at PNNL

PNNL will conduct the second phase of Flygt mixer testing. Flygt mixers will be tested in a 1.9-m- and/or an 5.7-m-diameter tank containing simulated Tank 19 solids. The simulant properties and test conditions will be adjusted so that the test results can be used to evaluate candidate scaling relationships and to help make predictions for full-scale Flygt mixing. Because achieving true dynamic and geometric similarity in the 1.9-m and 5.7-m tanks is impractical, assumptions will have to be made when designing the tests and the simulant. Efforts will be made to ensure that all assumptions made result in conservative, yet credible, results.

A detailed description of the Phase B tests and analyses at PNNL will be incorporated into this test plan once the Phase A tests are underway.

2.3 Phase C Tests at SRS

SRS will perform full-scale tests in a 25.9-m- (85-ft-) diameter (full-scale) tank. SRS will perform the tests using water, three or four Flygt mixers, and possibly a kaolin-clay-based sludge simulant. The mixers will be placed in the tank and, initially, only one mixer will be used. Subsequent tests will be performed using the additional mixers so that the effects of incrementally adding mixers can be quantified. The orientation of the mixers will be varied to determine an optimum configuration. The fluid velocities within the tank will be measured and compared with predictions based on the results from Phases A and B. Areas within the tank where fluid velocities are lower than the measured erosion/deposition velocities for 20x50-mesh zeolite (i.e., dead zones) will be identified during the full-scale tests. As part of this testing, methods for deploying the Flygt mixers into Tank 19 will be evaluated. As with the Phase B testing, this test plan will be revised to incorporate the Phase C plan before the Phase C tests commence.

3.0 Background Theory

Predicting the effectiveness of Flygt mixers in Tank 19 on the basis of scaled tests using simulants and full-scale tests in water requires a careful consideration of the relevant physics and scale-up relationships. Mixing slurries in tanks has received a great deal of attention in the scientific literature, yet no generally applicable correlations exist for predicting mixing. Thus, it is often necessary to develop empirical scaling relationships on a case-by-case basis using tests at smaller scales. This section is a discussion on the theoretical framework used to guide the Flygt mixer tests.

3.1 Definition of Terms

Several key terms are used throughout this document. To avoid confusion that may result from ambiguous terminology, the following definitions are given:

Sludge - The layer of settled solids on the tank floor. Currently, Tank 19 is thought to contain roughly 125 m^3 (33 kgal) of sludge, consisting of zeolite, salt crystals, and metal oxyhydroxide particles. This 125-m^3 estimate includes the volume of interstitial liquid. Thus, the actual volume of solids (excluding interstitial liquid) is estimated to be 76 m^3.

Supernate - The layer of clear liquid covering the sludge before mixing starts. The Tank 19 supernate is an aqueous solution of various nitrate, nitrite, carbonate, and sulfate salts.

Slurry - A mixture of particles with liquid that is fluid enough to be pumped or flow under its own weight. Mixing the Tank 19 sludge with the existing supernate will form a slurry.

Critical Shear Stress (τ_c) - The magnitude of the applied shear stress required to initiate erosion of sludge.

Shear Strength (τ_s) - The maximum shear stress a material can withstand without rupture. For sludge, this is most readily measured using a shear vane.

Yield Stress (τ_y) - The minimum stress needed to cause a Bingham-plastic to flow. See Section 3.4 for further discussion.

3.2 Constant-Wall-Shear-Stress-Scaling

Gladki (1997) outlines a methodology for predicting the mixing intensity required to maintain a suspension of solids (i.e., slurry) in a just-suspended condition. This method involves determining the magnitude of the average wall shear stress (τ_0) required to maintain solids in

suspension for a given tank geometry and type of solids. The magnitude of τ_0 in a tank is computed by dividing the Flygt mixer thrust by the wetted surface area (bottom and sides) of the tank. Mixer thrust (F) is conveniently measured in a submerged mixer test and is related to the mixer flow according to the equation:

$$F = \rho Q V_{jet} = \frac{\pi \rho D^2 V_{jet}^2}{4} \tag{A3.1}$$

where ρ = slurry density, kg/m^3
Q = slurry flow rate, m^3/s
V_{jet} = average bulk velocity of the discharged fluid, m/s
D = jet diameter ≈ propeller diameter, m.

According to this method, the value of τ_0 is independent of scale provided the same solids and liquid are used and the tank dimensions are geometrically scaled. Predicting the mixing requirements at large scale then requires that small-scale tests be conducted to determine the value of τ_0 required for solids suspension. The mixer thrust required to obtain this same τ_0 in the full-scale tank is then computed and used to determine the number and size of full-scale mixers needed for the tank configuration in question.

Gladki (1997) developed an empirical correlation between the particle settling velocities and the value of τ_0 required to maintain solids in suspension in small-scale tanks. Using the experimental parameters for Tests 1 and 2 as input to the correlation gives a predicted τ_0 of about 20 Pa for Test 1 and 10 Pa for Test 2.[a] The wetted area of the full-scale SRS tank (25.9-m diameter, waste depth of 2.1 m) is approximately 700 m^2, so the predicted total thrust required to maintain Tank 19 solids in suspension is (20 Pa)(700 m^2) = 14,000 N. The 37-kW Flygt mixers planned for use in Tank 19 each generate about 6200 N of thrust, so two or three Flygt mixers (14000/6200 = 2.3) are predicted to be required for Tank 19 using this scale-up method.

The Phase A, B, and C Flygt mixer tests will determine whether the constant τ_0 method of scaling can be applied to tanks as large as Tank 19. The Gladki correlations were developed using tanks smaller than 0.5 m. The value of the dimensionless group in Gladki's correlation that quantifies the required mixing intensity (Suspension Intensity Parameter) in Tank 19 is well beyond the range tested by Gladki. However, Flygt has successfully used this method to predict the mixing requirements for industrial applications based on an extrapolation of Gladki's correlation to larger values of the Suspension Intensity Parameter.

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[a]Test 1 conditions are tank diameter = 0.46 m, particle size = 0.7 mm, particle density = 1660 kg/m^3, propeller diameter = 7.8 cm, vol. fract. solids = 0.015, liquid level = 18 cm and 25 cm. Test 2 conditions are the same except that particle size = 0.25 mm.

3.3 Other Scaling Relationships

If constant τ_0 scaling is found not to apply to the Tank 19 situation, then efforts will be made to identify and evaluate other scaling relationships that may better predict Tank 19 mixing. Different scaling relationships will no doubt result in different predictions for full-scale mixing requirements. Because the predictions made by different scaling methods vary over a wide range, it is not feasible to accurately predict the effectiveness of Flygt mixers in Tank 19 without first conducting the series of scaled tests described in this test plan.

3.4 Sludge Mobilization

The discussion in Sections 3.2 and 3.3 centered on the mixing intensity required to maintain solids in suspension. Of course, in Tank 19 the solids will initially be settled and must be mobilized and mixed with the tank supernate before there can be any concern over the mixing intensity required to maintain the solids in suspension. This section discusses the issues associated with sludge mobilization.

Mobilization of sludge by impinging submerged fluid jets has been studied in scaled and full-scale tests at several DOE sites during the design of mixer-pump-based waste retrieval systems (Powell et al. 1997a). When the mixer pump fluid jets are started, the sludge nearest the discharge nozzles is rapidly mobilized because the stagnation pressure of the jet is considerably larger than the mechanical strength of the sludge. After a short while, however, the mechanism of mobilization changes from one of bulk sludge failure to erosion of particles and groups of particles from the sludge/slurry interface. This erosion process is very similar to the erosion of cohesive soils by turbulent flow, which is a problem that has been extensively studied by soil scientists.

Mobilization of the sludge continues until the mobilizing force of the mixer pump jet is no longer sufficient to overcome the mobilization resistance of the sludge. Soil scientists describe the point at which eroding force and erosion resistance are equal as the critical shear stress for erosion (τ_c). When the shear stress applied to the sludge surface by the turbulent jet exceeds the τ_c of the sludge, erosion occurs. When the applied stress is lower than τ_c, no significant erosion is observed. The maximum possible performance of a mixer pump or other jet-based mixing system is thus determined by the point at which the mixer's applied stress decays with distance to the point where it just equals the τ_c of the sludge.

The Flygt mixers in Tank 19 must be able to generate sufficient shear stress near the tank floor to overcome the τ_c of the Tank 19 sludge. Unfortunately, the τ_c for Tank 19 sludge is unknown. Efforts to correlate τ_c with easily measured properties like particle size, shear strength, and yield stress have been largely unsuccessful for predicting soil erosion in general, but correlations for specific soil types have been developed. Similarly, scaled tests using simulants for tank sludge have yielded useful correlations between sludge properties and

expected mixer pump performance. This success is one reason that a series of simulants with a range of yield stresses and shear strengths are proposed for the Phase A testing.

The approach taken at PNNL has been to correlate the sludge simulant's mobilization resistance (quantified by τ_c) with the vane shear strength of the sludge. Other physical properties have been investigated and were found either to not correlate with τ_c or to be too difficult to measure accurately to be useful. Vane shear strength is measured by inserting a four-bladed vane vertically into the sludge and measuring the torque required to begin rotating the vane. This technique is a standard way to measure shear strength in soil science (see ASTM standard D4648-94). The primary advantage of the shear vane method over other methods is that the sample disturbance prior to testing is kept to a minimum. Tests that require drilling test cores and/or loading the sample into a viscometer inflict considerable strain on the sample. Samples sensitive to disruption will often give much lower strength measurements after being disturbed. This behavior has been observed in tank wastes at the Hanford Site in Richland, Washington. A sample from Hanford Tank 102-SY, for example, resembled modeling clay as it was extruded from the core sampler. Its shear strength was measured at 4000 Pa (DiCenso et al. 1995). The sample was then thoroughly mixed and its yield stress was found to be less than 3 Pa (Onishi et al. 1996). Sample disruption can have a pronounced effect on sample strength.

SRS has historically used the sludge yield stress as a measure of mobilization resistance. Yield stress is measured by loading the undiluted sample into a viscometer and measuring the force required to initiate plastic deformation. The two types of yield stresses are static and dynamic. Static yield stress is measured by very slowly increasing the applied stress until plastic deformation occurs. Dynamic yield stress is measured using the shear stress vs. shear rate curve for the sample. The dynamic yield stress is estimated by extrapolating the observed shear stress data to zero shear rate. Dynamic yield stress measurements will be made on all the Phase A sludge simulants for Tests 4 through 8.

Dynamic yield stress does not provide an adequate measure of the sample's mobilization resistance because it is essentially a test on a disturbed sample. Any structure or interparticle bonding initially present in the sample is destroyed very early in the test and, therefore, does not contribute to the value of the dynamic yield stress. The ratio of the shear strength (or static yield stress) to the dynamic yield stress depends on the mechanism(s) by which the sludge gets its strength. Some materials exhibit approximately equal shear strength and yield stress, while others may have shear strengths a factor of 20 or more greater than the dynamic yield stress (e.g., the Hanford 102-SY sample described above).

Static yield stress is, theoretically, the same value as the vane shear strength. In practice, however, differences are often observed. The most common cause for differences is the disruption that occurs when the sample is loaded into the rheometer before measuring the static yield stress. Shear vanes reduce the extent of disruption before measurement, so they are thought to provide a more accurate shear strength measurement. This theory is consistent with the

observation that the shear vane and static yield stress data are most similar when the sample does not exhibit significant sensitivity to disruption.

The dynamic yield stresses of the cohesive sludge simulants that will be used for Tests 4 through 8 range from 10 to 150 Pa. Yield stress measurements will be made on the undiluted sludge simulants at the Flygt laboratory during the Phase A tests. The range of shear strengths for Test 4 through 8 simulants is from 10 to roughly 2000 Pa. Based on previous testing at PNNL, the τ_c values for these simulants are estimated to be less than about 20 Pa. Figure 3.1 is a plot showing the estimated critical shear stress as a function of vane shear strength for cohesive sludge simulants based on correlations in Powell et al. (1995) and Rajaratnam (1976).

Tests 4 through 8 using the Flygt mixer at small scale will provide an indication of the relationship between the applied average stress (τ_0) and the yield stress, shear strength, and τ_c of the sludge to be mobilized in a tank.

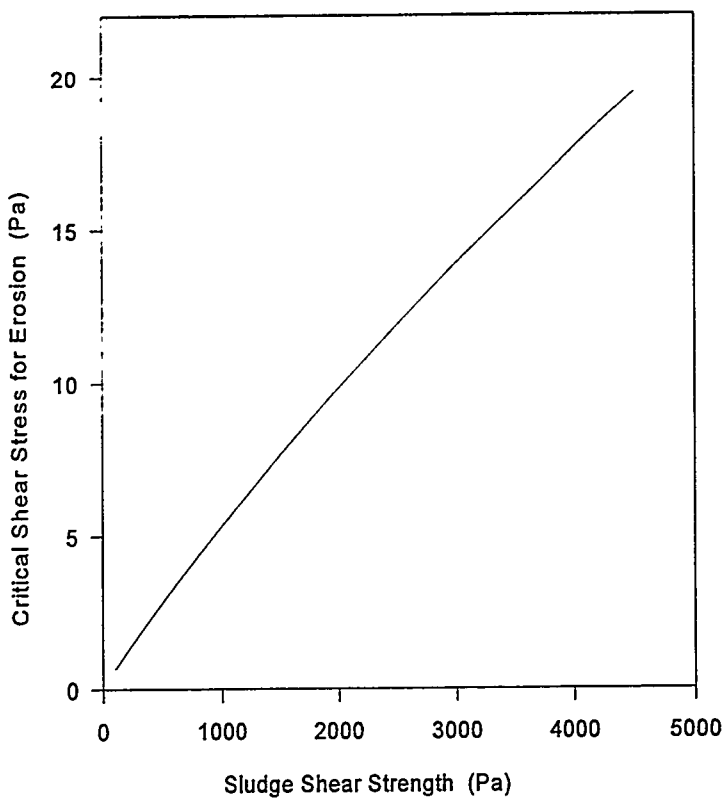

Figure 3.1. τ_c vs. Shear Strength

4.0 Phase A Approach

The small-scale Flygt mixer tests will be conducted using the equipment and general approach described in this section. Detailed test procedures are given in Section 6.0 of this test plan. The approach for the Phase B and C testing will be described in subsequent revisions to this document.

4.1 Test Setup

A 0.46-m-diameter tank will be used by ITT Flygt for the small-scale tests.[a] In all tests, the Flygt mixer will be positioned near the tank wall discharging across the tank floor. This arrangement is identical to that used by Gladki (1990). Figure 4.1 shows a sketch of the planned experimental apparatus.

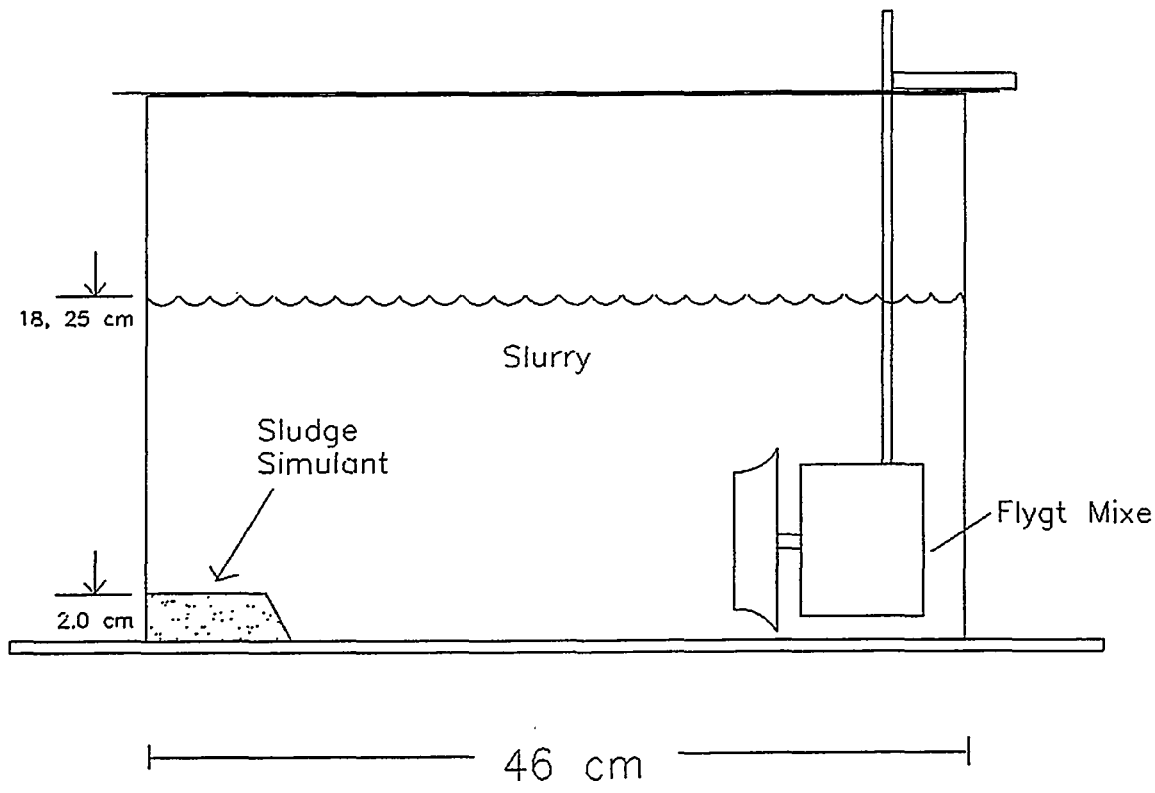

Figure 4.1. Small-Scale Flygt Mixer Testing Apparatus

[a]A smaller tank may be used if it is found that the 0.3 kW mixers do not adequately suspend the simulants in the 0.46-m-diameter tank. This will allow testing at higher average wall stresses using the same mixer.

4.2 Test Equipment and Instrumentation

The equipment and instrumentation needed for the small-scale Flygt mixer tests are described in this section.

4.2.1 Clear-Bottom Tank

The tank used for these tests will be a 0.46-m-diameter tank with a clear bottom, which will allow visual monitoring of both sludge mobilization and particle settling. A portion of the zeolite particles may be dyed red before testing using fabric dye to facilitate visual tracking of individual particles. For the sludge mobilization tests (4 through 8), water-soluble food or fabric dye may be added, as needed, to the mixing slurry to make the sludge/slurry interface more apparent.

In previous tests at this scale using scaled jet mixer pumps, a tendency for the sludge bank to be lifted vertically by the jet was noted. Lifting of the sludge bank is not a credible mechanism for sludge mobilization at full scale, so efforts must be made to avoid sludge bank lifting during small-scale Tests 4 through 8 (bank lifting is not applicable to Tests 1 through 3). If bank lifting is observed, the test must be repeated using some means of improving the adhesion between the sludge simulant and the tank floor. Pieces of wire mesh glued to the tank floor were found to improve the sludge adhesion during previous mixer pump tests at this scale (Shekarriz et al. 1997).

4.2.2 Small-Scale Flygt Mixer

A small Flygt mixer driven by a 300-W electric motor will be used for these tests. This mixer has a shrouded 7.8-cm propeller that can be driven at speeds within the range of 50 to 3000 rpm.

It is worth noting that the 7.8-cm-diameter propeller does not reflect geometric scaling of the full-scale Tank 19 Flygt mixer, which has a 51-cm propeller. A geometrically scaled mixer would have a propeller diameter of only 0.9 cm. It is not practical to fabricate such a small mixer for this test program. The lack of geometric similarity will complicate interpretation of the small-scale test results, but the Phase B and C tests will be designed to address some of these complicating factors.

For Tests 1 and 2 (zeolite suspension), the mixer speed will be adjusted until the just-suspended criterion used by Gladki (1997) is met. Test 3 mixer speeds will be adjusted to those found to meet the just-suspended criterion in Tests 1 and 2. Fluid velocity measurements will be made throughout the tank floor for each of these velocities using hot-film anemometry.

4.2.3 Slurry and Sludge Density Measurement

During Tests 4 through 8, the density of the mixed slurry will be periodically monitored to determine the fraction of sludge simulant that has been mobilized and mixed with supernate. An Anton-Paar DMA-200 hand-held density meter will be used to make these measurements.

Slurry density measurements are not likely to be an accurate indicator of the fraction of solids mobilized for Tests 1 and 2 because the rapid settling velocities of the zeolite particles will likely result in a vertical concentration gradient within the tank. Slurry samples will be withdrawn from the tank during Tests 1 and 2 only at the conclusion of each measurement (with the mixer still operating). The density of the slurry sample will be determined using a 100-mL calibrated density cup pycnometer. The DMA-200 is not appropriate for use with the zeolite solids because the particles are too large. Large particles will plug the digital density meter. This pycnometer will also be used to measure sludge simulant density.

4.2.4 Slurry Temperature Measurement

Slurry temperature will be periodically measured during the tests so that accurate values for water density and viscosity can be used when analyzing the test data. Temperature data are also needed to adjust the hot-film anemometer calibration if the probe is calibrated at a different temperature than that of the water during Test 3.

4.2.5 Sludge Simulant Characterization

Tests 1 and 2 will use the Flygt mixer to mobilize and mix a layer of settled zeolite particles. The tank supernate will be water. The zeolite solids will be characterized at PNNL by measuring the particle size distribution, the particle densities (wet and dry), and the settling velocity distribution. Particle size distribution will be performed via sieve analysis. Particle densities will be measured on the dry particulate using a helium pycnometer. Wet particle densities will be measured by a water displacement method. The wet and dry particle densities differ because the zeolite particles are porous. The wet particle densities are most relevant to the Flygt mixing tests. Settling velocity distribution will be measured by the time required for particles to fall a known distance.

No simulant characterization is required for Test 3. The physical properties of water are known functions of temperature. Published values for the water density and viscosity will be used for all data analysis.

Characterization of the sludge simulant for Tests 4 through 8 will include measurement of weight percent solids, vane shear strength, and yield stress. As in Tests 1 and 2, the supernate for Tests 4 through 8 will be water. Sludge simulant weight percent solids will be measured by the observed weight loss from drying at 150°C (or higher) for at least 24 hours. Vane shear strength will be measured at PNNL using a Haake M5 Rotovisco viscometer with a shear vane

attachment. Procedures for shear strength measurement are described in Powell et al. (1997b). Dynamic yield stress will be quantified using a viscometer at Flygt.

4.2.6 Fluid Velocity Measurements

Fluid velocities at selected locations within the tank will be measured during Test 3 using a Thermo-Systems, Inc. (TSI) model 1210-20W hot-film anemometer probe with a TSI model 1054B probe controller. The analog voltage output from the probe (roughly 10 to 24 V) will be routed to a computer-based data acquisition system to record the data. The hot-film anemometer will be calibrated at PNNL by inserting the anemometer into the middle of a pipe through which a known water flow rate is passed.

4.3 Simulant Development

According to Goslen (1986), the Tank 19 solids are composed of roughly 50 m^3 of zeolite, 50 m^3 of undissolved salt, and 25 m^3 of metal oxyhydroxide sludge. The Tank 19 zeolite is predominantly Linde AW-500, which was used to remove cesium from process waste streams. The zeolite was placed into Tank 19 as particles in the 0.3- to 0.85-mm size range (20 to 50 mesh). Some have speculated that years of exposure to caustic liquid may have caused the zeolite to degrade, which may have resulted in a decrease in the zeolite particle size.[a] The extent of this possible particle size decrease is not known and no reliable measurements of the current Tank 19 zeolite particle size distribution are available.

Zeolite particles will be used for Tests 1 and 2 to simulate the zeolite particles inside Tank 19. Test 1 will use particles of Linde AW-500 zeolite in the 0.3- to 0.85-mm size range. This simulant should be conservative with respect to particle size and settling velocity. Any in-tank degradation that may have occurred will have decreased the particle size compared with that used for Test 1. Test 2 will use smaller particles (roughly 0.15 to 0.3 mm) to provide a measure of the effect of particle size on the required mixing intensity.

Suspension and mixing of zeolite particles are expected to represent one of the more challenging aspects of Tank 19 heel mixing.[b] The other heel components, salt and metal oxy-hydroxide sludge, are not expected to be as difficult to mix. Salt crystals may dissolve during

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[a]Fowler, J.R., and R.M. Wallace. December 2, 1980. *CRC Zeolite in SRP Waste.* DPST-80-488, Memorandum to M.J. Plodinec.

[b]Note that in this test program the emphasis is on maintaining solids in the just-suspended condition rather than as a uniformly mixed slurry. The just-suspended condition is needed to allow solids to be pumped from the tank, which is the goal of Tank 19 retrieval. Uniformity of the mixed slurry is not an important aspect of the retrieval operation. As long as the solids are in motion on the tank floor, they can be collected by the retrieval pump suction.

mixing or they may be small enough that they are relatively easy to maintain in suspension.[a] Similarly, sludge particles are typically smaller than 0.1 mm and, compared with the zeolite, will be less difficult to maintain in suspension. Therefore, it is reasonable to concentrate on the zeolite particles when trying to estimate the mixing intensity needed for Tank 19.

The presence or absence of solids that simulate the Tank 19 salt and metal oxyhydroxide particles is not expected to have a significant effect on the mixing intensity required to maintain the zeolite particles in suspension. If the salt and oxyhydroxide particles were included in the simulant, the effective density and viscosity of the mixed slurry would likely increase, but the amount of increase is predicted to be small (i.e., less than about 10%). Including components for the oxyhydroxide and salt particles in Tests 1 and 2 would also complicate interpretation of the data and reduce the visibility of the zeolite particles inside the tank.

The volume fractions of zeolite in water to be tested for Tests 1 and 2 were selected to bound the range of zeolite thought to be present inside Tank 19. About 50 m^3 of zeolite is estimated to be in Tank 19. Assuming that this estimate refers to bulk volume and that zeolite packs to a volume fraction of about 0.6, the volume fraction concentration of zeolite in a fully mixed Tank 19 waste slurry is about 0.028. Tests 1 and 2 are to be conducted at zeolite volume fractions of 0.015 and 0.06. A solids fraction of 0.06 is selected as a conservatively high upper bound on the amount of zeolite in Tank 19. Testing at two concentrations quantifies the effect of changing particle concentration on the required mixing intensity.

Tests 4 through 8 will use sludge simulants composed of a mixture of kaolin clay, water, and in some cases, plaster of paris. Similar mixtures have been used for scaled mixer pump testing at PNNL, and the critical shear stresses required to mobilize these simulants can be estimated from previous testing. The shear strength and yield stress ranges selected for these tests is based on previous measurements of SRS tank waste rheology.

4.4 Test Procedure

The procedures that will be used to conduct the small-scale Flygt mixer tests are described in this section.

4.4.1 Test 1: Zeolite Suspension 0.3 to 0.85 mm

With a single Flygt mixer positioned within the 0.46-m-diameter tank, 548 g of Linde AW-500 zeolite (20x50-mesh) will be spread evenly on the tank floor. This quantity of zeolite

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[a]The size range of the salt particles is not known, so it cannot be stated with certainty that the salt particles will be easier to suspend than the zeolite. Further, the salt remaining in Tank 19 likely includes low-solubility carbonate and sulfate salts, which may not dissolve to any significant extent during Tank 19 waste heel mixing.

will result in a 0.015 volume fraction of particles in the fully mixed slurry. For added visibility, some fraction of the zeolite particles may be colored using clothing dye, if necessary. Water will be added to the tank in sufficient quantity to make the liquid surface 18 ± 0.5 cm above the tank floor. If the zeolite solids are disturbed while adding water, efforts will be made to make the zeolite layer smooth and uniform.

The Flygt mixer will then be activated and its speed slowly adjusted upward until all the zeolite solids are observed to be in motion on the tank floor. The mixer speed must be increased slowly to allow time for erosion of the settled solids. As the mixer thrust is slowly increased, notes will be made on the extent of solids suspension vs. mixer thrust. The mixer thrust and speed required to just mobilize all the solids, the location of the particles last to be suspended, and the slurry temperature will be recorded in the log book.

Once all the solids are suspended, the mixer speed will be slowly decreased to determine the mixer thrust and speed required to maintain the solids in the just-suspended condition used previously by Gladki (1997). Once this criterion is met, the mixer thrust and speed as well as the slurry temperature will be recorded. The areas on the tank floor where the first particles are observed to settle will also be mapped.

This procedure will be repeated when more liquid exists in the tank. Approximately 11,153 g of additional water will be added to the tank so that the liquid level reaches 25 ± 0.5 cm. The measurements described above will then be repeated. Testing at different liquid levels allows the effect of changing liquid level to be quantified.

Similar sets of two tests at different liquid levels will then be repeated using different particle volume fractions. The simulant compositions to be used for Test 1 are given in Table 4.1 below. Note that some water will need to be removed from the tank after Tests 1B, 1C, and 1E.

Table 4.1. Test 1 Simulant Compositions

Test No.	20x50 Zeolite (g)	Water (g)	Solids (wt%)	Volume Fraction (dimensionless)	Slurry Depth (cm)
1A	548	28,415	1.89	0.015	18.0
1B	548	39,568	1.37	0.0108	25.0
1C	762	39,465	1.89	0.015	25.0
1D	2194	27,625	7.36	0.060	18.0
1E	2194	38,778	5.36	0.0432	25.0
1F	3048	38,369	7.36	0.060	25.0

At the end of Tests 1A and 1D (other tests as time permits), a suction hose will be positioned near the tank floor to simulate the action of a retrieval pump. The ability of the suction hose to remove solids from the tank while mixer operation continues (at the same speed as was needed to maintain the solids in suspension) will be evaluated. Pumping slurry from the tank will continue until liquid is no longer being withdrawn from the tank. The Flygt mixer will be turned off once the liquid level falls to a height corresponding to that of the propeller centerline.

4.4.2 Test 2: Zeolite Suspension 0.15 to 0.3 mm

Test 2 will follow the same procedure as Test 1 except smaller size zeolite particles will be used for the test. This zeolite will be in the 0.15- to 0.3-mm size range. The quantities of zeolite and water used for Test 2 are shown in Table 4.2.

Table 4.2. Test 2 Simulant Compositions

Test No.	50x100 Zeolite (g)	Water (g)	Solids (wt%)	Volume Fraction (dimensionless)	Slurry Depth (cm)
2A	548	28,415	1.89	0.015	18.0
2B	548	39,568	1.37	0.0108	25.0
2C	762	39,465	1.89	0.015	25.0
2D	2194	27,625	7.36	0.060	18.0
2E	2194	38,778	5.36	0.0432	25.0
2F	3048	38,369	7.36	0.060	25.0

4.4.3 Test 3: Water Velocity Measurements

A hot-film anemometer will be used to measure the fluid velocities at specified positions within the tank. Water will be placed into the tank to a depth of 18 cm. The Flygt mixer will then be set to the speed found to mobilize all the solids in Test 1A. The anemometer probe will be placed at each of the positions shown in Figure 4.2 (all measurements will be made 1 cm above tank floor) and then slowly rotated until the velocity reading is maximized. A 10-second average velocity and peak velocity will then be recorded at this location using a computer-based data acquisition system before moving to the next location. In addition to the points in Figure 4.2, velocity measurements will be made in the regions of the tank where the last solids to be eroded and the first solids to settle are noted [shown as (x, y) in Figure 4.2].

This same procedure is to be repeated for the mixer speed found to be necessary to maintain solids in the just-suspended condition for Test 1A.

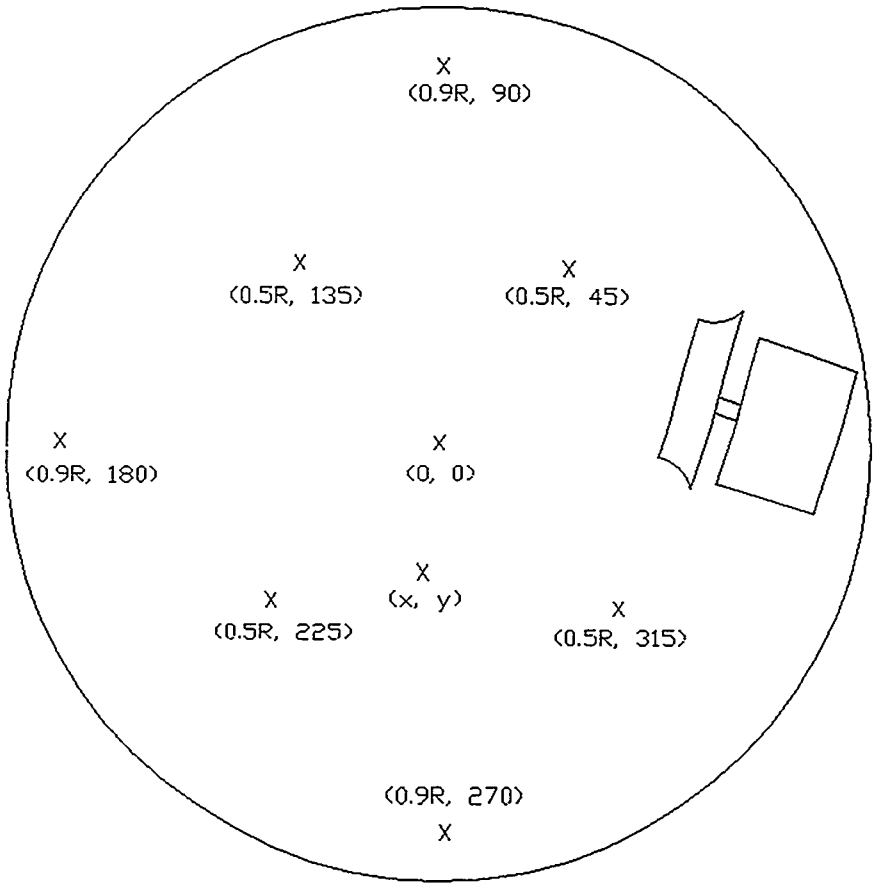

Figure 4.2. Fluid Velocity Measurement Locations

Thus, a complete set of velocity measurements will be made for two mixer speed settings for each of Test 1A, 1B, 1C, 1D, 2A, 2B, 2C, and 2D. Where appropriate, the tank water level will be made to be 25 cm prior to testing (i.e., tests 1B, 1D, 2B, and 2D). If time allows, similar measurements will be made for the mixing conditions present in Tests 4 through 8.

4.4.4 Test 4: 50 Pa Yield Stress Sludge Mobilization

A 2-cm-thick layer[a] of 50 Pa yield stress, 50 Pa shear strength sludge simulant will be placed on the tank floor. Water will be added (slowly to avoid disturbing the sludge) until the

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[a]The sludge layer thickness was selected to be 2 cm to reflect the approximate ratio of Tank 19 heel volume to total waste volume (33:290 ≈ 2:18). The minimum liquid level in the 46-cm tank is 18 cm to avoid vortexing of the mixer. A lower liquid level and sludge volume would more accurately reflect the geometric scaling of Tank 19 waste volumes, but these dimensions cannot be attained using Flygt's 7.8-cm-diameter mixer in the 46-cm-diameter tank.

liquid surface is 18 cm above the tank floor. The mixer speed will be gradually increased until significant sludge mobilization is noted and then kept constant and the slurry density measured every 5 minutes until no significant change is observed in the slurry density. The slurry will then be removed from the tank to reveal any remaining sludge.

Some brief scoping tests may be useful to establish reasonable ranges for mixer speed. As a first estimate, the mixer thrust should be adjusted so that the average shear stress within the tank is about equal to the predicted critical shear stress for the sludge. This condition is expected to result in the mobilization of some, but not all, of the sludge.

Simulant preparation instructions are given in Section 5.0.

4.4.5 Test 5: 100 Pa Yield Stress Sludge Mobilization

This test will be performed using the same procedure given for Test 4 with the exception that the 100 Pa yield stress, 100 Pa shear strength sludge simulant will be used. All other aspects of the test procedure are the same as those given in Section 4.4.4.

4.4.6 Test 6: 100 Pa Yield Stress, 800 Pa Shear Strength Sludge Mobilization

This test will be performed using the same procedure given for Test 4 except the 100 Pa yield stress, 800 Pa shear strength sludge simulant will be used. All other aspects of the test procedure are the same as those given in Section 4.4.4 except this sludge simulant must be prepared as described in Section 5.6.

4.4.7 Test 7: 150 Pa Yield Stress 2000 Pa Shear Strength Sludge Mobilization

This test will be performed using the same procedure given for Test 4 except the 150 Pa yield stress, 2000 Pa shear strength sludge simulant will be used. All other aspects of the test procedure are the same as those given in Section 4.4.4 except this sludge simulant must be prepared as described in Section 5.6.

4.4.8 Test 8: 10 Pa Yield Stress Sludge Mobilization

This test will be performed using the same procedure given for Test 4 except the 10 Pa yield stress, 10 Pa shear strength sludge simulant will be used. All other aspects of the test procedure are the same as those given in Section 4.4.4.

5.0 Test Instructions

The detailed instructions for each of the six small-scale Flygt mixer tests are given in this section. Data sheets for the tests are also included (Section 5.9).

5.1 Test 1 Instructions

With a single 300-W mixer positioned near the tank wall and on the tank floor, add the required quantities of water and 20x50-mesh IE95 zeolite (see Table 4.1, Test 1A for quantities). Allow 5 minutes for water to penetrate the pores of the zeolite particles, then smooth the settled zeolite layer to a uniform depth.

Activate the Flygt mixer and adjust the mixer speed to an initial speed of 1000 rpm. Wait 3 minutes or until the rate of solids erosion becomes small, then note in the data sheet the extent of solids mobilization and where solids remain unsuspended. Also record the slurry temperature and mixer thrust. Increase the mixer speed by up to 500 rpm. Every 2 minutes thereafter, note the coverage of unmobilized solids on the tank floor, record the thrust and temperature, measure the slurry density using the density flask,[a] and then raise the mixer speed by up to 500 rpm. Continue this process until all solids are observed to be in motion[b] on the bottom of the tank.

Note in the data sheet the regions of the tank where the last cluster of settled particles becomes suspended. Record the mixer rpm, thrust, and slurry temperature and density.

Decrease the mixer speed in increments of 100 rpm or less until particles are observed to begin depositing on the tank floor for more than one second. Record the locations in the tank where this occurs along with the slurry temperature and density and the mixer speed and thrust.

Repeat the above steps using the liquid height and zeolite concentration variations given in Table 4.1 (i.e., Tests 1B, 1C, 1D, 1E, and 1F).

Repeat the entire test sequence (1A through 1F) once to ensure the data can be reasonably replicated.

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[a]Withdraw slurry samples with the density cup located so that the slurry sample is taken from a level corresponding to roughly one-half the liquid height. These samples are not expected to be representative and will provide only a rough indication of the extent to which solids are mixed with the supernate.

[b]The just suspended criterion requires that no particles remain motionless on the tank floor for more than 1 second.

5.2 Test 2 Instructions

Test 2 is conducted according to the instructions given for Test 1 in Section 5.1 except the 50x100-mesh IE95 zeolite is used according to the amounts given in Table 4.2.

5.3 Test 3 Instructions

Add approximately 28.68 kg of clean water (soft, if possible) to the 0.46-m tank. Carefully clean the tank and mixer before adding the water to ensure the water remains clean during the test. The surface of the hot-film anemometer can become contaminated with solids, which will change its calibration.

Position the mixer(s) the same way as in Test 1A and then turn on the mixer and adjust it to the same speed as the speed resulting in particle resuspension in Test 1A. Allow at least 5 minutes of mixer operation at this condition to ensure the liquid circulation patterns become well-established.

Position the hot-film anemometer probe at each of the locations shown in Figure 4.2. At each location, slowly rotate the probe until the probe output voltage is maximized. Activate the data acquisition system to record 10 seconds of velocity data (at 20 Hz). Record the average probe voltage (displayed on the computer screen), water temperature, and probe orientation that gives maximum fluid velocity. Perform this procedure for each of the locations given in Figure 4.2 and for all the areas noted in Test 1A where the last particles to be resuspended were located.

Adjust the mixer speed to that noted to result in incipient particle sedimentation in Test 1A. Repeat all the velocity measurements after allowing at least 5 minutes for flow equilibration.

Repeat these measurements for each of the two mixer speeds recorded in Tests 1D, 2A, and 2D. Add water to the tank so the liquid level is 25.0 cm and perform these measurements for Tests 1B, 1C, 1E, 1F, 2B, 2C, 2E, and 2F. Also perform fluid velocity measurements for the mixer settings required to bring about sludge mobilization in Tests 4 through 8.

5.4 Test 4 Instructions

Prepare a sludge simulant according to the composition given in Table 5.1. The simulant is prepared by mixing the required amount of water with kaolin clay until a uniform slurry is formed. Transfer this mixture into the 0.46-m-diameter tank and smooth it to an even surface (if required). The specified quantities of simulant will yield a 2-cm-thick layer on the tank floor.

After adding the sludge, carefully add a layer of water (see Table 5.1 for quantity) to the tank to serve as supernate. Add the water slowly to avoid disrupting the sludge layer. A small

amount of vegetable-based dye can be added to the supernate to improve the visibility of the sludge/slurry interface as viewed from under the tank.

With the Flygt mixer(s) oriented as in Test 1, activate the mixer and adjust it to 1000 rpm. Every 5 minutes, observe and record the extent of sludge mobilization along with the slurry density and temperature and the mixer speed and thrust. If the rate of sludge mobilization is judged to be slow (from observing the sludge/slurry interface and the rate of change in slurry density), then increase the mixer speed by up to 500 rpm and repeat the data collection process. The goal is to determine the minimum mixer power, thrust, and rotation speed required to mobilize all the sludge simulant. If this point is reached, record the locations in the tank of the last sludge to be mobilized. Velocity measurements may be made at these points using the procedure outlined in Test 3. If all the sludge is not mobilized by operating the mixer at up to 30 minutes at 2500 rpm, then carefully pump the slurry away to reveal the remaining sludge, which will be sketched and/or photographed.

Table 5.1. Simulant Composition for Test 4

Material	Weight %	Mass Required (g)
Water for Sludge	56.5	2470
Kaolin Clay	43.5	1902
Water for Supernate	NA	25540

5.5 Test 5 Instructions

The test instructions for Test 5 are identical to those given for Test 4 in Section 5.4 except a different simulant is to be used. The simulant composition for Test 5 is given in Table 5.2.

Table 5.2. Simulant Composition for Test 5

Material	Weight %	Mass Required (g)
Water for Sludge	50.9	2337
Kaolin Clay	49.1	2255
Water for Supernate	NA	25540

5.6 Test 6 Instructions

The test instructions for Test 6 are identical to those given for Test 4 in Section 5.4 except a different simulant is to be used. The simulant composition for Test 6 is given in Table 5.3. This simulant must be prepared at least 6 hours before testing. To prepare this simulant, mix the kaolin clay and water (for the sludge) to form a uniform slurry. Then add the plaster of paris while mixing continues. Once a smooth slurry is evident, transfer the mixture into the test tank and cover it to prevent moisture loss. This simulant must then cure for at least 6 hours. Once the slurry is placed in the tank, it must not be disturbed because this will decrease its cured strength.

Table 5.3. Simulant Composition for Test 6

Material	Weight %	Mass Required (g)
Plaster of Paris	22.1	1039
Water for Sludge	50	2350
Kaolin Clay	27.8	1311
Water for Supernate	NA	25540

5.7 Test 7 Instructions

The test instructions for Test 7 are identical to those given for Test 4 in Section 5.4 except a different simulant is to be used. The simulant composition for Test 6 is given in Table 5.4. This simulant must be prepared at least 6 hours before testing. To prepare this simulant, mix the kaolin clay and water (for the sludge) to form a uniform slurry. Then add the plaster of paris while mixing continues. Once a smooth slurry is evident, transfer the mixture into the test tank and cover it to prevent moisture loss. This simulant must then cure for at least 6 hours. Once the slurry is placed in the tank it must not be disturbed because this will decrease its cured strength.

Table 5.4. Simulant Composition for Test 7

Material	Weight %	Mass Required (g)
Plaster of Paris	24	1173
Water for Sludge	46	2247
Kaolin Clay	30	1466
Water for Supernate	NA	25540

5.8 Test 8 Instructions

The test instructions for Test 8 are identical to those given for Test 4 in Section 5.4 except a different simulant is to be used. The simulant composition for Test 8 is given in Table 5.5.

Table 5.5. Simulant Composition for Test 8

Material	Weight %	Mass Required (g)
Water for Sludge	68	2707
Kaolin Clay	32	1274
Water for Supernate	NA	25540

5.9 Data Sheets

The data sheets to be used to collect data during the small-scale testing at Flygt are given in the following pages. In addition to the data collected on the data sheets, a computer-based data acquisition system will be used to collect Test 3 data.

5.9.1 Data Sheet for Tests 1 and 2

Test Number:_____ Date:_____ Start Time:_____

Test Setup:

Number of Mixers:_____

Mixer(s) Location and Orientation:_____

Simulant Description:

Liquid Level (cm):_____

Volume Fraction Solids:_____

Particle Size Range:_____

Time	Mixer Speed (rpm)	Thrust (N)	Power (W)	Liquid Temp. (°C)	Comments

5.9.2 Data Sheet for Test 3

Test Number:___3_____ Date:_____ Start Time:_____

Mixer Settings to Match Test:_____

Number of Mixers:_____
Mixer(s) Location and Orientation:_____
Mixer Speed Setting(s):_____
Mixer Power:_____

Simulant Description:

Water Level (cm):_____

Data Acquisition System Filename:_____

Probe Location	Probe Orientation (degrees)	RMS Avg. Velocity (cm/s)	Water Temp. (°C)	Comments

5.9.3 Data Sheet for Tests 4 through 8

Test Number:_____ Date:_____ Start Time:_____

Test Setup:

Number of Mixers:_____

Mixer(s) Location and Orientation:_____

Simulant Description:

Liquid Level (cm):_____

Simulant Composition:_____

Measured Yield Stress:_____

Sludge Density:_____

Time	Mixer Speed (rpm)	Thrust (N)	Power (W)	Liquid Temp. (°C)	Slurry Density (g/cm^3)	Comments

6.0 References

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Appendix B

Mixer Thrust Data

Appendix B
Mixer Thrust Data

Some of the mixer thrust data collected during the small-scale tests are known to have been in error due to a problem with the experimental apparatus. A small adjustment screw was observed to have vibrated into a position where it was biasing the thrust readings low. This problem was noticed near the end of zeolite Test 2F on the first day of testing (3/16/98). It was also noted that the load cell was not always in alignment with the lever arm connected to the mixer support. This misaligment would also tend to bias the thrust measurements low. Finally, the swirling flow pattern that resulted when two mixers were used was noted to cause a marked reduction in the thrust measurement because of the fluid impinging on the back side of the mixer support shaft.

Because it was uncertain which data from the first day of testing were valid and which were not, it was decided not to use the thrust data from the first day of tests. Similarly, the data gathered using two mixers were discarded because these data were known to have been biased low. In the interest of preserving all the data gathered, the mixer thrust data from all the tests are given in this appendix. Figure B.1 shows the data points used for the mixer thrust correlation (squares) and the data points not used for the correlation (circles). All of the individual measurements are given in Table B.1. The right-hand column gives the percent error between the mixer thrust correlation and each measurement. The table shows that agreement is generally within 10% for the data that were kept, and often, but not always, the agreement is worse than 10% for the discarded data.

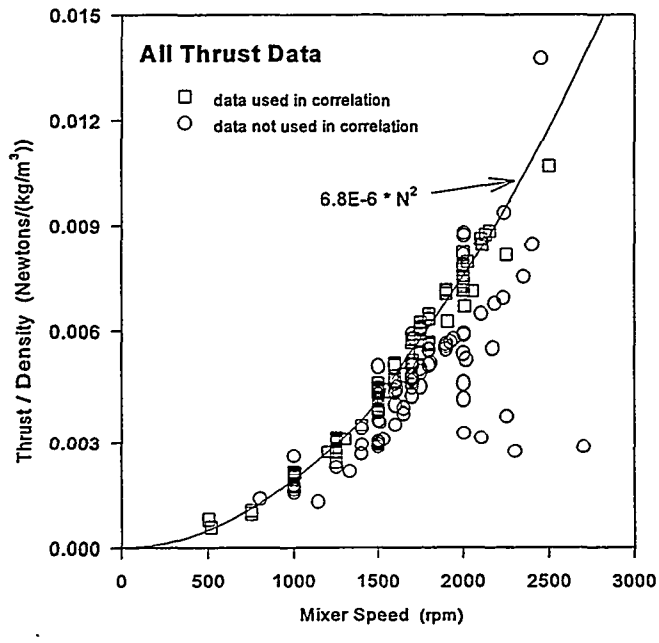


Figure B.1. Mixer Thrust Data from Small-Scale Testing

Table B.1. Mixer Thrust Data

Test No.	Date	Time	Mixer Speed (rpm)	Measured Thrust (g)	F / ρ * 1000 (m^4/s^2)	No. of Mixers	Used for Correlation (Y/N)	Percent Error From Correlation
1A	3/16/98	10:11 AM	2400	870	8.46	1	N	-22.3
1A	3/17/98	9:37 AM	1200	278.4	2.71	1	Y	-0.5
1A	3/17/98	9:40 AM	1300	320	3.11	1	Y	-2.5
1A	3/17/98	9:41 AM	1400	363.9	3.54	1	Y	-4.4
1A	3/17/98	9:42 AM	1500	455.1	4.42	1	Y	4.1
1A	3/17/98	9:43 AM	1554	459.3	4.47	1	Y	-2.1
1A	3/17/98	9:44 AM	1600	485.4	4.72	1	Y	-2.4
1A	3/17/98	9:45 AM	1651	497.4	4.84	1	Y	-6.1
1A	3/17/98	9:46 AM	1700	524.8	5.10	1	Y	-6.5
1A	3/17/98	9:51 AM	1600	483.4	4.70	1	Y	-2.8
1A	3/17/98	9:52 AM	1707	532.6	5.18	1	Y	-5.9
1A	3/17/98	9:52 AM	1800	577.1	5.61	1	Y	-8.3
1A	3/17/98	9:53 AM	1908	643.1	6.25	1	Y	-9.1
1A	3/17/98	9:54 AM	2007	686.9	6.68	1	Y	-12.2
1A	3/17/98	9:55 AM	2052	730.1	7.10	1	Y	-10.8
1B	3/16/98	10:28 AM	2235	961	9.37	1	N	-0.7
1B	3/16/98	10:29 AM	2450	1410	13.75	1	N	21.3
1B	3/17/98	10:01 AM	1500	471.5	4.60	1	Y	8.2
1B	3/17/98	10:02 AM	1600	525.3	5.12	1	Y	5.9
1B	3/17/98	10:02 AM	1700	583.4	5.69	1	Y	4.2
1B	3/17/98	10:03 AM	1800	647.8	6.32	1	Y	3.2
1B	3/17/98	10:04 AM	1900	721.4	7.03	1	Y	3.2
1B	3/17/98	10:04 AM	2000	808	7.88	1	Y	4.3
1B	3/17/98	10:06 AM	2150	906	8.83	1	Y	1.2
1B	3/17/98	10:12 AM	1900	726.9	7.09	1	Y	3.9
1B	3/17/98	10:13 AM	2000	794	7.74	1	Y	2.5
1B	3/17/98	10:14 AM	2100	883.5	8.62	1	Y	3.4
1C	3/16/98	11:05 AM	2230	712	6.92	1	N	-26.3
1C	3/16/98	11:23 AM	2000	477.5	4.64	1	N	-38.6
1C	3/16/98	10:25 AM	2180	695.7	6.76	1	N	-24.7
1C	3/17/98	10:20 AM	1900	734.2	7.14	1	Y	4.7
1C	3/17/98	10:21 AM	2000	805.2	7.83	1	Y	3.6
1C	3/17/98	10:22 AM	2110	869.3	8.45	1	Y	0.5
1C	3/17/98	10:25 AM	1900	735.5	7.15	1	Y	4.9
1C	3/17/98	10:26 AM	2000	810.6	7.88	1	Y	4.3
1C	3/17/98	10:27 AM	2126	898.3	8.73	1	Y	2.3
1D	3/16/98	11:52 AM	2170	584.7	5.52	1	N	-37.9
1D	3/16/98	11:53 AM	2016	553.4	5.22	1	N	-31.9
1D	3/16/98	11:58 AM	2000	570.6	5.39	1	N	-28.7

Table B.1. (contd)

Test No.	Date	Time	Mixer Speed (rpm)	Measured Thrust (g)	F / ρ * 1000 (m^4/s^2)	No. of Mixers	Used for Correlation (Y/N)	Percent Error From Correlation
1D	3/16/98	12:32 PM	1140	132.5	1.25	2	N	-49.0
1D	3/16/98	12:33 PM	1330	225.5	2.13	2	N	-36.3
1D	3/16/98	12:34 PM	1400	280.2	2.65	2	N	-28.5
1D	3/16/98	12:35 PM	1500	315.5	2.98	2	N	-29.9
1D	3/16/98	12:36 PM	1500	303.8	2.87	2	N	-32.5
1D	3/16/98	12:37 PM	1500	310.5	2.93	2	N	-31.0
1E	3/16/98	1:54 PM	1400	279.9	2.67	2	N	-27.9
1E	3/16/98	1:55 PM	1500	317.2	3.03	2	N	-28.8
1E	3/16/98	1:57 PM	1600	374.1	3.57	2	N	-26.2
1E	3/16/98	1:58 PM	1650	406.4	3.88	2	N	-24.6
1E	3/16/98	2:02 PM	1500	320.3	3.06	2	N	-28.1
1E	3/16/98	2:04 PM	1650	422.6	4.03	2	N	-21.6
1F	3/16/98	2:16 PM	1530	331.2	3.13	2	N	-29.3
1F	3/16/98	2:19 PM	2100	685.6	6.47	2	N	-22.3
1F	3/16/98	2:20 PM	1800	538.3	5.08	2	N	-17.0
1F	3/16/98	2:21 PM	1700	484.5	4.57	2	N	-16.2
1F	3/16/98	2:22 PM	1600	377.3	3.56	2	N	-26.3
1F	3/16/98	2:23 PM	1700	460.6	4.35	2	N	-20.3
1F	3/17/98	10:34 AM	1000	198.5	1.87	1	Y	-0.8
1F	3/17/98	10:36 AM	1500	487.8	4.61	1	Y	8.4
1F	3/17/98	10:37 AM	2000	825.5	7.79	1	Y	3.2
1F	3/17/98	10:38 AM	1800	683.3	6.45	1	Y	5.4
2A	3/16/98	3:37 PM	2350	774.4	7.53	1	N	-27.8
2A	3/16/98	3:45 PM	1400	354.6	3.45	1	N	-6.9
2A	3/16/98	3:46 PM	1510	374.8	3.64	1	N	-15.4
2A	3/16/98	3:51 PM	1600	424.1	4.12	1	N	-14.7
2B	3/16/98	4:01 PM	1400	301.8	2.94	1	N	-20.5
2B	3/16/98	4:02 PM	1500	401.7	3.92	1	N	-7.8
2B	3/16/98	4:03 PM	1700	495.4	4.83	1	N	-11.5
2B	3/16/98	4:04 PM	1800	562.5	5.49	1	N	-10.4
2B	3/16/98	4:06 PM	1500	404.7	3.95	1	N	-7.1
2B	3/16/98	4:07 PM	1600	456.4	4.45	1	N	-8.0
2B	3/16/98	4:08 PM	1800	561.4	5.47	1	N	-10.5
2C	3/16/98	4:12 PM	1500	447.5	4.35	1	N	2.4
2C	3/16/98	4:13 PM	1600	479.9	4.67	1	N	-3.5
2C	3/16/98	4:14 PM	1700	519.6	5.05	1	N	-7.5
2C	3/16/98	4:19 PM	1500	445.7	4.33	1	N	2.0
2C	3/16/98	4:20 PM	1608	465.5	4.53	1	N	-7.3

Table B.1. (contd)

Test No.	Date	Time	Mixer Speed (rpm)	Measured Thrust (g)	F / ρ * 1000 (m^4/s^2)	No. of Mixers	Used for Correlation (Y/N)	Percent Error From Correlation
2C	3/16/98	4:21 PM	1702	494.2	4.80	1	N	-12.2
2C	3/16/98	4:22 PM	1750	515.8	5.01	1	N	-13.3
2D	3/16/98	4:52 PM	1500	477.4	4.51	1	N	6.1
2D	3/16/98	4:53 PM	1700	626	5.91	1	N	8.3
2D	3/16/98	4:54 PM	1750	645.8	6.10	1	N	5.4
2D	3/16/98	4:56 PM	1500	489.4	4.62	1	N	8.7
2D	3/16/98	4:57 PM	1710	613.2	5.79	1	N	4.8
2D	3/16/98	4:58 PM	1750	636.9	6.01	1	N	3.9
2E	3/16/98	5:05 PM	1500	419.4	4.00	1	N	-5.8
2E	3/16/98	5:06 PM	1708	494.1	4.71	1	N	-14.4
2E	3/16/98	5:07 PM	1750	514.9	4.91	1	N	-15.1
2E	3/16/98	5:07 PM	1809	538	5.13	1	N	-16.9
2E	3/16/98	5:08 PM	1900	591.6	5.65	1	N	-17.2
2E	3/16/98	5:09 PM	1942	606	5.78	1	N	-18.8
2E	3/16/98	5:11 PM	1500	419.1	4.00	1	N	-5.9
2E	3/16/98	5:12 PM	1703	499.5	4.77	1	N	-13.0
2E	3/16/98	5:13 PM	1900	584.4	5.58	1	N	-18.2
2E	3/16/98	5:14 PM	1925	596.4	5.69	1	N	-18.7
2F	3/16/98	5:30 PM	1700	503.4	4.75	1	N	-12.9
2F	3/16/98	5:31 PM	1900	583.3	5.51	1	N	-19.2
2F	3/16/98	5:32 PM	2000	627.6	5.93	1	N	-21.6
2F	3/16/98	5:36 PM	1500	424.3	4.01	1	N	-5.7
2F	3/16/98	5:37 PM	1700	495	4.67	1	N	-14.4
2F	3/16/98	5:38 PM	2000	623.2	5.88	1	N	-22.1
2F	3/16/98	5:39 PM	2000	931.2	8.79	1	N	16.4
2F	3/16/98	5:42 PM	2000	922.9	8.71	1	N	15.3
2F	3/16/98	5:43 PM	2000	924.6	8.73	1	N	15.5
2F	3/16/98	5:44 PM	1500	535.2	5.05	1	N	18.9
2F	3/16/98	5:45 PM	1000	274.7	2.59	1	N	37.3
3A	3/16/98	6:43 PM	1000	154.6	1.52	1	N	-19.7
3A	3/16/98	6:44 PM	1507	450.4	4.42	1	N	3.0
3A	3/16/98	6:45 PM	1800	644	6.32	1	N	3.2
3A	3/16/98	6:46 PM	1000	176.4	1.73	1	N	-8.4
3A	3/16/98	6:47 PM	1500	452.7	4.44	1	N	4.5
3A	3/16/98	6:48 PM	2000	832.9	8.17	1	N	8.1
3A	3/17/98	9:15 AM	1000	171.1	1.68	1	Y	-11.1
3A	3/17/98	9:17 AM	1500	401.6	3.94	1	Y	-7.3
3A	3/17/98	9:18 AM	1800	577.5	5.66	1	Y	-7.4

Table B.1. (contd)

Test No.	Date	Time	Mixer Speed (rpm)	Measured Thrust (g)	F / ρ * 1000 (m^4/s^2)	No. of Mixers	Used for Correlation (Y/N)	Percent Error From Correlation
3A	3/17/98	11:40 AM	1000	201.1	1.97	1	Y	4.4
3A	3/17/98	11:40 AM	1250	323.1	3.17	1	Y	7.3
3A	3/17/98	11:40 AM	1500	470.4	4.61	1	Y	8.5
3A	3/17/98	11:40 AM	1750	615.9	6.04	1	Y	4.4
3A	3/17/98	11:40 AM	2000	767	7.52	1	Y	-0.5
3B	3/17/98	1:30 PM	1000	207.2	2.03	1	Y	7.6
3B	3/17/98	1:30 PM	1250	315	3.09	1	Y	4.7
3B	3/17/98	1:30 PM	1500	461.3	4.52	1	Y	6.5
3B	3/17/98	1:30 PM	1750	614.8	6.03	1	Y	4.2
3C	3/17/98	2:16 PM	1000	168.7	1.66	1	Y	-12.4
3C	3/17/98	2:16 PM	1250	288.3	2.83	1	Y	-4.2
3C	3/17/98	2:16 PM	1500	417.4	4.10	1	Y	-3.6
3C	3/17/98	2:16 PM	1750	634.1	6.22	1	Y	7.5
3E	3/17/98	3:13 PM	1000	198	1.94	1	Y	2.8
3E	3/17/98	3:13 PM	1250	316.8	3.11	1	Y	5.3
3E	3/17/98	3:13 PM	1500	456.1	4.47	1	Y	5.3
3E	3/17/98	3:13 PM	1750	619.4	6.08	1	Y	5.1
3F	3/17/98	3:39 PM	1000	213.1	2.09	1	Y	10.7
3F	3/17/98	3:39 PM	1250	318.9	3.13	1	Y	6.0
3F	3/17/98	3:39 PM	1500	470.1	4.61	1	Y	8.5
3F	3/17/98	3:39 PM	1750	634.6	6.23	1	Y	7.6
3G	3/17/98	3:59 PM	1000	204.3	2.00	1	Y	6.1
3G	3/17/98	3:59 PM	1250	308.3	3.03	1	Y	2.5
3G	3/17/98	3:59 PM	1500	430	4.22	1	Y	-0.7
3G	3/17/98	3:59 PM	1750	581.7	5.71	1	Y	-1.3
3G	3/17/98	3:59 PM	2000	749.9	7.36	1	Y	-2.6
3H	3/17/98	4:22 PM	1000	207.2	2.03	1	Y	7.6
3H	3/17/98	4:22 PM	1250	309.6	3.04	1	Y	2.9
3H	3/17/98	4:22 PM	1500	453.9	4.45	1	Y	4.8
3H	3/17/98	4:22 PM	1750	602.6	5.91	1	Y	2.2
3H	3/17/98	4:22 PM	2000	761.4	7.47	1	Y	-1.1
3I	3/17/98	4:41 PM	1000	207.9	2.04	1	Y	8.0
3I	3/17/98	4:41 PM	1250	315.6	3.10	1	Y	4.9
3I	3/17/98	4:41 PM	1500	448.3	4.40	1	Y	3.5
3I	3/17/98	4:41 PM	1750	603.7	5.92	1	Y	2.4
3I	3/17/98	4:41 PM	2000	742.4	7.29	1	Y	-3.6
3J	3/17/98	5:00 PM	1000	215.1	2.11	1	Y	11.8
3J	3/17/98	5:00 PM	1250	323.3	3.17	1	Y	7.5

Table B.1. (contd)

Test No.	Date	Time	Mixer Speed (rpm)	Measured Thrust (g)	F / ρ * 1000 (m^4/s^2)	No. of Mixers	Used for Correlation (Y/N)	Percent Error From Correlation
3J	3/17/98	5:00 PM	1500	453.7	4.45	1	Y	4.8
3J	3/17/98	5:00 PM	1750	603.1	5.92	1	Y	2.3
3J	3/17/98	5:00 PM	2000	725.7	7.12	1	Y	-5.7
3K	3/17/98	5:20 PM	1000	210.6	2.07	1	Y	9.4
3K	3/17/98	5:20 PM	1250	311.8	3.06	1	Y	3.7
3K	3/17/98	5:20 PM	1500	431.4	4.23	1	Y	-0.4
3K	3/17/98	5:20 PM	2000	839.2	8.24	1	Y	9.0
4A	3/17/98	6:51 PM	514	55.6	0.54	1	Y	7.9
4A	3/17/98	6:53 PM	750	102.9	0.99	1	Y	-6.9
4A	3/17/98	6:59 PM	1007	216.5	2.06	1	Y	7.8
4A	3/17/98	7:05 PM	1250	329.1	3.13	1	Y	5.9
4A	3/17/98	7:08 PM	1500	472.8	4.49	1	Y	5.5
4A	3/17/98	7:14 PM	1600	534.7	5.07	1	Y	4.8
4A	3/17/98	7:19 PM	1700	607.8	5.76	1	Y	5.5
4A	3/17/98	7:30 PM	1800	666.9	6.32	1	Y	3.3
4A	3/17/98	7:34 PM	1900	753.8	7.14	1	Y	4.8
4A	3/17/98	7:44 PM	2025	840	7.95	1	Y	2.7
5A	3/18/98	4:01 PM	800	136.8	1.34	2	N	10.6
5A	3/18/98	4:04 PM	1000	166.3	1.60	2	N	-15.4
5A	3/18/98	4:09 PM	1250	238.7	2.25	2	N	-23.8
5B	3/18/98	6:10 PM	1000	176	1.72	1	Y	-9.1
5B	3/18/98	6:30 PM	1250	252.6	2.38	1	Y	-19.2
6	3/18/98	9:28 AM	1000	170.5	1.67	1	Y	-11.5
6	3/18/98	9:30 AM	1500	404.8	3.97	1	Y	-6.6
6	3/18/98	9:32 AM	1750	552.1	5.41	1	Y	-6.5
6	3/18/98	9:37 AM	2000	737.3	7.22	1	Y	-4.5
6	3/18/98	9:50 AM	2250	840.6	8.16	1	Y	-14.6
6	3/18/98	9:55 AM	2500	1105	10.68	1	Y	-9.5
6	3/18/98	10:32 AM	1500	382.2	3.68	2	N	-13.3
6	3/18/98	10:41 AM	1750	475.5	4.57	2	N	-21.0
6	3/18/98	10:45 AM	2000	443.7	4.25	2	N	-43.7
6	3/18/98	10:57 AM	2100	331.3	3.16	2	N	-62.1
6	3/18/98	11:14 AM	2300	289.1	2.74	2	N	-72.6
7	3/19/98	8:42 AM	1000	172.2	1.69	2	N	-10.6
7	3/19/98	8:47 AM	1500	312.4	3.06	2	N	-27.9
7	3/19/98	8:52 AM	2000	337.3	3.31	2	N	-56.3
7	3/19/98	9:00 AM	2250	389.7	3.82	2	N	-60.1
7	3/19/98	9:06 AM	2700	297	2.88	2	N	-79.1

Table B.1. (contd)

Test No.	Date	Time	Mixer Speed (rpm)	Measured Thrust (g)	F / ρ * 1000 (m^4/s^2)	No. of Mixers	Used for Correlation (Y/N)	Percent Error From Correlation
8	3/18/98	5:02 PM	500	77.4	0.75	1	Y	59.5
8	3/18/98	5:10 PM	750	93.8	0.91	1	Y	-14.3
8	3/18/98	5:12 PM	1000	165.6	1.59	1	Y	-15.8
8	3/18/98	5:22 PM	1250	280	2.68	1	Y	-9.2
8	3/18/98	5:28 PM	1500	414.7	3.96	1	Y	-6.7
8	3/18/98	5:30 PM	1700	535.3	5.12	1	Y	-6.2

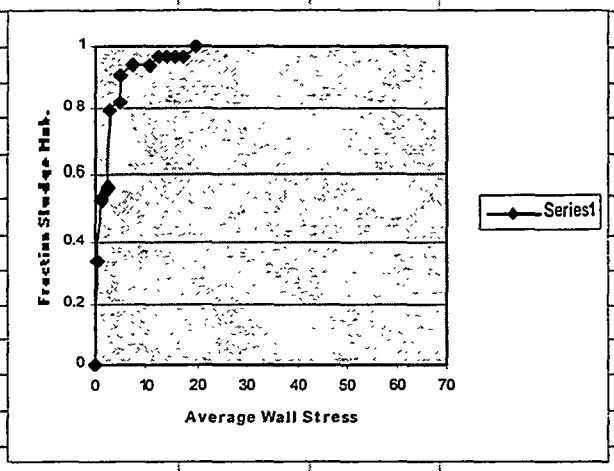
Appendix C

Sludge Mobilization Test Results

Appendix C
Sludge Mobilization Test Results

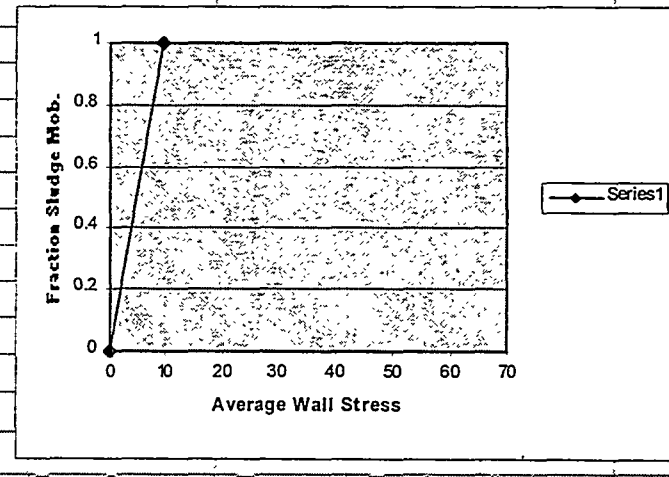
This appendix contains copies of the Excel spreadsheets used to generate the Table 4.4 and Figures 4.23 and 4.24 in Section 4.4 of this report. Refer to Section 4.4 for an explanation of these calculations.

Test No:	4A	3/17/98	6:43 PM
Temp =	19.5	deg. C	
Final rho=	1.035	g/mL	
Vtank =	28205	mL	
Vsludge=	3223	mL	
Vsupernt=	24982	mL	
A tank =	0.410221	m^2	
yield str =	2 to 50 Pa	shear str=	2 to 50 Pa
rho H2O=	0.998308		



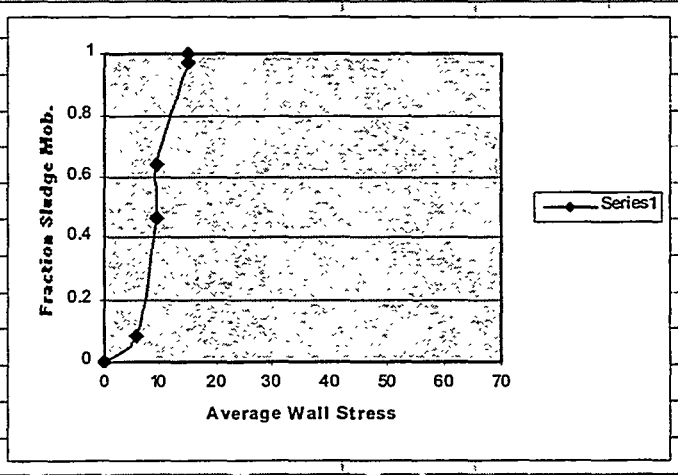
Time	Time	RPM	Density	Frac. Sus	Thrust	Tau 0	# Mixers
6:43	0.00	0	0.998	0	0	0	1
6:46:55	3.92	309	1.012	0.345248162	0.182517	0.444924	1
6:51:40	8.67	514	1.019	0.533907082	0.508519	1.239621	1
6:53:54	10.90	750	1.02	0.561578475	1.08375	2.641869	1
6:57	14.00	750	1.028	0.789786535	1.09225	2.662589	1
6:59:10	16.17	1007	1.029	0.819196585	1.970973	4.804662	1
7:03:40	20.67	1007	1.032	0.908654673	1.97672	4.81867	1
7:05:25	22.42	1250	1.033	0.938890493	3.048785	7.432054	1
7:08:10	25.17	1500	1.033	0.938890493	4.39025	10.70216	1
7:11	28.00	1500	1.033	0.938890493	4.39025	10.70216	1
7:14:45	31.75	1600	1.034	0.969338191	4.999964	12.18847	1
7:17:25	34.42	1600	1.034	0.969338191	4.999964	12.18847	1
7:19:15	36.25	1700	1.034	0.969338191	5.644491	13.75963	1
7:30:15	47.25	1800	1.034	0.969338191	6.32808	15.42603	1
7:34:20	51.33	1900	1.034	0.969338191	7.050731	17.18764	1
7:44:35	61.58	2025	1.035	1	8.016722	19.54245	1

Test No:	4B	3/18/98	3:09 PM
Temp =	20	deg. C	
Final rho=	1.033	g/mL	
Vtank =	28205	mL	
Vsludge=	3223	mL	
Vsupernt=	24982	mL	
A tank =	0.410221	m^2	
yield str =	2.4 Pa	shear str=	2.4 Pa
wt% =	26	approx	
rho H2O=	0.998206		

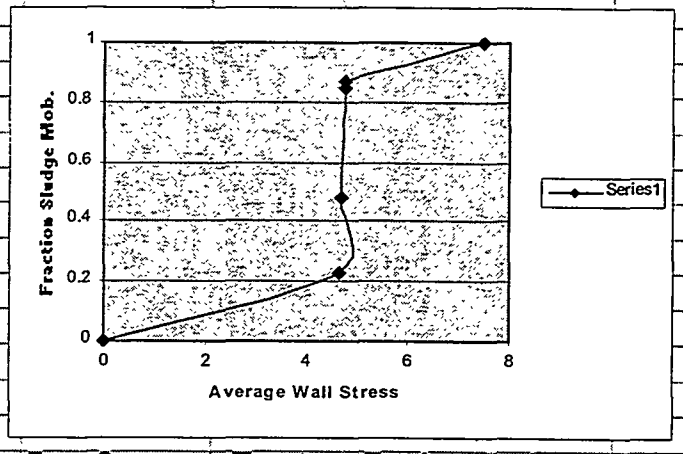


Time	Time	RPM	Density	Frac. Sus	Thrust	Tau 0	# mixers
3:09	0.00	0	0.999	0	0	0	2
3:13:20	4.00	1000	1.033	1	3.902444	9.513029	2

Test No:	5A	3/18/98	3:54 PM				
Temp =	14	deg. C					
Final rho=	1.041	g/mL					
Vtank =	28205	mL					
Vsludge=	3223	mL					
Vsupernt=	24982	mL					
A tank =	0.410221	m^2					
yield str =	100 Pa	shear str=	100 Pa				
rho H2O=	0.999246						
Time	Time	RPM	Density	Frac. Sus	Thrust	Tau 0	# mixers
3:54	0.00	0	0.999	0	0	0	2
4:00:02	5.86	800	1.003	0.080463244	2.425031	5.911524	2
4:04	10.50	1000	1.02	0.46676901	3.853333	9.393311	2
4:07:20	13.16	1000	1.027	0.63714273	3.879778	9.457775	2
4:10:50	16.66	1250	1.04	0.973043749	6.138889	14.96483	2
4:15:20	21.16	1250	1.041	1	6.144792	14.97922	2

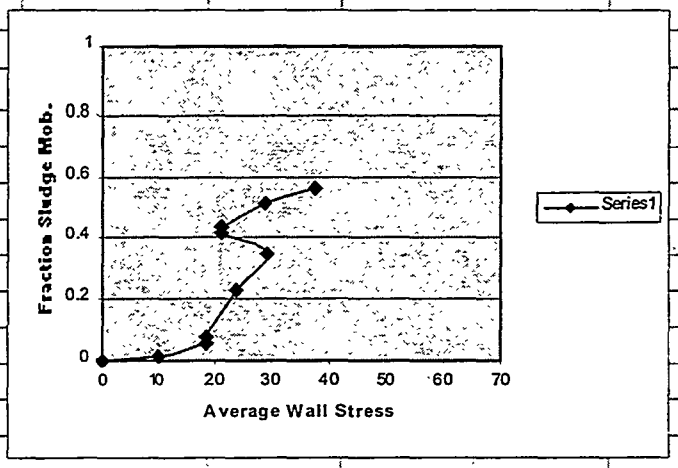


Test No:	5b	3/18/98	6:07 PM
Temp =	13	deg. C	
Final rho=	1.042	g/mL	
Vtank =	28205	mL	
Vsludge=	3223	mL	
Vsupernt=	24982	mL	
A tank =	0.410221	m^2	
yield str =	100 Pa	shear str=	100 Pa
rho H2O=	0.999379		



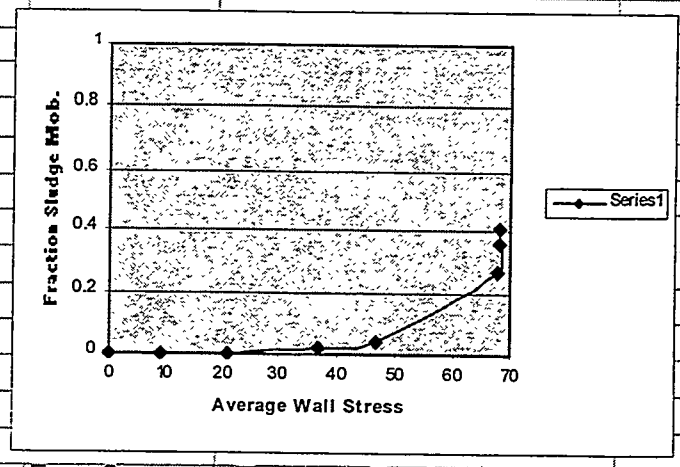
Time	Time	RPM	Density	Frac. Sus	Thrust	Tau 0	# mixers
6:07	0.00	0	1	0	0	0	1
6:12:30	5.43	1000	1.01	0.227196973	1.907778	4.65061	1
6:18	11.68	1000	1.021	0.476970899	1.928556	4.70126	1
6:24:50	17.76	1000	1.036	0.843899076	1.956889	4.770328	1
6:29:40	22.60	1000	1.037	0.869528009	1.958778	4.774933	1
6:25:45	18.68	1250	1.042	1	3.075347	7.496806	1

Test No:	6	3/18/98	9:24 AM
Temp =	18.5	deg. C	
Final rho=	1.04	g/mL	
Vtank =	28205	mL	
Vsludge=	3223	mL	
Vsupernt=	24982	mL	
A tank =	0.410221	m^2	
yield str =	100 Pa	shear str=	800 Pa
rho H2O=	0.998503		



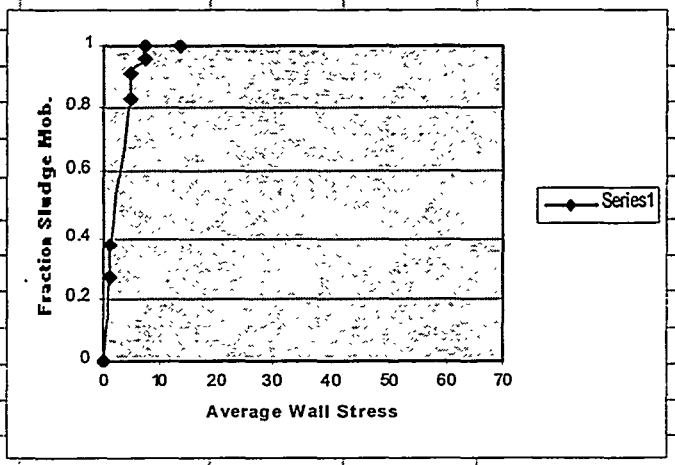
Time	Time	RPM	Density	Frac. Sus	Thrust	Tau 0	# mixers
9:24	0.00	0	0.999	0	0	0	1
9:30:15	5.83	1500	0.999	0.01061591	4.24575	10.34991	1
9:37	12.61	2000	1.001	0.053659484	7.563111	18.43667	1
9:42:40	18.25	2000	1.002	0.075360794	7.570667	18.45509	1
9:43:40	19.25	2250	1.009	0.230716112	9.648563	23.5204	1
9:55:56	31.51	2500	1.014	0.345514561	11.97083	29.18142	1
10:32:32	34.11	1500	1.017	0.415992459	8.6445	21.07279	2
10:37:15	38.83	1500	1.018	0.439758543	8.653	21.09351	2
10:42:20	43.91	1750	1.021	0.511894001	11.8124	28.79522	2
10:50:05	51.66	2000	1.023	0.560694341	15.45867	37.68375	2
10:57:15	58.83	2100	1.028	0.685254796	17.12648	41.7494	2
11:07:30	69.08	2300	1.033	0.813605344	20.64393	50.32393	2

Test No:	7	3/19/98	8:36 AM
Temp =	16	deg. C	
Final rho=	1.04	g/mL	
Vtank =	28205	mL	
Vsludge=	3223	mL	
Vsupernt=	24982	mL	
A tank =	0.410221	m^2	
yield str =	150 Pa	shear str=	2000 Pa
rho H2O=	0.998945		



Time	Time	RPM	Density	Frac. Sus	Thrust	Tau 0	# mixers
8:36	0.00	0	0.999	0	0	0	2
8:42:50	6.08	1000	0.999	0.001196351	3.774	9.199919	2
8:46	9.75	1000	0.999	0.001196351	3.774	9.199919	2
8:50:50	14.08	1500	0.999	0.001196351	8.4915	20.69982	2
8:53:15	16.50	2000	1	0.022837237	15.11111	36.83651	2
8:56:35	19.83	2000	1	0.022837237	15.11111	36.83651	2
9:01:30	24.75	2250	1.001	0.044599284	19.14413	46.66783	2
9:06:15	29.50	2700	1.011	0.269113862	27.84294	67.87302	2
9:11:10	34.42	2700	1.015	0.362582808	27.9531	68.14156	2
9:17:35	40.83	2700	1.017	0.41013904	28.00818	68.27583	2
9:24:20	47.58	2700	1.02	0.482527921	28.0908	68.47724	2
9:29:55	53.17	2700	1.021	0.506943759	28.11834	68.54437	2
9:32:15	55.50	2700	1.023	0.556212439	28.17342	68.67864	2
9:41:30	64.75	2700	1.027	0.656534746	28.28358	68.94718	2
9:47:15	70.50	2700	1.028	0.68199507	28.31112	69.01431	2
9:55:50	79.08	2700	1.034	0.838055111	28.47636	69.41712	2
10:07:10	90.42	2700	1.032	0.78539726	28.42128	69.28285	2
10:12:20	95.58	2700	1.033	0.81164523	28.44882	69.34998	2

Test No:	8	3/18/98	4:55 PM				
Temp =	12	deg. C					
Final rho=	1.025	g/mL					
Vtank =	28205	mL					
Vsludge=	3223	mL					
Vsupernt=	24982	mL					
A tank =	0.410221	m^2					
yield str =	10 Pa	shear str=	10 Pa				
rho H2O=	0.999499						
Time	Time	RPM	Density	Frac. Sus	Thrust	Tau 0	# mixers
4:55	0.00	0	1	0	0	0	1
5:02:40	7.17	500	1.007	0.2695945	0.475528	1.159199	1
5:06	10.83	500	1.01	0.382742303	0.476944	1.162652	1
5:07:15	11.75	500	1.01	0.382742303	0.476944	1.162652	1
5:12:30	17.00	1000	1.021	0.82641946	1.928556	4.70126	1
5:19:20	23.83	1000	1.023	0.912340359	1.932333	4.710469	1
5:24:25	28.92	1250	1.024	0.955949555	3.022222	7.367303	1
5:27:20	31.83	1250	1.025	1	3.025174	7.374497	1
5:34:00	38.50	1700	1.025	1	5.595361	13.63987	1
5:42:45	47.25	1700	1.025	1	5.595361	13.63987	1



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