Pacific Northwest National Laboratory

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

Test Results from Phase B: Mid-Scale Testing at PNNL

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March 1999

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

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Summary

Staff from the Savannah River Site (SRS), Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory, and ITT Flygt Corporation are conducting a joint mixer testing program to evaluate the applicability of Flygt mixers to SRS Tank 19 waste retrieval and waste retrieval in other U.S. Department of Energy tanks. This mixer testing program consists of three phases. The first phase, Phase A, was performed in a 0.45-m-diameter tank at the ITT Flygt Corporation laboratory in Trumbull, Connecticut. The second phase, Phase B, was performed in 1.8- and 5.7-m-diameter tanks at PNNL. Phase C tests were performed in a 25.9-m-diameter tank.

This report provides the results of the Phase B Flygt mixer tests, which were conducted at PNNL in May and June 1998. The Phase A results are provided in Powell et. al. (1999). An analysis of the Phase C data (full-scale water velocity measurements) is underway. The Phase C report will contain a summary of all the conclusions drawn from all three phases of testing.

During Phase B testing, stationary submerged jet mixers manufactured by ITT Flygt Corporation were tested in 1.8- and 5.7-m-diameter tanks to evaluate their ability to mobilize cohesive sludge and maintain rapidly settling solids in suspension. The data gathered in the Phase B tests were compared with similar tests conducted in a 0.45-m tank as part of the Phase A tests, which were conducted at the ITT Flygt laboratory in Connecticut. This comparison allowed inferences to be drawn regarding the scale-up of Flygt mixers over the range of configurations and waste simulants tested. While some of the Phase B tests were geometrically similar to selected Phase A tests (0.45-m tank), none of the Phase B tests were geometrically, kinematically, or dynamically similar to the planned Tank 19 mixing system. Therefore, the mixing observed during the Phase B tests is not *directly* indicative of the mixing expected in Tank 19.

The following key conclusions and recommendations resulted from the analyses of the Phase A (small-scale) and Phase B (mid-scale) tests.

- Three stationary 37-kW (50-hp) Model 4680 Flygt mixers are unlikely to provide sufficient mixing energy to either mobilize all of the Tank 19 heel or to maintain the rapidly settling zeolite solids in suspension so they can be pumped from the tank.
- Continuously rotating (or oscillating) the Flygt mixers is expected to significantly improve their performance, but it is not yet known whether the full-scale performance of such a system will be acceptable. Tests are being planned to address this issue.

- Scaling up the Flygt mixers to mix rapidly settling particles appears to follow a constant-power-per-unit-volume relationship over the range of tank sizes and simulant compositions tested. It is unknown whether this relationship holds for tanks as large as Tank 19.
- A correlation between sludge shear strength and required mixer thrust is apparent in the data. This correlation cannot be applied to the Tank 19 sludge because the strength properties of the sludge are unknown. Further, it is not known whether this correlation holds in tanks larger than those tested.

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, David Robinson, and David Day, all of whom are affiliated with ITT Flygt Corporation. Their assistance during the tests is greatly appreciated.

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Acronyms and Nomenclature

D	propeller diameter, m
DOE	U.S. Department of Energy
F	mixer thrust, N
k	mixer performance coefficient, 1/revolution
lpm	liters per minute
min	minute
N	mixer speed, s^{-1}
N_f	thrust affinity law coefficient
N_{mix}	required number of mixers
ORNL	Oak Ridge National Laboratory
P	total hydraulic mixing power in the tank, W
P_{mixer}	hydraulic power provided by one mixer, W
P/V	power per unit volume, W/m^3
$(P/V)_{req}$	required mixing power intensity to reach desired solids suspension, W/m^3
PNNL	Pacific Northwest National Laboratory
rms	root-mean-square
rpm	rotations per minute
SRS	Savannah River Site
T	tank diameter, m
V	total slurry volume in tank, m^3
v_{avg}	time-averaged fluid velocity, cm/s
v_{peak}	average peak velocity on a 1-second basis, cm/s
W	watts
Z	liquid level, m
α	azimuthal angle for velocity probe alignment in 5.7-m tank, degrees
λ	Kolmogorov turbulent length scale, m
μ	slurry viscosity, Pa-s
ρ	fluid density, kg/m^3
τ_0	average wall shear stress, Pa
τ_s	sludge shear strength, 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 m³ (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. During fiscal year 1998, staff from Pacific Northwest National Laboratory (PNNL),^(a) Oak Ridge National Laboratory (ORNL), SRS, and ITT Flygt Corporation conducted 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 consisted of three phases. The first phase involved small-scale (0.45-m diameter tank) mixer testing at the ITT Flygt laboratory in Trumbull, Connecticut. The second phase involved larger-scale (1.8-m and 5.7-m diameter tanks) tests of Flygt mixers at PNNL. The third and final phase involved full-scale mixer testing at SRS. Testing in different tank sizes was needed to evaluate and validate scaling methods so that the results of the relatively inexpensive small-scale tests could 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 rotations per minute (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).

This report focuses on the Phase B tests (i.e., those conducted at PNNL). Phase B tests were performed in 1.8-m and 5.72-m tanks using 3-kW (4-hp) Model 4640 Flygt mixers. The ability of these Flygt mixers to suspend rapidly settling particles and to mobilize simulated tank sludge was evaluated through testing. The data from these tests, and their comparison to the Phase A tests in a 0.45-m tank, are described in this report.

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

Section 2.0 of this report provides the key findings of the Phase B Flygt mixer tests. Modifications to the tests outlined in the original test plan for this work are described in Section 3.0. Section 4.0 presents the results from the Phase B Flygt mixer tests. An analysis of the Phase B data is provided in Section 5.0. Publications referenced in this report are listed in Section 6.0. The Phase B Test Plan is provided in Appendix A. Appendix B provides the water velocity data for the 1.8-m tank tests, and Appendix C provides the water velocity data for the 5.7-m tank tests.

Figure 1.1. Flygt Mixer

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

2.0 Conclusions and Recommendations

Pacific Northwest National Laboratory (PNNL) performed mixer tests using 3-kW (4-hp) Flygt mixers in 1.8- and 5.7-m-diameter tanks at the 336 building facility in Richland, Washington to evaluate candidate scaling relationships for Flygt mixers used for sludge mobilization and particle suspension. These tests constituted the second phase of a three-phase test program involving representatives from ITT Flygt Corporation, the Savannah River Site (SRS), the Oak Ridge National Laboratory (ORNL), and PNNL. The results of the first phase of tests, which were conducted at ITT Flygt's facility in a 0.45-m-diameter tank, are documented in Powell et al. (1999).

Although some of the Phase B tests were geometrically similar to selected Phase A tests (0.45-m tank), none of the Phase B tests were geometrically, kinematically, and/or dynamically similar to the planned Tank 19 mixing system. Therefore, the mixing observed during the Phase B tests is not *directly* indicative of the mixing expected in Tank 19 and some extrapolation of the data is required to make predictions for Tank 19 mixing. Of particular concern is the size of the mixer propellers used for the 5.7-m tank tests. These propellers were more than three times larger than required by geometric scaling of the Tank 19 mixers. The implications of the lack of geometric similarity, as well as other factors that complicate interpretation of the test results, are discussed in Section 5.4.

2.1 Conclusions

The key findings and implications of the Phase B tests are documented in this report. An overall summary report of the fiscal year 1998 Flygt mixer tests (Phases A, B, and C) will be prepared and issued in fiscal year 1999. At present, the key findings from the Phase B tests are as follows:

- Fluid velocity measurements indicate that time-averaged velocities in the 30- to 50-cm/s range (measured 5 cm above the tank floor) are required to maintain 20x50-mesh zeolite particles in suspension. This range is reasonably consistent with the velocity measurements made during Phase A tests. If an all-particles-in-motion condition is to be met, the average fluid velocities near the tank floor (5 cm above) need to exceed approximately 50 cm/s in all locations.
- The mixing intensity required to induce sludge mobilization can be estimated based on the sludge shear strength. The average wall shear stress (τ_0) required to result in about 80% of the sludge mobilized is on the order of 5% to 15% of the sludge shear strength. Evidence exists that these percentages increase with increasing scale, but it is unclear whether this is a real effect or an artifact of differences in the simulants tested. It should

also be noted that it may be possible to reach 80% mobilized at τ_0 levels somewhat lower than implied by these percentages if the mixers are run for longer periods of time.

- Slurry pump-down tests conducted during this test program in a 1.8-m tank imply that mixing to the all-particles-in-motion condition results in recovery of approximately 90% of the rapidly settling solids from a single pump-down when the initial solids concentration and liquid-level-to-tank-diameter ratio are in the range of those tested. If the mixing intensity is not sufficient to reach this condition, solids recovery is likely to be poorer, although it is not clear how best to predict this reduction in solids recovery based on the existing test data. The relationship between solids recovery in the 1.8-m tank and solids retrieval in Tank 19 is unclear, but the 1.8-m tank solids recovery data imply that effective solids retrieval can be achieved in *some* tanks when mixing to the all-particles-in-motion condition.
- Retrieval of the sludge portion of the solids, which is expected to be composed of slow settling solids, is not expected to present difficulty provided the sludge can be mobilized. Once mobilized, the slowly settling solids are maintained in suspension with relatively gentle agitation.
- Constant-power-per-unit-volume (P/V) mixer scaling is consistent with the Phase A and Phase B experimental observations. Constant-P/V scaling predicts that significantly more than three stationary 37-kW (50-hp) Model 4680 Flygt mixers will be required in Tank 19 to achieve an all-particles-in-motion-on-the-tank-floor condition, although the accuracy of the exact number of predicted mixers is questionable because the effects of changing the number of mixers and the liquid-level-to-tank-diameter ratio are not well understood.
- The constant-wall-shear-stress method for predicting required mixing intensity (Gladki 1997) apparently does not apply to rapidly settling particles in large tanks (i.e., 1.8-m diameter and larger). Roughly 40% of the waste heel in SRS Tank 19 is expected to be rapidly settling zeolite, which was originally placed in the tank as 20x50-mesh zeolite particles (Goslen 1986).

2.2 Recommendations

Based on the results of the Phase A and B Flygt mixer test programs, the following recommendations are made:

- The Model 4680 Flygt mixers planned for installation in SRS Tank 19 should not be deployed without a mechanism for continuously (or periodically on a timescale of minutes) reorienting the mixers. Proceeding with the previously planned three Model 4680 mixers with fixed orientation is likely to result in poor recovery of fast-settling waste components from Tank 19.

- A combination of numerical modeling, scaling analysis, and experimentation should be used to examine the potential effectiveness of Model 4680 Flygt mixers configured for continuously adjustable orientation.
- Kaolin clay with a shear strength of about 400 Pa should be tested in the 0.45-m tank used previously for the Phase A tests in Trumbull, Connecticut. This test will allow a comparison of sludge mobilization using Flygt mixers and the same sludge simulant in 0.45-m, 1.8-m, and 5.72-m tanks.
- Improved slurry pump-down techniques should be explored, and an improved understanding of the pump-down process should be developed to aid in the design and interpretation of pump-down tests. The Phase B testing implies that mixing intensity must be near (i.e., P/V of at least half, perhaps three-quarters) that required to reach an all-particles-in-motion condition if slurry retrieval is performed without continuously reorienting the mixers and without systematically varying the mixer speeds during pump-down. Zeolite recovery may also be improved if the retrieval pump intake is positioned as close as is practical to the tank floor instead of 13 cm above the floor as was used in our 5.7-m tank tests. Further testing may be required to determine the extent of improvement that can be achieved and the relationship between applied mixing intensity, the number of mixers employed, the liquid-level-to-tank-diameter ratio, and the fraction of solids retrieved.
- Efforts should be made to quantify the shear strength of the Tank 19 heel. Without these data, the number of mixers required to effect mobilization of the sludge cannot be predicted with sufficient accuracy. Accurate measurements of the Tank 19 waste heel particle size distribution and the supernate density and viscosity are also needed to improve the Tank 19 mixing predictions.

3.0 Modifications Made to Phase B Test Plan

The Phase B Test Plan (Appendix A) describes the experimental apparatus and procedures used for Phase B testing. This section and Section 4.0 describe modifications made to the test plan for Tests 1 through 9.

The as-built diameter of the 1.8-m clear-bottomed tank was measured at 1.815 m. Thus the volume at the 70.6-cm liquid level was 1.827 m³, and the volume at 103.8 cm was 2.686 m³.

3.1 Test 1: Zeolite Suspension in 1.8-m Tank

Test 1 was performed according to the test plan except that two slurry pump-down tests were performed rather than just one. In addition to the planned Tests 1A, 1B, and 1C, a fourth test (Test 1D) was conducted with the mixer orientation changed as described in Section 4.1.

3.2 Test 2: Limestone Suspension in 1.8-m Tank

Tests 2A and 2B were performed as described in the test plan, but Tests 2C and 2D were not performed. The mixer was not able to achieve complete particle motion for Tests 2A or 2B, so Tests 2C and 2D, which would have required even more mixing intensity, were not performed. Instead, additional mixer orientations were tested during both Test 2A and 2B. Also, fluid velocity measurements were not performed during this test.

3.3 Test 3: Water Velocity Measurements in 1.8-m Tank

Test 3 was performed as described in the test plan.

3.4 Test 4: 405-Pa Sludge Mobilization in 1.8-m Tank

Test 4 was performed according to the test plan except that the sludge shear strength was lower than the target strength of 500 Pa. The measured shear strength was 405 ± 83 Pa.^(b) The shear strength was measured on a sample withdrawn from the tank prior to testing using a four-blade shear vane connected to a constant strain rheometer (see Powell et al. 1995a for description

^(b)Unless otherwise noted, all reported uncertainty values refer to the 95% confidence interval of the mean computed based on the assumed Gaussian data scatter from replicate measurements. The relatively large uncertainty in the shear strength measurements results primarily from the variations in simulant properties throughout the tank. The uncertainty was estimated based on the variance of measurements taken from various locations in the tank.

of the procedure). The sample was collected on the day of the test and placed in a sealed container for storage. Shear strength measurements were made six days after the mixing test, but the strength of the kaolin-based sludge simulant does not change with time provided the water content is maintained (Powell et al. 1995a).

Some difficulties with the slurry density measurements were encountered during the test at high mixer speeds as air became entrained in the slurry and biased the slurry density readings low. This effect is discussed further in Section 4.4.

3.5 Test 5: 2070-Pa Shear Strength Sludge Mobilization in 1.8-m Tank

Test 5 was performed according to the test plan, but the sludge strength was higher than the 1500 Pa target. The measured sludge shear strength was 2070 ± 600 Pa. Shear strength measurements were made several days after the mixing test, but, like kaolin, the kaolin/bentonite simulant used in this test does not exhibit variations in strength with time (Powell et al. 1995a). The same shear strength measurement procedure used for Test 4 was used for Test 5.

3.6 Test 6: Limestone Particle Suspension in 5.72-m Tank

Test 6A was performed as described in the test plan. Tests 6B and 6C were not performed because the mixers did not provide adequate solids suspension in Test 6A. Starting with the Test 6A conditions, the slurry was pumped from the tank to reveal the remaining solids. Two additional pump-down tests were performed using revised mixer and retrieval pump positions. The Pitbull pump was not used for slurry retrieval. Instead, a 5.1-cm (2-in.) inside diameter flexible pipe was positioned vertically in the tank with its inlet roughly 13 cm above the tank floor, 30 cm from the tank wall, and directly opposite the mixer pointing across the tank center (i.e., Mixer No. 2). Slurry was pumped through this pipe using a double-diaphragm pump capable of pumping roughly 300 lpm. The location and elevation of the retrieval pipe inlet was selected based on the planned retrieval pump location in Tank 19, which is approximately 1.5 m from the tank wall, 13 cm above the tank floor, and in the riser directly opposite that used to install Mixer No. 2.

3.7 Test 7: Water Velocity Measurements in 5.72-m Tank

Test 7 was performed as described in the test plan except that an additional set of measurements were made at the 45-degree position (southeast direction). Velocity measurements were made with the electromagnetic fluid velocity probe located 5 cm above the tank floor. Measurements were made at five radial points (0.12R, 0.3R, 0.5R, 0.7R, and 0.84R where R is the tank radius) along each of three radial directions (south, southeast, and east).

Measurements were made at each of these points for mixer speeds of 860 rpm with all three mixers running, with Mixers Nos. 1 and 3 running, and with Mixer No. 2 running.

Measurements were also made at 430 rpm for all three mixers running. Water levels of 1.0, 1.5, and 2.0 m were tested.

3.8 Test 8: 363-Pa Sludge Mobilization in 5.72-m Tank

Test 8 was performed as described in the test plan except that a liquid depth of 2.0 m rather than 2.2 m was used and the sludge shear strength was lower than the 500 Pa target. The actual shear strength was measured at 363 ± 50 Pa. The strength measurement procedure was identical to that of Tests 4 and 5.

The mixers were run at the 2-m liquid level until the sludge erosion rate was negligible. Slurry was then pumped from the tank until the liquid level was 1.0 m. Mixing continued until the erosion rate was low (i.e., the rate of slurry density increase was judged to be negligible). The slurry was pumped from the tank and the remaining solids collected.

3.9 Test 9: 20x50-Mesh Zeolite Suspension in 5.72-m Tank

Test 9 was not included in the original test plan. In general, the test was performed similarly to Test 6. A description of Test 9 is given in Section 4.9.

4.0 Test Results

This section provides the Phase B Flygt mixer test results. The analysis of the data and conclusions drawn from the tests are given in Section 5.0.

4.1 Test 1: Zeolite Suspension in 1.8-m Tank

A total of 35.6 kg of dry IE95 20x50-mesh zeolite was placed in the clear-bottom, 1.8-m diameter tank. Water was added so the liquid level was 70.6 ± 1 cm, making the zeolite concentration equal to that used for Phase A, Test 1A (i.e., 1.93 wt% solids). The 3-kW (4-hp) mixer was positioned to be geometrically similar to the Phase A mixer position. The mixer speed was gradually increased and the fraction of the tank floor with solids in motion was observed. Fluid velocity and slurry density data were taken at selected locations and mixer speeds. All fluid velocity measurements were made using a Marsch-McBirney Model 511 electromagnetic velocity probe. Slurry densities were measured using a Krohne Coriolis mass flow meter, the readings from which were periodically verified using a 100 mL pycnometer.

A mixer speed of about 720 rpm was found to be required to meet the all-particles-in-motion-on-the-tank-floor criterion. This same criterion was used for the Phase A tests conducted at the ITT Flygt Laboratory. The uncertainty in the required mixer speed measurement is estimated to be less than about ± 70 rpm (see footnote on bottom of page 5.2).

Water was added to the tank so the total liquid level was 103.8 ± 1 cm, making the zeolite concentration equal to 1.32 wt%, which was identical to that used in Phase A, Test 1B. The mixer speed was gradually increased until the solids motion criterion was judged to be met. Again, the required speed was found to be about 720 rpm.

An additional 16.7 kg of zeolite was added to bring the zeolite concentration back to 1.93 wt% at the 103.8-cm liquid level. This concentration was equal to that in Test 1C in Phase A. The mixer speed found to be required was determined to be about 860 rpm (full speed).

One more test was then performed in which the mixer orientation was changed to determine if the mixing would be improved. The Test 1C zeolite concentration and tank level were maintained. However, the mixer was shifted toward the tank center so it was still pointing due south but the propeller rotation axis was now only 7.6 cm east of the north-south tank diameter rather than the 25-cm distance used for Tests 1A, 1B, and 1C. Once again, a mixer speed of about 860 rpm was required to reach the desired particles suspension level. Thus, the change in mixer orientation did not noticeably improve the mixing effectiveness. This additional test was assigned the test identifier, "Test 1D."

A pump-down test was then performed in which the retrieval pump suction was positioned 2.5-cm above the tank floor in the position labeled "A" in Figure 4.3 (i.e., along the east-west diameter, 0.6 m from the tank center). With the mixer speed at 860 rpm and in the revised (Test 1D) mixer position, slurry was pumped from the tank at an average rate of 50 lpm (13 gpm). Slurry pumping commenced once the target mixer speed was reached and the slurry density had stabilized. A plot of the total slurry volume retrieved vs. time is given in Figure 4.1.

Six slurry samples were taken from the retrieval pump discharge during the pump-down period. These samples were dried to determine their solids concentrations. The solids concentration data are also given in Figure 4.1. Once the mixer speed was reduced to 500 rpm (and then turned off shortly thereafter), the solids concentration was greatly reduced. The reduced mixer speed probably allowed some particle settling to take place thereby decreasing the solids concentration. It is likely, however, that this effect was due primarily to the fact that most of the solids had already been removed from the tank by the time the mixer speed was reduced.

Averaging the three samples taken while the mixer was running at full speed gives an average concentration of 3.4 wt%. Assuming that slurry was removed at this concentration for the first 27.5 minutes of the pump-down test, the estimated total mass of zeolite (on a dry basis) removed from the tank was 47.4 kg.

Figure 4.1. Test 1 Pump-Down Data

The actual quantity of zeolite removed was determined by weighing the solids remaining in the tank and adjusting for the moisture content. About 5.7 kg of zeolite (dry basis) remained in the tank after the pump-down. Thus, 46.6 kg of zeolite was retrieved. This quantity is consistent with the quantity estimated from the slurry samples taken during the pump-down. Eighty-nine percent of the solids were retrieved in this pump-down test.

A second pump-down test was performed by adding water to the solids remaining in the tank after the first pump-down until the liquid surface was even with the top of the vortex suppressor (roughly 50 cm). The mixer was operated as before while pumping slurry from the same location. An additional 3.4 kg of the 5.7 kg (i.e., 60% of the solids) remaining after the first pump-down was transferred. Overall, 95.6% of the solids were retrieved from both pump-down tests. The fact that the solids recovery rate was lower for the second pump-down test implies that the solids concentration during the first pump-down likely would have dropped even if the mixer speed had been maintained at 860 rpm. It is also worth noting that the solids recovery from the second pump-down tests would likely have been improved somewhat if the initial liquid level had been 70 cm rather than 50 cm.

4.2 Test 2: Limestone Suspension in 1.8-m Tank

The 3-kW Flygt mixer was positioned in the 1.8-m tank so the propeller axis was 25 cm east of the north-south tank diameter. This position was also used for Tests 1A, 1B, and 1C. A total of 75.8 kg of crushed limestone (MarbleWhite 30 from Synergistic Performance Corporation, Seattle, Washington) was placed in the 1.8-m tank and water was added until the liquid level reached 70.6 ± 1 cm. This amount of limestone resulted in the same volume fraction of particles (1.53 vol%) as that used for the zeolite tests in Phase A and Phase B, Test 1. The weight percent solids for the limestone at this concentration is equal to 4.0 wt%.

Mixer speed was increased as in Test 1 while observing the motion of particles on the tank floor. To facilitate the observations, roughly 1 kg of 20x50-mesh IE95 zeolite was added to the slurry while mixing. When the mixer reached full speed (860 rpm), a small amount of limestone remained largely motionless on the tank floor, but the solids in an area corresponding to approximately 95% of the tank bottom were observed to be in motion.

Further tests were planned at higher limestone concentrations and liquid levels (Tests 2B, 2C, and 2D in the test plan). However, because the mixer was not able to fully maintain all of the solids in suspension in Test 2A, more challenging tests were not performed because the outcome was known (i.e., full mixer speed would not be capable of suspending all the solids). Instead, the mixer was repositioned in an effort to improve the mixer effectiveness. The mixer was first moved to the 7.6-cm offset position that was used in Test 1D. Then the mixer was moved back to the 25-cm offset position, but reoriented so its discharge was approximately 15 degrees to the east from the north-south direction. Neither of these two additional mixer positions significantly improved the limestone suspension at full mixer speed. The location of

the settled pile moved somewhat when the mixer position was changed, but the apparent size of the pile (as indicated by its area on the tank floor) did not noticeably change.

Water was added to the tank to reach the 103.8 ± 1 -cm liquid level (Test 2B) and the test was repeated at all three mixer positions at 860 rpm mixer speed. The results were essentially the same as in Test 2A.

With the mixer initially operating at 860 rpm, the slurry was pumped out of the tank from the same location used in Test 1. The average slurry retrieval rate was 50.6 lpm. Samples were taken from the retrieval pump discharge and used to determine the solids concentration at selected points during the pump-down. The slurry volume and solids concentration data from the Test 2 pump-down are provided in Figure 4.2. Integrating the data in Figure 4.2 leads to an estimate of 58 kg of limestone retrieved. The actual quantity retrieved was 68.5 kg or 89% of the original solids. The low estimate based on integrating the Figure 4.2 data would likely be closer to the actual retrieved quantity if more solids concentration measurements were made during the pump-down.

Figure 4.2. Test 2 Pump-Down Data

4.3 Test 3: Water Velocity Measurements in 1.8-m Tank

Fluid velocity measurements were made in the 1.8-m tank at mixer speeds of 430, 720, and 860 rpm. Two liquid levels (70.6 cm and 103.8 cm) and two mixer orientations (Test 1A position and circumferential as was used in Test 2A and 2B) were tested. The output from the velocity meter was sampled at 10 Hz for approximately 20 seconds at each measurement point. The Test 3 velocity data are provided in this section. Plots of all Test 3 velocity data are included in Appendix B.

4.3.1 Estimate of Critical Velocity for Zeolite Suspension

Because the velocities required to suspend 20x50-mesh zeolite are of interest, the velocity data for the baseline mixer orientation—70.6-cm liquid level and 720 rpm—are provided in Table 4.1 below. A mixer speed of 720 rpm was necessary to reach an all-solids-in-motion mixing criterion for Test 1A. The root-mean-square (rms) fluctuating velocity for each set of velocity measurements is also given in Table 4.1 to provide an indication of the velocity fluctuation at each position. Note that there is no position D.

Table 4.1. 1.8-m Tank Velocity Data, 720 rpm, 70.6-cm Level

Position	Average Velocity (cm/s)	rms Fluctuating Velocity (cm/s)
A	146	25
B	112	92
B9	204	134
C	80	20
E	174	47
E9	330	34
F	100	26
G	61	26
H	40	20
I	30	15
J	44	19

Most of the fluid velocity measurements were made with the probe positioned 5 cm above the tank floor (the probe cannot be positioned closer). Measurements were made at nine locations in the tank, shown in Figure 4.3. The coordinates for each point are given in polar coordinates where “R” is the tank radius (0.908 m) and the angles are measured starting with the 3 o’clock position and proceeding counterclockwise. The 3 o’clock position was the west side of the tank so the mixer was oriented to discharge to the south. In addition to the nine measurements near the tank floor, two additional measurements were made at points B and E with the probe positioned in line with the propeller axis (23 cm above the tank floor). These points are labeled B9 and E9 in Table 4.1.

Of greatest interest are the velocities at positions H, I, and J. As the mixer speed was increased during Test 1A, progressively more and more of the solids were observed to be in motion on the tank floor. In the 650 to 720 rpm mixer speed range, some solids remained motionless on the tank floor in the region near points H, I, and J. Once the speed exceeded about 720 rpm, those solids began moving. Thus, the fluid velocities observed at positions H, I, and J at a mixer speed of 720 rpm are indicative of the velocities required to maintain 20x50-mesh zeolite in suspension. The measured average velocities range from about 30 to 45 cm/s in this region. These velocities are consistent with the 20 to 50 cm/s velocities required in the Phase A testing (Powell et al. 1999). Based on these tests, the critical average velocity for the suspension of zeolite is clearly between about 20 and 50 cm/s.

4.3.2 Effect of Mixer Speed on Average and Peak Velocities

For each velocity measurement, an average 1-second peak velocity was calculated. Each measurement was discretized into 1-second intervals. The maximum velocity within each interval was determined and then all the maximum velocities for the 20-second scan were averaged. The average 1-second peak velocities (v_{peak}) and the time-averaged velocities (v_{avg}) for location H with a 70.6-cm liquid level are plotted in Figure 4.4. Similar plots for all of the velocity measurements are provided in Appendix B.

A 1-second basis for the peak velocity analysis was selected because the criterion used in the solids suspension tests was that no particles remained motionless on the tank floor for more than about 1 second.

The error bars on the time-averaged velocities in Figure 4.4 represent the magnitude of the rms fluctuating velocity. The 95% confidence intervals for the time-averaged velocities are smaller than the rms fluctuating velocities. To estimate the 95% confidence intervals for the time-averaged velocities, multiply the rms fluctuating velocity by 0.14. The error bars on the average 1-second peak velocities are the estimated 95% confidence intervals.

Figure 4.3. Velocity Measurement Locations in the 1.8-m Tank (Note that the mixer discharge points due south toward the top of the figure.)

Figure 4.4. Location H in 1.8-m Tank at 70.6-cm Liquid Level

In general, the magnitude of the average 1-second peak velocity is approximately equal to the time-averaged velocity plus the rms velocity (shown in Figure 4.4). The upper error bars for the time-averaged velocities are close to the average 1-second peak velocities. This trend is seen in other plots of the velocity data (see Appendix B).

4.3.3 Comparison with Phase A Water Velocity Tests

As mixer speed is increased to between 430 and 860 rpm, the measured velocities increase in some regions but decrease in others. Figures 4.5 and 4.6 provide two such examples. In the Phase A tests in the 0.45-m tank, fluid velocities increased monotonically with increasing mixer speed (Powell et al. 1999). This qualitative difference in the effect of mixer speed implies that the flow patterns in the Phase B 1.8-m tank are more complicated than those in the Phase A 0.45-m tank. The difference in flow patterns demonstrates that the fluid streamlines in the 1.8-m tank are not simply a geometrically scaled version of those in the 0.45-m tank.

Figure 4.5. Location E in 1.8-m Tank at 70.6-cm Liquid Level

Figure 4.6. Location F in 1.8-m Tank at 70.6-cm Liquid Level

The ratio between the maximum velocities in the tank and the minimum velocities near the tank floor was higher in the 1.8-m tank than in the 0.45-m tank. The maximum velocities in both cases were found just downstream of the mixer discharge as expected. The minimum velocities near the tank floor are, in both cases, the critical velocity for zeolite suspension if the comparison is made with the mixer speeds set to those found to just meet the all-particles-in-motion-on-the-tank-floor mixing criterion. For Test 1A in the 1.8-m tank, the mixer discharge velocity was 330 cm/s, as given in Table 4.1 for position E9. From Powell et al. (1999), the corresponding propeller discharge velocity from the tests in the 0.45-m tank was about 110 cm/s. In both cases the minimum velocity near the tank floor was the critical velocity for zeolite suspension, so the ratio of maximum-to-minimum velocities in the 1.8-m tank is roughly three times greater than in the 0.45-m tank.

An increase in the range between the minimum and maximum velocities upon scale-up is a well-known phenomenon (Bisio and Kabel 1985). The range of velocities and the streamline paths will be the same at two scales only if the tanks and mixers are geometrically scaled, the mixers are operated at the appropriately scaled speeds, and the physical properties of the tank contents are scaled so that all relevant dimensionless groups are matched. The Phase A and B tests did not meet these criterion, so differences in the ranges of velocities and the flow patterns are to be expected.

The velocities at locations H, I, and J all show a decrease in the fluid velocities as the mixer speed is increased from 430 rpm. As mentioned earlier, these three locations are of particular interest because the last pile of zeolite to be suspended in Test 1 was in this region. It is speculated that a recirculation zone becomes established in this region at mixer speeds in excess of 430 rpm. The velocities near the center of a recirculation zone are relatively low and solids-settling can occur. The fact that the velocities at 430 rpm in locations H, I, and J were *higher* than the critical velocity for zeolite suspension (estimated at 20 to 50 cm/s) implies that these regions did not have solids accumulations at the 430 rpm mixer speed. Only when the mixer speed was increased did solids begin accumulating near locations H, I, and J.

These velocity data are consistent with observations made through the clear-bottom tank floor. At low mixer speeds (i.e., near 430 rpm), the slurry exhibited a fairly uniform clockwise recirculation motion. The solids were settled in a large pile in the center of the tank, but few regions with solids accumulation existed near the tank wall. Increasing the mixer speed eventually cleared the solids from the center of the tank, but they then settled near locations H, I, and J. Only when the mixer speed was increased to about 720 rpm (in the case of Test 1A) did the solids near H, I, and J meet the all-particles-in-motion criterion.

4.3.4 Effect of Liquid Level on Measured Velocities

Figures 4.7 and 4.8 show the effect of liquid level (Z) on the time-averaged and 1-second peak velocities. As before, the error bars for the average velocities are the rms fluctuating velocities and the error bars on the average 1-second peak values are 95% confidence intervals.

No consistent trends are apparent in the data. In some locations, the increased liquid level results in higher velocities, but lower velocities result in other locations. Generally, for a given mixer speed, fluid velocities are expected to increase as the liquid level decreases because the mixing energy per unit volume of fluid is increasing. However, changes in the flow patterns resulting from changes in the liquid level can put the velocities at specific locations in contradiction with this general principle.

Figure 4.7. Effect of Z on v_{avg} in 1.8-m Tank at 720 rpm

Figure 4.8. Effect of Z on v_{peak} in 1.8-m Tank at 720 rpm

4.4 Test 4: 405-Pa Shear Strength Sludge Mobilization in 1.8-m Tank

With the mixer in the same position as in Test 1A, an 8-cm-thick layer of kaolin clay sludge simulant was placed in the tank and covered with water until the liquid level reached 70.6 ± 1 cm. The sludge was nominally 57 wt% kaolin clay. The actual weight percent solids was measured at 56.1 ± 0.5 wt%. A total of 318 kg of this sludge was initially present in the tank. The vane shear strength was measured and found to be 405 ± 83 Pa, which was somewhat lower than the 500-Pa target strength.

The mixer speed was gradually increased while the density was monitored. The density and mixer speed versus time data are given in Figure 4.9. The mixer was allowed to run for an extended period at 430 rpm to ensure that the mobilization of sludge had effectively stopped. Before the slurry was pumped away at the end of the test, the mixer was run at 860 rpm to mobilize the sludge remaining on the tank floor; thus, no solids were left in the tank after the test.

Figure 4.10 gives the fraction of sludge mobilized (as computed from the slurry density) and the average wall stress (as computed from the mixer speed) versus time. From this plot, it is estimated that a mixer speed of about 500 ± 40 rpm was needed to mobilize 80% of the sludge. The average wall stress at this mixer speed is approximately 42 ± 7 Pa. The ratio between the wall stress required to achieve 80% sludge mobilization and the shear strength is 0.10 ± 0.03 . Stated another way, the wall stress required to reach 80% sludge mobilization is $10 \pm 3\%$ of the sludge shear strength. This result is similar to the roughly 5% relationship observed in the 0.45-m tank during Phase A testing of sludge with strengths greater than 100 Pa. This same sludge simulant, however, was not tested in Phase A. A test in the 0.45-m tank using this simulant would determine how much of the difference in ratio is due to scale-up effects alone.

4.5 Test 5: 2070-Pa Shear Strength Sludge Mobilization in 1.8-m Tank

Test 5 was conducted similarly to Test 4 except a stronger sludge simulant was used. The target shear strength for this test was 1500 Pa, but strength measurements conducted on samples taken from the tank indicated a higher strength of 2070 ± 600 Pa was attained. It is unclear why the strength was higher than the target, but it is speculated that a different brand of bentonite clay was used to prepare the sludge for these tests than was used to develop the correlation between sludge strength and composition (Powell et al. 1997).

The sludge simulant layer was 8-cm thick and composed of 204 kg of EPK Pulverized kaolin clay (Feldspar Corporation), 4.2 kg of CS-100 bentonite clay (American Colloid Company), and 126 kg of water. The bentonite clay was added to the mix to increase the fraction of sludge strength due to cohesion rather than friction. Kaolin clay sludge simulants in the >500 Pa shear strength range obtain a significant fraction of their strength from interparticle friction rather than cohesion alone, so bentonite is added to ensure the simulant strength is principally due to cohesion (Powell et al. 1995a).

Figure 4.9. Slurry Density Data for Test 4

Figure 4.10. Fraction of Sludge Mobilized and Average Wall Shear Stress for Test 4

Figure 4.11 shows the density and mixer speed vs. time for Test 5. Disruptions in the continuity of the density data exist at elapsed test times of about 160 and 380 minutes. These disruptions were due to excessive air entrainment in the slurry. This problem was fixed by repositioning the intake to the density meter (Krohne Model 2000-300P) so it was near the tank floor. Periodically during the test, samples were withdrawn using a 100.0 mL pycnometer, which was subsequently weighed to determine the slurry density. The pycnometer is less vulnerable to entrained air bubbles because the larger bubbles tend to be released from the pycnometer before the volume is adjusted to 100.0 mL. Agreement between the pycnometer and the Krohne density meter is excellent during most of the test. Only at 860 rpm mixer speed was the Krohne reading systematically biased low due to severe air entrainment.^(a)

Figure 4.12 shows the fraction of sludge mobilized and the applied wall shear stress vs. time. Most of the test was run with the mixer at 720 rpm. Once the mixer speed was adjusted to 720 rpm, a period of relatively rapid mobilization occurred from about 140 to 270 min followed by a period of relatively slow mobilization (270 to 380 min). If the test been continued longer at 720 rpm, some additional mobilization would probably have occurred, but it is unknown whether this mobilization would have been significant.

At the time the mixer speed was increased from 720 rpm, about 80% of the sludge had been mobilized. The ratio between the wall stress required to reach this level and the shear strength of the sludge is $(85 \text{ Pa}) / (2070 \pm 600 \text{ Pa}) = 4.1 \pm 1.2\%$.

4.6 Test 6: Limestone Particle Suspension in 5.72-m Tank with Three Mixers

Three 3-kW Flygt mixers were placed inside the 5.72-m tank in the positions and orientations shown in Figure 4.13 (and Figure 4.2 in the test plan), where the north edge of the tank is shown at the top of the figure. The mixer placement for this test was recommended by ITT Flygt. Each mixer was secured to a 400-kg steel plate to keep the mixers in place. Two of the mixers inside the 5.72-m tank are shown in Figure 4.14.

A total of 1043 kg of MarbleWhite 30 crushed limestone (Synergistic Performance Corp., Seattle, Washington) was added to the 5.72-m tank and then water was added so that the total depth in the tank was $1.00 \pm 0.02 \text{ m}$. The limestone particle size distribution, shown in Figure 4.15, was determined by a sieve analysis. The average particle size by volume (50 wt%

^(a)The Krohne density meter was accurately reporting the density of the air-laden slurry, but the density of the slurry *without* entrained air is needed to calculate the fraction of solids in suspension. The pycnometer data more accurately reflect the weight percent solids because large air bubbles are allowed to escape before the pycnometer measurement is made.

Figure 4.11. Slurry Density and Mixer Speed Data for Test 5

Figure 4.12. Fraction Sludge Mobilized and Wall Stress for Test 5

Figure 4.13. Mixer Locations in 5.72-m Tank (north is at top of figure)

Figure 4.14. Flygt Mixers (Nos. 2 and 3) in 5.72-m Tank

passing) of the limestone is approximately 0.2 mm. This size was selected because the model developed by Gladki (1997) predicts that 0.2-mm limestone requires roughly the same mixing intensity as 20x50-mesh zeolite to reach a just-suspended condition.

Once the limestone and water were in place, the mixers were activated and the mixer speed slowly increased to 860 rpm over a period of about 4 hours. The slurry density was monitored during this period by the Krohne density meter. Slurry was pumped through the Krohne at approximately 50 lpm. The slurry was withdrawn from the tank continuously from a point 30 cm above the tank floor, 50 cm radially inward from the tank wall, and 60 cm south of the east-most point of the tank. Slurry density and mixer speed data are shown in Figure 4.16. Three samples of the slurry exiting the Krohne meter were collected during the test at the times indicated in Figure 4.16. These samples were dried and the weight percent solids determined (0.990 wt%, 0.958 wt%, and 1.263 wt%). The grab sample density was then estimated based on the known densities of water and limestone. These estimated densities are shown in Figure 4.16, which are systematically lower than the Krohne densities. This difference, though small, is probably not just due to random error. The Krohne densities compared very well with samples of clay slurry taken in Test 5.

With all three mixers running at full speed (860 rpm), the slurry density was measured at about 1.0105 kg/L. If all the limestone was uniformly distributed in the water, the average slurry density would be 1.0246 kg/L. Thus, based on the concentration of slurry withdrawn from 30 cm above the tank floor, about 45% of the solids were suspended.

Slurry density profile measurements were made at mixer speeds of 430, 570, 720, and 860 rpm. The density profile data are provided in Figure 4.17. The total amount of solids in suspension can be estimated by integrating the curves in Figure 4.17. At the maximum mixer speed of 860 rpm, the density profile shown in Figure 4.17 is integrated to give an average solids concentration of 2.0 wt%. If all the solids were in suspension, the average concentration would be 4.0 wt%, so the curve in Figure 4.17 indicates that roughly half of the limestone was in suspension at 860 rpm. Note, however, that the Krohne density measurements may have been biased high according to the grab sample measurements. The solids concentration of the sample collected during operation at 720 rpm was about 85% of that indicated by the Krohne density meter. If this correction is applied to the Krohne data, the estimated fraction in suspension becomes 42.5%. It is not clear whether this correction is appropriate because the reason for the difference between the Krohne and grab sample measurements is not understood.

After the density profile measurements were complete, a 5-cm inside diameter pipe was positioned 30 cm from the tank wall along the same diameter as Mixer No. 2 but on the opposite side of the tank (see Figure 4.13). One end of the pipe was positioned 13 cm above the tank floor and the other end was connected to a double-diaphragm slurry pump. This location corresponds to the planned location for the retrieval pump in SRS Tank 19.

Figure 4.15. Particle Size Distribution for Limestone
(Results for three replicate analyses)

Figure 4.16. Slurry Density Data for Test 6

Figure 4.17. Slurry Density Profiles for Test 6

The location of the slurry sampling point for the Krohne density meter was moved so it was next to the retrieval pump pipe inlet.

Pumping of the slurry commenced and the Krohne density meter was used to monitor the slurry density. Flow rate through the retrieval pipe was monitored using a Micromotion mass flow meter. The slurry density and mixer speed versus time data are given in Figure 4.18. The solids concentration in the retrieved slurry (estimated from the Krohne data) and the cumulative mass of solids removed are plotted in Figure 4.19.

The slurry density values periodically decrease sharply and then return to the previous higher value. The cause of this fluctuation is unknown, but the regularity with which it occurs suggests an electrical cause rather than changes in the slurry. The cumulative mass of solids recovered is calculated based on the raw density data from the Krohne meter to be about 190 kg. Because the raw data are periodically decreasing for reasons not directly related to the solids concentration, the estimated amount of solids is probably biased low. To correct for this effect, the periodic drops in density were ignored and the resulting curve integrated, yielding an estimate of 386 kg of solids retrieved during the pump-down.

Figure 4.18. Test 6 Pump-Down Slurry Density and Mixer Speed

Figure 4.19. Test 6 Pump-Down Solids Retrieval

Once all the slurry had been pumped from the tank, the remaining solids were collected into steel drums to determine the remaining solids volume (430 liters of wet solids). Samples of the wet solids were taken to determine the average solids concentration in the steel drums (78.9 wt%). The total mass of solids retrieved from the tank was estimated at 374 kg, which is very close to that estimated using the modified slurry density data. Because 1043 kg of solids were originally placed in the tank, 36% of the total solids was retrieved.

Most of the solids remaining in the tank were found in a mound in the center of the tank. Because the Flygt mixers as positioned in this test induce a clockwise swirling flow in the tank, the fluid velocities are lowest near the tank center. Thus, it is expected that solids accumulations, if any, are most likely to be present at or near the tank center.

Two more pump-down tests were performed using the limestone in the 5.72-m tank. Mixer No. 2, which previously pointed about 15 degrees off the tank diameter (see Figure 4.13), was repositioned for the second pump-down test so it discharged directly across the tank diameter. The solids remaining in the tank after the first pump-down (roughly 669 kg) were spread evenly throughout the tank, and then water was added to the tank so the liquid level was once again 1.0 m. All three mixers were activated and adjusted to 860 rpm. After 30 minutes of operation, slurry retrieval commenced in the same manner as described above for the first pump-down test.

The plots for the second pump-down test are given in Figures 4.20 and 4.21. The cumulative mass of solids retrieved according to the integrated Krohne density meter data was about 80 kg. The actual mass of solids retrieved was determined to be 87 kg by measuring the volume of the solids remaining in the tank once all the slurry had been pumped away. Again, the agreement is reasonably good. As a fraction of the 669 kg of limestone in the tank at the start of the second pump-down test, the 87 kg is about 13%.

The comparatively poor solids retrieval from the second pump-down test is mainly because the first pump-down removed much of the fine particles, thus the residual solids had a larger average particle size. The before and after particle size distributions are shown in Figure 4.22.

A third pump-down test was performed in which the mixer locations were the same as in the second pump-down test, but the retrieval pump suction was positioned in the center of the tank 13 cm above the tank floor. The residual solids in each of the first two pump-down tests were primarily located in the center of the tank. It was hypothesized that the fraction of retrieved solids might improve by pumping from the tank center.

The 582 kg (dry basis) of solids remaining in the tank from the second pump-down test were used for the third pump-down. The solids were distributed evenly on the tank floor, and then water was added to reach a liquid level of 1.0 ± 0.02 m. Mixer No. 2 was started at -3.5 min and rapidly adjusted to 860 rpm. At -2.0 min, Mixers 1 and 3 were started and adjusted to

Figure 4.20. Krohne Density and Mixer Speed for Second Test 6 Pump-Down

Figure 4.21. Solids Retrieval for Second Test 6 Pump-Down

Figure 4.22. Limestone Particle Sizes Before and After Pump-Down

860 rpm. At 0.0 min, the retrieval pump was activated. This mixer startup sequence was used to avoid rapidly forming a pile around the retrieval pipe suction because this pile might plug the suction.

The density versus time data for this pump-down test are provided in Figure 4.23. At some point during the test, the hose feeding the pump for the Krohne density meter is suspected to have become plugged with solids, resulting in invalid density readings. Unfortunately, it is not known when this might have happened. At the end of the test it was discovered that the Krohne pump was no longer functioning properly so it was turned off. Based on the shape of the curve in Figure 4.23 and on the known quantity of solids recovered during this test (66 kg = 11.4% of the initial 582 kg), the Krohne readings were likely biased high relatively early in the pump-down test. Integrating the Krohne density readings and the retrieval flow rate data predicts that 66 kg of solids should have been retrieved in only the first 6 minutes of the pump-down.

Once all the slurry had been removed from the tank, the remaining solids were observed to have accumulated near the center of the tank, but the center of the pile was about 60 cm to the southwest of center. The retrieval pump intake was located near the edge of the pile and had formed a crater in the solids that reached the tank floor. The remaining solids are shown in Figure 4.24. All the solids were collected and placed into drums to determine the volume remaining in the tank. It was estimated that 516 kg of solids remained in the tank following the pump-down. Thus, as stated above, 66 kg of solids (11.4% of the initial 582 kg) was retrieved/transferred.

Figure 4.23. Density Data from Third Test 6 Pump-Down (These data are suspect. See page 4.23 for explanation)

Figure 4.24. Limestone Solids Remaining After Third Pump-Down

4.7 Test 7: Water Velocity Measurements in 5.72-m Tank

Measurements of the fluid velocities near the tank floor were made in the 5.7-m tank in a manner similar to that used in Test 3 (1.8-m tank). Values for time-averaged velocities and 1-second peak velocities were calculated for each set of measurements using the procedure described in Section 4.3. Plots of all the Test 7 velocity data are given in Appendix C.

A considerable variation in fluid velocities exists at some locations. Consequently, the average velocity measurements do not always show the expected trends. Taking measurements for longer than 15 seconds at each point would improve this variation. Future fluid velocity tests should probably collect data for at least 50 seconds at each point.

4.7.1 Effect of Position and Mixer Speed

With the three mixers positioned as shown in Figure 4.13, water was added to the tank to a depth of 1.0 ± 0.02 m. A Marsch-McBirney Model 511 electromagnetic velocity probe was used to make fluid velocity measurements at selected positions within the tank. The probe was positioned 5 cm above the tank floor. With the mixers running, the probe was moved to radial positions of 0.12R, 0.3R, 0.5R, 0.7R, and 0.84R, where R is the tank radius, equaling 2.85 m. Velocities were measured along three radial lines. The first radial line was due south from the tank center to the tank wall. This line was labeled 0 degrees. Another line was in the southeast direction (45 degrees) and the third line was due east (90 degrees). Velocities were measured at all five radial positions for each of these three angles. All velocity measurements were made with the center of the probe 5 cm above the tank floor.

Velocity measurements were made at the positions described above for water levels of 1.0, 1.5, and 2.0 m. Measurements were made with all three mixers operating at 430 rpm and 860 rpm. Measurements were also made with Mixer 2 at 860 rpm (Mixers 1 and 3 off) and with Mixers 1 and 3 at 860 rpm (Mixer 2 off). The fluid velocity data for the cases where all three mixers were operating at 860 rpm are provided in Figures 4.25 through 4.30. All measurements were made with the center of the probe 5 cm above the tank floor.

The measurements show that, as expected, the velocities are lowest near the center of the tank. With all three mixers running, the average velocities near the center (0.12R) are about 15 cm/s for the 430 rpm mixer speed and 1.5- and 2.0-m liquid levels. At the 1.0-m liquid level, the velocities at 430 rpm are in the 30 to 40 cm/s range. At 860 rpm, the average velocities at the 1.0-m level near the tank center are in the 60- to 80-cm/s range, and the velocities for 1.5- and 2.0-m levels are lower at about 55 and 35 cm/s, respectively.

Figure 4.25. Effect of Z on v_{avg} in 5.7-m Tank for 0-Degree Angle

Figure 4.26. Effect of Z on v_{peak} in 5.7-m Tank for 0-Degree Angle

Figure 4.27. Effect of Z on v_{avg} in 5.7-m Tank for 45-Degree Angle

Figure 4.28. Effect of Z on v_{peak} in 5.7-m Tank for 45-Degree Angle

Figure 4.29. Effect of Z on v_{avg} in 5.7-m Tank for 90-Degree Angle

Figure 4.30. Effect of Z on v_{peak} in 5.7-m Tank for 90-Degree Angle

4.7.2 Estimate of Critical Velocity for Zeolite Suspension

Based on the Test 7 velocity measurements and the size and location of the limestone (Test 6) and zeolite (Test 9) remaining after the solids suspension tests, solids settling will likely occur wherever the average velocity (as measured 5 cm above the tank floor by the EM probe) is less than about 80 cm/s. This value is somewhat higher than the 20 to 50 cm/s observed in the Phase A tests using zeolite and in the Phase B tests in the 1.8-m tank (see Section 4.3). The Phase A measurements were made 1.0 cm above the tank floor rather than 5 cm above the floor, so the Phase A values would be expected to be somewhat lower; however, this difference in measurement locations does not explain why the velocities in the 1.8-m tank were lower.

During Test 9, velocity measurements near the tank floor were made both in regions where solids accumulations could be felt and in regions where no solids were present. In all cases where solids were present, the velocities were less than about 50 cm/s. In all cases where no solids were present, the velocities were greater than about 50 cm/s. These measurements are consistent with the zeolite suspension velocity measurements made in the 0.45-m and 1.8-m tanks. Based on these measurements, the validity of the 80-cm/s average velocity measurement is questioned.

The Test 7 velocity measurements were made with only water present in the tank. Tests 6 and 9, however, involved a considerable quantity of solids. Perhaps the presence of solids in the center of the tank affected the flow patterns in the slurry thereby reducing the velocities near the tank center even further so that additional solids settling took place. This explanation seems unlikely, though, because it presumes that a pile of solids was able to form in the center of the tank even though the average velocities should have been high enough in that region to prevent any solids accumulations.

Possibly, the large-scale, clockwise swirling of fluid in the 5.7-m tank forced most of the solids to the center of the tank, thereby greatly increasing the local concentration of solids near the tank center. The higher measured velocities near the tank center, then, represent a lower bound for the velocities required to maintain zeolite in suspension when the concentration of zeolite is high. Further testing would be required to determine whether this hypothesis has merit.

Because of the consistency of the critical velocity measurements made in the 0.45-m and 1.8-m tanks along with the agreement with the velocity measurements made during Test 9, it is reasonable to discount the validity of the 80-cm/s average velocity value from Test 7. The critical velocity for zeolite suspension is therefore estimated to be in the 20- to 50-cm/s range.

4.7.3 Effect of Liquid Level on Fluid Velocities

Figures 4.31 and 4.32 show the effect of changes in liquid level on the time-averaged and average 1-second peak velocities at selected locations. Plots for all the locations measured are provided in Appendix C. Like velocity measurements from the 1.8-m tank, increasing liquid

Figure 4.31. Fluid Velocity vs. Liquid Level for 0.12 R, 90 Degrees

Figure 4.32. Fluid Velocity vs. Liquid Level for 0.84 R, 90 Degrees

level results in increased velocities in some locations and decreased velocities in others. This result implies qualitative changes in the flow patterns as the liquid level is changed.

4.8 Test 8: 363-Pa Sludge Mobilization in 5.72-m Tank

To evaluate the effects of scale-up on sludge mobilization using Flygt mixers, a kaolin-clay-based sludge simulant was placed in the 5.72-m tank. The shear strength and composition of this simulant were nominally the same as that used for Test 4 in the 1.8-m tank. The actual shear strength and solids concentration were slightly lower than that used in Test 4, but the mobilization behavior of kaolin clay in this strength range has been shown to not be a strong function of shear strength (Powell et al. 1995a).^(a) The shear strength for the sludge placed in the 5.72-m tank was measured at 363 ± 50 Pa and the solids concentration was 56.1 ± 0.8 wt%.

Eighty 50-lb bags of EPK Pulverized Kaolin Clay were emptied into the 5.72-m tank. Water was then added using a hose and nozzle at a known rate. The target quantity of water was 1370 kg, which should have resulted in a 57 wt% sludge simulant. However, the average kaolin bag probably contained somewhat less than 50 lb. Subsequent measurements have shown an average net kaolin weight of about 48.5 lb per bag. This error can account for the actual solids concentration being lower than the 57-wt% target. The simulant was manually mixed using shovels and walking repeatedly through the mixture. Manual mixing continued until the slurry strength appeared to be uniform.

Water was added slowly to avoid disturbing the sludge until the liquid level reached 2.0 ± 0.02 m. With the mixers in the same positions as in Test 6 for the first pump-down (the positions recommended by ITT Flygt and shown in Figure 4.13), all three mixers were activated and adjusted to 430 rpm. Little increase in the slurry density was observed over 30 minutes, so the mixer speed was increased to 570 rpm. Again, little increase in density was observed, so the mixer speed was adjusted to 720 rpm after an additional 25 minutes. Operation at this speed continued until 6 hours had elapsed since the test began. The slurry density was still increasing slowly, but only about 20% of the sludge had been mobilized. The mixer speed was then set to 860 rpm. The mixer speed was maintained for 24 hours and the slurry density stabilized (or was increasing very slowly) at about 1.009 kg/L. This slurry density corresponds to approximately 55% of the sludge mobilized. The density and mixer speed data for this test versus time are plotted in Figure 4.33. The fraction of sludge mobilized and the average wall stress data are provided in Figure 4.34.

^(a)Sludge mobilization tests using scale model mixer pumps show that the mobilization resistance of kaolin/water sludge simulant does not vary strongly with shear strength. Many other simulants, including mixtures of kaolin and bentonite, do exhibit a strong dependence.

Figure 4.33. Slurry Density and Mixer Speed for Test 8

Figure 4.34. Fraction of Sludge Mobilized in 5.7-m Tank

After 24 hours of mixing at 860 rpm, the retrieval pump was activated for one hour and the liquid level decreased from 2.0 to 1.0 m. Full-speed mixer operation continued under this new condition for an additional 15 hours. During this time, the density increased to nearly 1.022 kg/L and the fraction of sludge mobilized reached about 85% (based on the total amount of sludge simulant initially placed in the tank).

With the mixers continuing to operate, the retrieval pump was again activated and the remaining slurry pumped out. The remaining sludge was collected in a steel drum to determine its volume. A total of 210 L of unmobilized sludge was collected. The initial sludge volume was estimated at 2050 L, so 90% of the sludge was mobilized and removed from the tank. The discrepancy between the 85% value indicated by the density measurements and the 90% value is likely due to a combination of experimental uncertainty and the additional sludge mobilized as the liquid level decreased during pump-down.

The average wall shear stress required to result in 80% of the sludge mobilized is estimated to be about 53 Pa. Mixing at the 2.0-m liquid level (40 Pa average stress) resulted in about 55% of the sludge mobilized and mixing at the 1.0-m level (56 Pa average stress) resulted in 85% of the sludge mobilized. Interpolating linearly between these two points gives an estimate of 53 Pa being required to yield 80% of the sludge mobilized.

The shear strength of the sludge simulant used in this test was measured at 363 ± 50 Pa. Assuming an uncertainty in the average wall stress estimate of about ± 10 Pa, the ratio between applied average wall stress and sludge shear strength required to achieve 80% mobilized is $14.6 \pm 3.4\%$. This ratio is somewhat higher than the ratio observed in the 1.8-m tank.

Previous work (Powell et al. 1995a) has shown that the erosion resistance of kaolin clay is relatively independent of shear strength over a strength range of about 250 to 2000 Pa. Kaolin clay is an unusual sludge simulant in this respect. The mobilization resistance exhibited by kaolin clay during small-scale jet mixer tests is equivalent to that observed for a variety of other simulants with a shear strength of about 1000 Pa (e.g., kaolin/plaster, kaolin/bentonite, bentonite, kaolin/Ludox, and kaolin/salt). Thus, it is perhaps more appropriate to calculate the ratio of required stress to shear strength using a shear strength of 1000 Pa rather than 363 Pa because tank sludge is unlikely to exhibit the same unusual erosion resistance property as kaolin. Using this approach changes the ratio to about 5.3%, which is consistent with the ratio observed during Phase A using kaolin/plaster sludge simulants. It would be worthwhile to conduct a test in the 0.45-m Phase A tank using 363 Pa kaolin clay to determine if the ratio observed at small scale is closer to 5% or to 15%.

4.9 Test 9: 20x50-Mesh Zeolite Suspension in 5.72-m Tank

Based on the Gladki (1997) mixing intensity prediction method, the three 3-kW mixers used in Test 6 should have been capable of achieving a just-suspended condition for the limestone slurry. Test 6, however, indicated that there was not sufficient mixing intensity.

Evidence for this conclusion includes the fact that stationary piles of limestone sediment were detected in the tank during mixing by probing the tank floor with a long pole. The vertical slurry concentration profiles (Figure 4.17) also indicate that a relatively small fraction of the limestone solids were in suspension. Finally, the pump-down tests were unable to retrieve a sizeable quantity of the solids. By contrast, the pump-down tests in the 1.8-m tank achieved roughly 90% solids retrieval when the pump-down was initiated with the mixing speed adjusted to achieve the all-particles-in-motion-on-the-tank-floor condition.

Because of the discrepancy between the predicted and actual mixing effectiveness for the limestone, there was some speculation that the limestone might settle to form a sediment bed that is significantly more difficult to erode and mix than the 20x50-mesh zeolite solids, which the limestone was supposed to simulate. To address this issue, an additional 410 kg of IE95 20x50-mesh zeolite was procured. The zeolite remaining from Test 1 and this additional zeolite formed a 1.53 vol% zeolite slurry in the 5.72-m tank with a liquid depth of 1.0 m.

A total of 503 kg (dry basis) of IE95 zeolite was placed in the 5.72-m tank and spread to an even thickness. The mixers were oriented per the original guidance provided by ITT Flygt (see Figure 4.13). Water was added to the tank to make the total liquid depth 1.0 ± 0.02 m. The mixers were started at 430 rpm and the density was monitored using the Krohne density meter. The suction pipe for the pump feeding the Krohne was positioned 13 cm above the tank floor in the same location as was subsequently used for the retrieval pump suction (i.e., 30 cm from tank wall along tank diameter intersecting Mixer 2).

Mixer speed was increased as shown in Figure 4.35. After at least 30 minutes of operation at each mixer speed, a vertical density profile was obtained by vertically moving the suction pipe for the Krohne meter. The density profile data are given in Figure 4.36. The concentration profile data indicate that little of the zeolite was in suspension very far (if at all) above the tank floor. Some of the density measurements made 7.6 cm above the tank floor (notably the measurements for 570 and 720 rpm) were relatively high on average but varied considerably with time. It is suspected that the pump inlet was very near the top of a pile of settled zeolite and periodically the top of the pile reached the pump inlet.

Grab samples were collected from the discharge of the Krohne density meter at selected times during the test. In general, the densities measured for these samples were higher than those reported by the Krohne density meter by about 0.002 kg/L. Air entrainment in the slurry is thought to have resulted in the Krohne readings being biased low compared with the grab samples.^(a)

^(a)The Krohne density meter was accurately reporting the density of the air-laden slurry, but the density of the slurry *without* entrained air is needed to calculate the fraction of solids in suspension. The pycnometer data more accurately reflect the weight percent solids because large air bubbles are allowed to escape before the pycnometer measurement is made.

Figure 4.35. Slurry Density and Mixer Speed for Test 9

Figure 4.36. Vertical Density Profiles for Test 9

At time = 390 minutes, the retrieval pump was activated and the slurry pumped from the tank with the mixers continuing to run until the mixer motors were exposed (this same procedure was followed in all other tests). The zeolite remaining in the tank was located primarily in the center of the tank as a large mound (shown in Figure 4.37), which is similar to the location of the solids remaining after the limestone pump-down tests. The solids were collected and about 430 kg (dry basis) of the original 503 kg of zeolite remained in the tank. Thus, about 15% of the zeolite was removed from the tank by the pump-down test. This 73 kg removed is consistent with the 77 kg estimated based on an integration of the grab sample weight percent solids data.

A second pump-down test was performed using the residual zeolite and an alternative mixer arrangement. Mixers 1 and 3 were angled outward (toward the tank wall) so their propeller axes each made a 45-degree angle with the tank diameter between the mixers. Mixer 2 was removed from its mounting plate and placed in a Flygt PortaCleanse mixer stand in the center of the tank. This mixer stand holds the mixer vertically with the propeller pointing down. The mixer was mounted so the propeller blade was 20 cm above the tank floor. The zeolite remaining after the first pump-down test was spread throughout the tank and water added until the 1.0-m liquid level was reached.

All three mixers were activated and adjusted to 860 rpm. Roughly 8 minutes later, the PortaCleanse-mounted mixer tipped sideways until its restraint cable tightened. The mixers were shut off and a more rigid support for the PortaCleanse mixer was attached. Mixing then resumed at 860 rpm and pump-down commenced 8 minutes after the mixers were restarted.

The slurry density and solids concentration data for the zeolite pump-down test using the Porta-Cleanse mixer are given in Figure 4.38. When the mixers were first started both times, a brief period of relatively high solids concentration occurred. The mixers were restarted at time = 45 minutes, and the pump-down was started at time = 53 minutes.

After all the slurry was pumped from the tank, the remaining solids, which were distributed roughly in the shape of a donut surrounding the PortaCleanse mixer, were collected to determine the volume. Of the estimated 473 kg (dry basis) of zeolite in the tank at the beginning of the second pump-down, roughly 9.6% (45 kg) were retrieved from the tank.

Figure 4.37. Zeolite Remaining in 5.7-m Tank After First Pump-Down

Figure 4.38. Slurry Density and Solids Concentration for Second Test 9 Pump-Down

5.0 Key Findings from Data Analyses

Based on Phase A and B Flygt mixer test results, some rough predictions can be made for the mixing requirements at full-scale for both particle suspension and sludge mobilization. The key findings and predictions are presented in this section. Section 5.1 discusses key findings from the experimental data and their implications for particle suspension scaling relationships. Section 5.2 addresses sludge mobilization. Section 5.3 provides predictions for Tank 19 mixing requirements based on the Phase A and B experimental data. Section 5.4 discusses some of the major uncertainties and difficulties associated with using the experimental data to make predictions for full-scale mixing requirements.

5.1 Particle Suspension

A comparison of the Phase A and B Flygt mixer test data implies that the suspension of rapidly settling particles, such as 20x50-mesh zeolite, follows a constant-P/V scaling relationship. This relationship appears to hold over the range of tank sizes used in this testing, but it is not known whether this same relationship applies to tanks as large as Tank 19. The scaling implications of the Phase A and B particle suspension data are discussed below.

5.1.1 Constant- τ_0 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. One of the principal goals of the Phase B testing was to evaluate the applicability of Gladki's constant-wall-shear-stress mixer scaling method to mixer sizing for rapidly settling solids such as 20x50-mesh zeolite. 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 total 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 speed according to the equation:

$$F = N_f \rho N^2 D^4 = \frac{\pi}{32} \rho k^2 N^2 D^4 \quad (5.1)$$

where N_f = empirical thrust affinity law proportionality constant, dimensionless
 ρ = slurry density, kg/m³
 N = propeller rotation speed, rotations per second
 D = propeller diameter, m
 k = empirical constant related to N_f — value of 1.49 for Model 4640 mixers.

According to the constant- τ_0 method, the value of τ_0 is independent of scale if the same solids and liquids 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 Phase A 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) This prediction is consistent with the observations made during the Phase A tests. The initial wetted area of Tank 19 (25.9-m diameter, 2.1-m waste depth) is approximately 700 m², so the predicted total thrust required to maintain Tank 19 zeolite in suspension is (20 Pa)(700 m²) = 14,000 N. The 37-kW Flygt mixers planned for use in Tank 19 each generate about 6200 N of thrust, so three stationary Flygt mixers (14000/6200 = 2.3) are predicted for Tank 19 using this method and the Phase A test data.

The Phase A and B Flygt mixer tests were designed to determine whether the constant- τ_0 method of scaling can be applied to rapidly settling particles in tanks as large as Tank 19. The Gladki correlations were developed using tanks smaller than 0.5 m and the value of the dimensionless group in Gladki's correlation that quantifies the required mixing intensity 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. These extrapolations, however, were made for mixing particles with comparatively slow settling velocities.

Phase B Tests 1A, 1B, and 1C were designed to directly test the applicability of the constant- τ_0 scaling method for rapidly settling particles. The 1.8-m tank containing a Flygt Model 4640 mixer is very nearly geometrically scaled with respect to the Phase A tests in the 0.45-m tank. The scale factor based on tank diameter is 4.0. The scale factor based on mixer propeller diameter is 4.7. Both propellers have a blade angle of about 11 degrees. The Phase B mixer had a shroud and vortex suppressor installed while the Phase A mixer had neither.

Based on the Phase A tests using 20x50-mesh zeolite, an average wall shear stress of about 16 ± 3 Pa was required to achieve an all-solids-in-motion-on-the-tank-floor condition in the 0.45-m tank for Tests 1A, 1B, and 1C. If constant- τ_0 scaling applies to 20x50 zeolite, then this same τ_0 is required to achieve the same degree of solids suspension in the 1.8-m tank.

^(a)Test 1 conditions are tank diameter = 0.45 m, particle size = 0.7 mm, particle density = 1660 kg/m³, propeller diameter = 7.8 cm, volume fraction solids = 0.015, liquid level = 18 cm and 25 cm. Test 2 conditions are the same except that particle size = 0.25 mm.

The Model 4640 mixer used for Phase B tests achieves a thrust of about 810 N at 860 rpm. The wetted area of the 1.8-m tank is 6.16 m² at the 70.6-cm liquid level and 8.51 m² at the 103.8-cm liquid level. In Phase B tests 1A and 1B, a mixer speed of 720 ± 70 rpm was required to achieve the “all solids in motion” criterion.^(a) Test 1C required 860 ± 70 rpm. The τ_o values for these mixer speeds are given in Table 5.1.

Table 5.1. Comparison of Required τ_o Values for Zeolite in 0.45-m and 1.82-m Tanks

Test No.	0.45-m Tank Required τ_o (Pa)	1.82-m Tank Mixer Speed (rpm)	1.82-m Tank Required τ_o (Pa)	Ratio of 1.8-m to 0.45-m τ_o
1A	16.5 ± 3	720 ± 70	86 ± 17	5.2 ± 1.4
1B	16.3 ± 1	720 ± 70	62 ± 12	3.8 ± 0.8
1C	16.1 ± 1.5	860 ± 70	89 ± 14	5.5 ± 1.0

The average wall stresses required in the 1.8-m tank are significantly higher than those predicted by the 0.45-m tank tests and the assumption of constant- τ_o scaling. As the right-most column in Table 5.1 shows, the stresses required in the 1.8-m tank are actually about 4.8 ± 0.6 times greater (on average) than are predicted by constant- τ_o scaling. It appears that the required wall stress is increasing roughly in direct proportion to the increase in scale. In other words, as the tank size increases by a factor of N , the required average wall shear stress also increases by a factor of N . This observation should only be applied to rapidly settling particles such as 20x50-mesh zeolite.^(b)

The data from the 5.72-m tank cannot directly be used to verify this proportionality between increasing tank size and required τ_o because the three Model 4640 Flygt mixers were not able to achieve the all-particles-in-motion-on-the-tank-floor condition in Test 9. Indirectly, however, this fact supports the conclusion that constant- τ_o scaling does not apply to zeolite. With all three mixers operating at full-speed (860 rpm) in the 5.72-m tank, the applied τ_o was about 55 Pa. If constant- τ_o scaling applied, the 16 ± 3 Pa τ_o measured in the 0.45-m Phase A tank should have been sufficient to mix the solids.

^(a)An uncertainty of ±70 rpm has been assigned to the required mixer speed estimates based on the fact that step changes in mixer speed of about 70 rpm were used for the tests. Smaller increments in mixer speed did not produce changes in the solids suspension that were apparent. The ±70 rpm estimated uncertainty reflects the subjective nature of the solids suspension assessment.

^(b)The free settling velocity of 20x50-mesh zeolite particles averages about 5 cm/s.

5.1.2 Constant-P/V Scaling

An alternative mixer scaling method is apparently required for predicting the mixing requirements of zeolite slurries. Constant- τ_0 scaling implies that the required total mixer thrust increases linearly with the wetted surface area of the tank. For geometrically scaled tanks and mixers, the constant- τ_0 method implies that the mixer power-per-unit-wetted-surface-area is constant.^(a) The ratio between the τ_0 required in the 1.8-m tank to that required in the 0.45-m tank was approximately equal to the scale factor between the tanks (i.e., an average ratio of 4.8 ± 0.6 compared with a scale factor of 4.0). This fact implies that the required mixing power is actually increasing in direct proportion to the wetted surface area *multiplied by* the scale factor. In other words, the required power is increasing in direct proportion to the fluid volume, known as constant-P/V scaling.

Constant-P/V Scaling in the Mixing Literature

Constant-P/V scaling is an often used heuristic for mixing system scale-up. Most often, constant-P/V scaling results in a significant overprediction of the mixing power required upon scale-up. Uhl and Gray (1986) report constant-P/V scaling results in significant oversizing of mixer systems in more than 80% of mixer scale-up applications. Consequently, constant-P/V scaling is often dismissed in the mixing literature as being too conservative. However, circumstances exist in which constant-P/V scaling does *not* overpredict the mixing power required upon scale-up. The suspension of rapidly settling particles is apparently one such circumstance where constant-P/V scaling is reported to apply in the mixing literature.

Most of the relevant solids suspension data available in the open literature apply to mixing systems wherein the diameter of the mixer propeller (or impeller) is on the order of 30% or more of the tank diameter. These systems may behave in a qualitatively different manner than systems where the mixing action is supplied by a submerged fluid jet with a diameter much smaller than the tank diameter (i.e., a Flygt mixer in a large-diameter tank). However, because no relevant data have been found describing the jet mixing of rapidly settling particles, the data for tanks with large impellers is discussed below.

Uhl and Gray (1986) and Oldshue (1983) report the data of Herringe (1979) showing that mixer power increases in direct proportion to volume (constant-P/V scaling) when the median particles size is between about 0.4 mm and 0.8 mm. The 50 wt% passing size for the 20x50-mesh zeolite used in Phases A and B testing is about 0.7 mm (Powell et al. 1999). Herringe's

^(a)This statement is only approximately true because as mixer size increases, changes in the mixer thrust and power affinity coefficients can occur that must be considered. If the coefficients are equal and the same number of geometrically scaled mixers are used in both tank sizes, then total mixer power will increase in direct proportion to the wetted tank area, assuming constant- τ_0 scaling applies.

data show that the required P/V decreases on scale-up for silica particles smaller than about 0.4 mm and *increases* on scale-up for particles larger than 0.8 mm.

Myers et al. (1994, Figure 10) provides a plot of the effect of particle-settling velocity on the scale-up exponent for mixer power. Consistent with the Herringe data, the required P/V is shown to decrease on scale-up for slowly settling particles and increase on scale-up for rapidly settling particles. The particle-settling velocity where constant-P/V scaling is expected to apply, according to Figure 10 in Myers et al. (1994), is about 6 cm/s, which is close to the 5 cm/s settling velocity of 0.7-mm zeolite particles.

Constant-P/V Analysis of Phase A and Phase B Data

The Phase A and Phase B data appear to show that constant-P/V scaling was observed for the zeolite suspension tests conducted in the 0.45-m and 1.8-m tanks. As discussed below, the P/V required to suspend the zeolite in the 0.45-m tank is consistent with the P/V required in the 1.8-m tank. Insufficient mixing energy was available in the 5.72-m tank to mix the solids so the required P/V could not be determined.

Accurately determining the hydraulic mixing power for the small mixer used in the Phase A tests is difficult (see Powell et al. 1999 for further discussion).^(a) Fahlgren and Tammelin (1992) measured the shaft power, thrust, and fluid velocities produced by a 7.8-cm diameter Flygt mixer identical to that used for the Phase A tests. In the Phase A tests, the mixer was positioned near the tank floor while Fahlgren and Tammelin tested the mixer about 27 cm above the tank floor and 27 cm from the nearest wall surface. This difference may change the mixer power characteristics, but it is assumed here that the mixer shaft power data given by Fahlgren and Tammelin apply to the Phase A tests.

The data in Figure 9b of Fahlgren and Tammelin (1992) were used to determine the mixer power affinity law coefficient for the Phase A mixer. A value of 0.165 was calculated. The data from Phase A tests 1A, 1B, and 1C were reviewed and the average required P/V for each test was determined. Values of 530, 512, and 501 W/m³ were determined for Phase A Tests 1A, 1B, and 1C, respectively. These three tests were conducted using 20x50-mesh zeolite.

During Phase B testing, a sample of the MarbleWhite 30 limestone used for Phase B Tests 2 and 6 was taken by ITT Flygt to their mixing laboratory in Trumbull, Connecticut. The limestone was subjected to the same conditions (liquid level, mixer position, and volume fraction

^(a)In the Phase A test report (Powell et al. 1999), mixer power is calculated based on the measured thrust versus mixer speed curve. In this report, the Phase A mixer power values are estimated based on measurements made by Fahlgren and Tammelin (1992). In all Phase B analyses, the reported mixer shaft power (i.e., 2.4 kW at 860 rpm) is used to calculate the Model 4640 mixer power.

solids) as were used for Phase A Test 1A. This test found that 95% of the tank floor had solids in motion at a mixer speed of 2100 rpm. Presumably this mixer speed is close to the speed meeting the all-particles-in-motion mixing criterion. At a speed of 2100 rpm, the P/V for the limestone test under Test 1A conditions is estimated at 725 W/m³. The actual required power density may be somewhat higher, but mixer vortexing prevented operation at higher speeds.

The Model 4640 mixers used for all Phase B tests are reported to have a shaft power output of 2.39 kW (3.2 hp) at 860 rpm. This value implies a power affinity law coefficient of about 0.122. Using the stated shaft horsepower at full speed and the known tank liquid volumes in the Phase B tests, the P/V required for each of the tests in the 1.8-m tank was computed. As described earlier, a ± 70 rpm uncertainty was assumed for the required mixer speed measurements in Tests 1 and 2. The results are shown in Table 5.2.^(a)

Table 5.2. P/V Data for Phase A and B Tests

Phase B: 1.8-m Tank			Phase A: 0.45-m Tank
Test	Required Mixer Speed (rpm)	P/V (W/m ³)	P/V (W/m ³)
1A	717 $\pm$ 70	760 $\pm$ 220	530 $\pm$ 130
1B	717 $\pm$ 70	510 $\pm$ 150	512 $\pm$ 110
1C	860 $\pm$ 70	890 $\pm$ 150	501 $\pm$ 110
2A	> 860 $\pm$ 70	> 890 $\pm$ 220	> 725
2B	> 860 $\pm$ 70	> 890 $\pm$ 150	Not Measured

Kolmogorov Turbulent Length Scale

The P/V's required in the Phase B tests may be somewhat higher than those estimated for the Phase A tests, but the differences in the table do not appear to be statistically significant. In general, agreement exists between the P/V's required in the 0.45-m tank and those required in the 1.8-m tank. Based on this agreement, and on the supporting literature, it appears likely that constant-P/V scaling applies to the 20x50-mesh zeolite particles for tank sizes between 0.45 m and 1.8 m.

^(a)Note that the P/V values shown in Table 5.2 apply to zeolite mixing with a single Flygt mixer in 0.45-m and 1.8-m tanks. Using multiple mixers is expected to reduce the required P/V as is discussed in Section 5.1.3.

An alternative way to express the concept of constant-P/V scaling is to use the Kolmogorov turbulent length scale (λ), which is given by Tatterson (1991):

$$\lambda = \left(\frac{V\mu^3}{P\rho^2} \right)^{\frac{1}{4}} \quad (5.2)$$

where V = slurry volume, m^3
 P = hydraulic mixing power, J/s
 μ = slurry viscosity, Pa-s
 ρ = slurry density, kg/m^3 .

Because Equation (5.2) contains the term P/V , constant- P/V scaling clearly implies that the value of λ is kept constant upon scale-up. Constant- λ scaling is, therefore, functionally equivalent to constant- P/V scaling. In Phase A Test 1A, zeolite mixing to the all-particles-in-motion condition required a λ of about 37 microns. In Phase B Test 1A, the required λ was 34 microns. In Phase B Tests 6 and 9 (5.7-m tank), λ was approximately 44 microns.

Conceptually, λ is the scale of the smallest turbulent eddies in the turbulent flow. At the scale of λ , flow energy is dissipated by the fluid viscosity into heat. Strictly speaking, the value of P/V in Equation (5.2) is the *local* energy dissipation rate. Using the total mixer hydraulic power and total slurry volume in Equation (5.2) gives a value of λ based on the *average* energy dissipation rate within the tank.

It is not clear whether the Kolmogorov length scale approach provides a more useful framework for understanding the zeolite suspension data. Further investigation is required to determine whether Kolmogorov's theory of turbulent microscales can be used to improve the analysis of the Flygt mixer test data.

Comparison of Pump-Down Results

A comparison of the pump-down results for the Phase A and Phase B zeolite tests shows that the zeolite might have been mixed to greater uniformity in the Phase B tests. In the first pump-down cycle for Phase B Test 1, about 90% of the zeolite was retrieved from the 1.8-m tank. This amount is compared with the Phase A Test 1 pump-down in which only about 50% of the solids were recovered. One possible interpretation of this difference is that mixing in the 1.8-m tank was more vigorous, resulting in improved vertical zeolite suspension and, consequently, improved solids recovery. However, this comparison is complicated by the differences between the Phase A and Phase B pump-down tests. In the Phase A test, the retrieval suction was placed 1 cm above the tank floor in a region of the tank where the fluid velocities were relatively low, but in the Phase B test the suction was 2.5 cm above the floor and in a region

of high fluid velocities. No attempt was made to scale either suction location or pump-down flow rates.

The enhanced solids retrieval in the 1.8-m tank may also be the result of that tank being relatively *less* mixed than the Phase A 0.45-m tank. There is an optimum level of solids suspension beyond which the solids concentration in the retrieved slurry decreases. If the retrieval suction is placed near the tank floor, the goal is to suspend the solids just enough to get the maximum solids concentration at the suction level. Mixing the slurry closer to complete vertical uniformity results in lower solids concentration in the retrieved slurry.

Because of these complications, it is unlikely that the solids recovery data can be used to infer the relative extent of solids suspension in the Phase A and B tests.

Summary of Constant-P/V Analysis

In summary, a comparison of the 0.45-m tank and 1.8-m tank results implies that mixing zeolite to the all-particles-in-motion condition in these tank sizes requires that the input mixing power be proportional to the slurry volume. It is not certain that this relationship holds for larger tank sizes, but the data from the 5.72-m tank are consistent with this trend. With all three Model 4640 mixers running at 860 rpm in the 5.72-m tank and the liquid level at 1.0 m (Test 9 conditions), the P/V supplied to the fluid was about 280 W/m^3 . Based on the tests in the 0.45-m and 1.8-m tanks, constant-P/V scaling would have predicted that 280 W/m^3 in the 5.72-m tank would not be sufficient to achieve the desired degree of zeolite mixing, which was observed. Piles of zeolite solids were felt on the tank floor even with all three mixers running at full speed.

5.1.3 Complicating Factors for Scale-Up Relationships

The particle suspension tests using zeolite in the 0.45- and 1.8-m-diameter tanks demonstrated that a P/V of about $600 \pm 200 \text{ W/m}^3$ is required to achieve the desired all-particles-in-motion-on-the-tank-floor condition. Applying this same required P/V to full scale to predict the required number of mixers for Tank 19 would likely result in erroneous predictions because of the effects discussed below and in Section 5.4.

It is very important to note that the 600-W/m^3 power intensity neglects the effect of liquid-level-to-tank-diameter ratio, which may increase the required P/V beyond that measured in the Phase A and B tests. Further, this value neglects the *beneficial* effect of multiple mixers in the tank. Before predictions can be made for full scale, the required P/V must be adjusted for these two effects. Possible ways to account for these conflicting effects are discussed below.

Effect of Liquid Level and Tank Diameter

For a given tank diameter (T), the required power intensity (P/V) is expected to increase as the liquid level (Z) decreases once Z decreases below some critical value.

Rapidly settling particles, such as zeolite, require a continuous input of mixing energy to keep them from settling to the tank floor. If the liquid flow lifts a given particle from the tank floor,^(a) the particle will immediately begin to descend back toward the floor at a rate determined by its settling velocity. The amount of time required for the suspended particles to fall back to the tank floor is a function of (a) the average height the particles are lifted above the tank floor and (b) the settling velocities and concentration of the particles.

To avoid solids accumulations in those regions of the tank where the flow is largely unidirectional and steady (i.e., away from the tank center in the 5.7-m tank tests), the average fluid velocity must exceed the critical particle suspension velocity, which is estimated to be on the order of 10 to 30 cm/s for 20x50-mesh zeolite.^(b)

In regions where the flow changes direction and/or is highly unsteady (i.e., near the center of the 5.7-m tank), the particles are not swept continuously along the tank floor in the same manner as they are in the other regions of the tank. Instead, the solids are kept from accumulating by turbulent eddies that periodically suspend the particles. To not have a net accumulation of solids in these regions, the eddies must be strong enough to sweep the particles away and they must occur often enough to prevent a large quantity of solids from settling between eddies. The size and strength of the eddies determines how high, on average, the particles are lifted above the tank floor. The frequency of the eddies determines how often the particles are lifted.

The following thought experiment is useful for understanding the effect of liquid level (Z) on the P/V required for solids suspension. Imagine you are juggling tennis balls in a room with a high ceiling. As long as the ceiling is higher than the balls are thrown, the ceiling does not affect your ability to juggle the balls. As the ceiling moves down toward the floor, however, there will be a point where the balls cannot be thrown as high without contacting the ceiling. To account for this decrease in ceiling height, it will be necessary to juggle the balls more quickly. The height each ball is thrown is related to how long it spends in the air. As the ceiling descends, juggling will become progressively more difficult. Maintaining rapidly settling solids in suspension as the liquid level decreases is a similar process.

^(a)This argument is based on the premise that the mixing level is targeted at a just-suspended condition. The Phase A and B tests have actually been focused on the all-particles-in-motion criterion, which is somewhat less stringent. The argument still applies, however, because in the regions of the tank where the bulk velocities are low because the axis of fluid rotation passes through these regions (i.e., in the center of the tank for the 5.7-m tank tests), the periodic sweeping and lifting of particles from the tank floor prevents the formation of a stationary pile of solids.

^(b)This range of velocities is based on correlations given in Graf (1971). As is discussed in Section 4.7.2, the Phase A and B tests imply critical velocities in the 20- to 50-cm/s range.

The liquid level in the tank (Z) sets an upper limit for how high the particles can be lifted into the mixture each time a turbulent eddy sweeps by. As Z decreases, the particles are, on average, lifted to lower distances above the tank floor. Thus, less time is available between each eddy to keep the particles from falling to the floor. To counteract this effect, the frequency and/or magnitude of the turbulent eddies near the floor need to increase. This increase is brought about by putting more energy per unit volume into the mixture.

Thus, as Z decreases, the P/V required to keep the particles from falling to the floor and forming piles will increase if Z is below some critical level. This effect can partially or fully (or more, depending on exact circumstances) offset the fact that the supplied P/V increases as Z decreases because all the mixers are kept running at full speed (i.e., power is constant).

Before the Phase A and B mixing test data can be used to make predictions for the full-scale mixing requirements, some accounting must be done to address the fact that the Z/T ratio at full scale is significantly smaller than in any of the tests. No defensible way to make this correction is currently available, but several possibilities are discussed below. The suggestions that follow should be considered highly speculative.

Myers et al. (1994) indicate that the mixer power required to reach the just-suspended condition is constant with respect to changes in liquid level. Thus, as the liquid level decreases, the required P/V is expected to increase in direct proportion to the inverse of the tank volume. The statement in Myers et al. (1994) applies to mechanically stirred tanks. Whether this statement can be applied to tanks mixed by turbulent fluid jets is not known.

As mentioned earlier, the change in required P/V with liquid level is relevant because the Z/T ratio in Tank 19 is smaller than was used in any of the Phase A and B tests. This ratio implies that the required P/V in Tank 19 may be higher than the roughly $600 \pm 200 \text{ W/m}^3$ observed in the Phase A and B tests. Test 1A in both Phase A and Phase B used a Z/T ratio of 0.39. The initial ratio in Tank 19 is about 0.078. Assuming the required power is independent of Z , the required P/V in Tank 19 is then estimated to be perhaps as high as $(0.39/0.078)(600) = 3 \pm 1 \text{ kW/m}^3$. This estimate, however, ignores the beneficial effect of multiple mixers, which is discussed in the next subsection. Further, this estimate assumes that the Phase A and B tests should be compared with Tank 19 on the basis of the Z/T ratio. It is unlikely that the effect of Z on required P/V can be adequately quantified simply by considering the value of Z/T . The magnitudes of Z and T are both probably needed to describe the effect.

Tests in the 0.45-m (Phase A) and the 1.8-m (Phase B) tanks were performed in which the suspension of zeolite was studied at two different liquid levels. Contrary to the implications in Myers et al. (1994), the Phase A and B data imply that the required P/V does not change significantly with the Z/T ratio when Z/T ranges from 0.39 to 0.57. The average P/V required in Phase A Test 1A was 530 W/m^3 , which is well within experimental uncertainty of the 513 W/m^3 required in Test 1C. Both tests had the same concentration of zeolite and differed only in the liquid level. A comparison of Phase B Tests 1A and 1C leads to the same conclusion. The

required P/V's for Phase A Tests 1A, 1C, 2A, 2C, 2D, and 2F are provided in Table 5.3 along with the P/V's for Phase B Tests 1A and 1C.

Table 5.3. Required P/V Values for Changing Z/T Ratio

Test No.	Volume Fraction Solids	Zeolite Mesh Size	Z/T Ratio	Required P/V (W/m ³)
Phase A: 1A	0.0153	20x50	0.39	530 ± 130
Phase A: 1C	0.0153	20x50	0.57	501 ± 110
Phase A: 2A	0.0153	50x100	0.39	285 ± 50
Phase A: 2C	0.0153	50x100	0.57	274 ± 50
Phase A: 2D	0.06	50x100	0.39	420 ± 100
Phase A: 2F	0.06	50x100	0.57	427 ± 100
Phase B: 1A	0.0153	20x50	0.39	760 ± 220
Phase B: 1C	0.0153	20x50	0.57	890 ± 150

The data in Table 5.3 imply that the required P/V does not change significantly with Z/T. However, the uncertainties in the P/V values are relatively high so the expected increase in required P/V with decreasing Z/T is possibly hidden by experimental uncertainty. Further, only Z/T's of 0.39 and 0.57 have been tested. The initial Z/T for Tank 19 is about 0.078. Based on the juggling tennis ball analogy discussed above, the effect of Z/T likely becomes progressively more significant as Z/T decreases. If so, then nonconservative predictions may result from using the P/V versus Z/T relationship observed between Z/T = 0.39 and Z/T = 0.57 (i.e., required P/V is constant) to make predictions for Tank 19.

Gladki's (1997) constant-wall-shear-stress method, described in Section 5.1, can also be used to evaluate the effect of Z/T on required P/V. Although Gladki's model apparently does not accurately predict the mixing energy needed upon scale-up for mixing rapidly settling zeolite particles, the model can provide an indication of the Z/T effect's magnitude. Gladki's model was developed using small tanks (0.45-m diameter and smaller) and a variety of particle sizes and liquid levels. Gladki's model, therefore, should be a reasonable predictor of the effect of Z/T ratio in small tanks with particles in the size and concentration ranges tested.^(a)

^(a)Gladki tested solids concentrations ranging from 0.01 vol% to 3.5 vol% and particle diameters ranging from 0.2 to 5 mm. Z/T ratios tested ranged from 0.28 to 0.72, solids densities ranged from 1.03 to 2.5 g/cm³, and liquid density ranged from 0.998 to 1.26 g/cm³.

Applying Gladki's model to the experimental conditions in Phase A Test 1A (e.g., 1.53-vol% solids, 0.7-mm-diameter zeolite particles, 0.453-m-diameter tank) and varying the assumed Z/T ratio yields the data in Figure 5.1. The predictions indicate that as Z/T decreases below about 0.3, the required P/V increases significantly. It is important to note that the lowest Z/T tested by Gladki was 0.28, so the sharp upward trend in predicted P/V with decreasing Z/T constitutes an extrapolation of Gladki's model. Tests at lower Z/T ratios are not practical in the small tanks used to develop Gladki's model because the mixer propeller diameter (7.8 cm) sets a lower bound for the tank liquid level.

According to Figure 5.1, as Z/T increases from 0.39 to 0.57, the required P/V increases by only 6%. This small increase is consistent with observations made during Phase A and B tests where Z/T had little, if any, effect on the required P/V . As Z/T decreases from 0.39 to 0.078, however, the required P/V is predicted to increase by nearly 40%.

It is not certain that this relationship would be observed if tests were performed at Z/T 's in the range of 0.078. Even if this relationship is assumed to be accurate for small tanks, it is unknown whether it would be similar for much larger tanks such as Tank 19.

Figure 5.1. Predicted Effect of Z/T Ratio on Required P/V

Further study will be required before the effect of the Z/T ratio on required P/V can be more accurately estimated for large tanks. It seems possible, though, that the required P/V will significantly increase as the Z/T decreases from 0.39 to 0.078 and lower, so this effect must be considered when full-scale predictions are made (see Section 5.3).

Effect of Multiple Mixers on the Required P/V

The Phase A and B tests indicated that a P/V of $600 \pm 200 \text{ W/m}^3$ is required to achieve the all-particles-in-motion condition when using a single Flygt mixer. The required P/V is expected to decrease if multiple mixers are used. Using multiple mixers allows the mixing energy to be more equitably distributed over the tank floor.

The effect of multiple mixers has not yet been sufficiently studied to allow an accurate quantitative prediction of the effect, but some inferences can be drawn from the Phase A and B data.

Phase A Test 1D was conducted at a Z/T of 0.39 using 6 vol% 20x50-mesh zeolite (Powell et al. 1999). Tests were performed under these conditions using both one and two mixers. When using one mixer, the average required P/V was found to be 712 W/m^3 . When using two mixers, the required P/V decreased to 530 W/m^3 . The ratio of the one-mixer P/V to the two-mixer P/V is then about $712/530 = 1.34$. However, this estimate is uncertain. The accuracy of each of the required P/V measurements is probably not better than $\pm 20\%$.

The Phase B tests in the 5.7-m tank can also be used to infer the magnitude of the multiple mixer effect. With a single mixer operating in either the 0.45-m (Phase A) or the 1.8-m (Phase B) tank, zeolite suspension required about $600 \pm 200 \text{ W/m}^3$. With three mixers operating in the 5.7-m tank at the 1.0-m liquid level, a P/V of 280 W/m^3 was found to *not* provide adequate zeolite mixing.

Before the effect of going from one mixer to three mixers can be examined, the P/V from the 5.7-m tank must first be adjusted to the same liquid-level-to-tank-diameter ratio as that used in the 0.45-m and 1.8-m tanks. As was discussed in the preceding subsection, it is not clear how best to make this adjustment.

The predictions of the *extrapolated* Gladki model will be assumed to adequately reflect the Z/T effect for tanks in the 0.45-m to 5.7-m size range. Further, it will be assumed that the correction can be applied simply on the basis of a comparison of the Z/T ratios rather than on the specific values of Z and T . Neither of these assumptions are thought to be particularly good, but they provide a basis for discussing the multiple-mixer effect.

The Z/T used in the 5.7-m tank was 0.175 instead of 0.39, which was used in the 0.45-m and 1.8-m tanks. According to Figure 5.1, the required P/V for $Z/T = 0.175$ is 5% higher than for

$Z/T = 0.39$. Thus, the required P/V in the 5.7-m tank for one mixer is estimated at about $(1.05)(600) = 630 \pm 210 \text{ W/m}^3$.

The P/V of 280 W/m^3 in the 5.7-m tank was not sufficient to reach the all-particles-in-motion criterion, so the required P/V is known to be *greater than* 280 W/m^3 for three mixers and in a tank with a Z/T of 0.175. Based on the tests in the 0.45-m and 1.8-m tanks, and on the assumed adjustment for the effect of Z/T ratio, the expected required P/V on a one-mixer basis is about 630 W/m^3 . Going from one to three mixers, then, reduced the required P/V by *less than* 55%. The ratio of the expected one-mixer P/V to the three-mixer P/V is less than $630/280 = 2.25$. This ratio is likely significantly less than 2.25 because the three mixers in the 5.7-m tank did not appear to be very close to reaching the all-particles-in-motion criterion. The slurry density measurements, the estimated size of the zeolite pile during mixer operation, and the pump-down results imply that the percentage of solids in motion on the tank floor in the 5.7-m tank was not high and was perhaps less than 50%.^(a)

Because the P/V required for three mixers appears to be significantly more than one-third of that for one mixer, it is unlikely that the required P/V is inversely proportional to the number of mixers. The available data, however, are consistent with the required P/V varying with the number of mixers to the -0.5 power. Switching from one mixer to two mixers in Phase A Test 2D resulted in a one-mixer to two-mixer P/V ratio of 1.34. A ratio of 1.41 would be expected if the required P/V varies with the number of mixers to the -0.5 power. Going from one to three mixers gave a ratio *less than* 2.25; a ratio of 1.73 is expected based on the -0.5 power relationship.

The validity of this relationship cannot be determined from current data, but the -0.5 power relationship is assumed to apply for the calculations discussed below. The relationship between the number of mixers and the required P/V is probably not this simple, but it will be assumed to apply for making preliminary estimates for the Tank 19 mixing requirements. A more rigorous treatment of the multiple-mixer effect is expected to require that the location and orientation of each mixer also be addressed.

Assuming that the required P/V varies in direct proportion to the number of mixers raised to the -0.5 power, the number of mixers required to achieve the all-solids-in-motion-on-the-tank-floor condition in Tank 19 can be estimated from:

^(a)This quantity is difficult to estimate because a clear-bottom 5.7-m tank was not used. The slurry density and pump-down results imply that less than 20% to 30% of the solids were in suspension to a level 13 cm above the tank floor. It is not known how to best interpret these data so that the fraction of solids in motion on the tank floor can be determined. The “perhaps less than 50%” estimate is based on a combination of the pump-down results, the slurry concentration profiles, and the estimated size of the settled solids pile on the tank floor during mixer operation.

$$N_{mix} = \left(\frac{(V)(P/V)_{req}}{P_{mixer}} \right)^{\frac{2}{3}} \quad (5.3)$$

where N_{mix} = the required number of mixers
 V = the volume of waste in Tank 19, m³
 $(P/V)_{req}$ = the required power intensity for one mixer at the same liquid-level-to-tank-diameter ratio, W/m³
 P_{mixer} = hydraulic power supplied by each mixer, W.

Equation (5.3) is used in Section 5.3 to account for the multiple-mixer effect when making predictions for full-scale mixing. Although the -0.5 power relationship assumed for Equation (5.3) is consistent with the Phase A and B experimental data, the relationship is speculative.

Other Complicating Factors

In addition to the liquid level and multiple-mixer effects discussed above, assumptions implicit in the Phase A and B experiments raise questions regarding the applicability of the experimental data to full scale. In particular, the lack of geometric, kinematic, and dynamic similarity between these experiments and the full-scale application limit the degree to which the small-scale results can be used to make predictions for full scale. Section 5.4 gives a more thorough discussion of these issues.

5.2 Sludge Mobilization

The sludge mobilization process is qualitatively different than the suspension of rapidly settling solids. Therefore, a different analysis approach is used.

For our purposes, sludge is composed of very small, cohesive particles. To mobilize a given piece of sludge away from the sludge/slurry interface, the local fluid velocity (or shear stress) must exceed some minimum value for some minimum amount of time. The exact value of the required velocity and time is a function of the sludge properties and to some extent the slurry properties. Once these criteria are met, a particle or group of particles (flake) is removed from the sludge surface thereby exposing the particles underneath to the erosive action of the flowing slurry. Then the process is repeated.

The dislodged pieces of sludge tend to be small, usually millimeter size and smaller. The millimeter size and smaller flakes of sludge are rapidly ground down to particles and clumps of particles with sizes on the order of tens of microns and smaller as the flakes circulate through more strongly mixed regions of the tank (i.e., through the mixer propellers). From there, the particles are slowly settling and only a small amount of agitation is required to maintain them in

suspension off the tank floor. Thus, once a piece of sludge is dislodged from the bulk, it effectively no longer presents a difficult challenge from a mixing perspective if sufficient agitation exists in the tank to ensure that the dislodged pieces are broken down into very small, slow settling particles that do not flocculate. For sludge mobilization, the challenging step in the process is dislodging small pieces of sludge from the bulk of the sludge layer. The subsequent mixing is usually comparatively easy and is ignored in the analysis.

Because maintaining the sludge particles in suspension can be accomplished using comparatively little mixing energy (compared with that required for either maintaining zeolite particles in suspension or mobilizing sludge particles from the bulk), the effect of decreasing liquid level is not expected to have an adverse effect on the sludge mobilization process as it does for zeolite suspension. In fact, decreasing the liquid level results in an increase in the average wall shear stress, which is expected to result in a greater degree of sludge mobilization.

Sludge mobilization will occur whenever the applied shear stress at the sludge surface exceeds some minimum value. This minimum shear stress for mobilization is called the critical shear stress; it is related to the physical properties of the sludge. Previous work with sludge simulants has shown that critical shear stress can be correlated with sludge shear strength. As a *rough* approximation, the critical shear stress is on the order of 1/200th of the shear strength (Powell et al. 1995b; Nearing 1991).

The approach used in the Phase A and B sludge mobilization analyses relates the sludge shear strength to the average wall shear stress^(a) required to achieve 80% of the sludge mobilized. The 80% level was arbitrarily chosen to represent an acceptable degree of mobilization. This same criterion was applied to all the tests for a more direct comparison. This approach does not consider the changes in shear stress distribution on the sludge surface with changes in mixer speed, number of mixers, or the extent of sludge mobilized.

A more rigorous analysis of the Phase A and B sludge mobilization test data requires that the shear stress distribution be determined for each of the tests and for the planned full-scale application. Such an effort was beyond the scope of the present work, but may be worthwhile if future plans call for the use of fixed-position Flygt mixers.

Tests using Flygt mixers to mobilize and mix cohesive sludge simulants were performed in both Phase A and B tests. Phase A testing indicated that the average wall stress (τ_o) required to achieve 80% of the sludge mobilized was about $5 \pm 1.5\%$ of the sludge shear strength when the strength was greater than about 100 Pa (Powell et al. 1999). The findings of the Phase B tests are consistent with those of Phase A, although additional testing in the 0.45-m tank is needed to conclusively evaluate the effects of scale-up on Flygt mixer sludge mobilization.

^(a)As was defined earlier, the average wall shear stress (τ_o) is equal to the total mixer thrust divided by the wetted surface area of the tank.

Three sludge mobilization tests were conducted during Phase B. Two tests were performed in the 1.8-m tank and one test was performed in the 5.72-m tank.

Test 5 used a kaolin/bentonite/water sludge simulant with a shear strength of 2070 ± 600 Pa. The τ_o required to achieve 80% mobilization was found to be $4.1 \pm 1.2\%$ of the shear strength.^(a) This result is consistent with Phase A Test 7 (0.45-m tank) in which a kaolin/plaster sludge simulant with a shear strength estimated to be 2000 Pa required a τ_o of 3.5% of the sludge strength.

Phase B Tests 4 and 8 used a kaolin/water sludge simulant with a shear strength in the 400 Pa range (Test 4 was 405 ± 83 Pa and Test 8 was 363 ± 50 Pa). The average wall shear stress required to reach 80% mobilization in Test 4 was 42 ± 7 Pa. The average wall stress required for Test 8 is more difficult to estimate because a wall stress of about 40 Pa yielded 55% mobilization and 56 Pa yielded 85% mobilization. An estimate of 53 Pa was generated based on a linear interpolation between these two points, but the relationship is probably not linear (the true relationship should depend on the way the shear stress distribution on the sludge surface changes with changes in mixer speed). Thus, in Test 4, the average wall stress required to achieve 80% mobilization was $10 \pm 3\%$ of the sludge strength. In Test 8, the required stress was estimated at $14.6 \pm 3.4\%$ of the sludge strength.

As discussed in Section 4.8, kaolin clay is unusual in that its erosion resistance is relatively independent of its strength over the strength range of about 250 to 2000 Pa (see Powell et al. 1995a for description of this phenomenon). Tank sludge is unlikely to behave in this manner. Thus, using the ratio of required shear stress to sludge simulant shear strength is probably not appropriate for kaolin clay in this strength range. Kaolin clay was selected as the sludge simulant for this testing principally because it is inexpensive and large quantities of kaolin-based sludge simulant can be manually mixed. Further, it was hoped that Phase C testing (full-scale tank) might involve a kaolin-based sludge simulant and that the Phase B data be comparable to that gathered in Phase C. Kaolin is also preferred for examining scale-up effects *because* its mobilization resistance is relatively insensitive to its composition. Small differences in the kaolin-based simulant compositions for tests at two or more scales will not significantly affect the test results; observed differences in the test results should be principally due to scale-up effects.

When comparing the Test 4 and 8 results, it is perhaps more appropriate to assume that the sludge simulants used for Tests 4 and 8 were identical with respect to erosion resistance. Further, based on a comparison of kaolin clay erosion with many other sludge simulants (Powell et al. 1995a), the *effective* shear strength of the kaolin clay simulant is about 1000 Pa. Using this value, the required τ_o values for 80% mobilization in Tests 4 and 8 become roughly $4.2 \pm 1.1\%$

^(a)This percentage may have been reduced if the test had been continued, but the magnitude of the possible reduction is not known.

and $5.3 \pm 1.5\%$, respectively. These percentages are consistent with those observed in the Phase A tests.

The difference between 42 ± 7 Pa and $53 \pm 10^{(a)}$ Pa may not be significant. Further tests could be used to determine whether this is the case. In particular, the 400-Pa kaolin clay sludge simulant should be tested in the 0.45-m tank at the ITT Flygt laboratory. If the required wall stress is found to be on the order of 40 to 50 Pa, then it can be concluded that the difference between the Test 4 and Test 8 results is probably not due to a scale-up effect. If the required stress is in the 30 Pa or less range, then a scale-up effect is likely in which the required stress (for a given sludge) increases with scale. Such an effect could make sludge mobilization in a full-scale (85-ft diameter) tank very challenging.

A more accurate and complete understanding of the Flygt mixer sludge mobilization process can likely be attained by considering the shear stress distribution within the tanks used for testing and the full-scale tanks. In the mean time, a rough estimate of the total mixer thrust required to achieve 80% mobilization is given by multiplying the sludge shear strength by 0.1 ± 0.05 .

5.3 Predictions for Full Scale

Based on the Phase A and B tests, the following two guiding principles for Flygt mixer system design have been developed:

- 1) Constant-P/V scaling should be applied in designing a Flygt mixing system that uses fixed-position mixers to mix rapidly settling particles such as zeolite.
- 2) The average wall shear stress required to reach 80% sludge mobilization is likely between 5% and 15% of the sludge shear strength. Some further testing is required to refine this conclusion and to ensure that an adverse scale-up effect does not exist.

These conclusions can be used to predict the required Flygt mixing system design for SRS Tank 19. Predictions for the required number of fixed-position 37-kW (50-hp) Model 4680 Flygt mixers are given in this section. Predictions are given based on both the particle suspension and sludge mobilization mixing requirements. All predictions apply to fixed-position mixers rather than to mixers mounted so they can be periodically or continuously reoriented. Mixers that can be reoriented are expected to be more effective than the fixed-position mixers.

^(a)The uncertainty in the 53-Pa estimate is not easily estimated because the error introduced by the linear interpolation is unknown. It is likely, however, that the uncertainty in the Test 8 average wall shear stress is higher than the estimated ± 7 Pa uncertainty for Test 4. An uncertainty of ± 10 Pa is used here to reflect the increased uncertainty in the Test 8 result.

5.3.1 Description of Tank 19 Waste

Tank 19 contains a 33-kgal waste heel covered by a salt solution supernate layer to about the 280-kgal level (2-meter total depth). The waste heel is composed of used zeolite (20x50-mesh), sludge, and undissolved salt. The waste heel is thought to contain about 13 kgal of zeolite, 7 kgal of sludge, and 7 kgal of undissolved salt (Goslen 1986). The accuracy of these estimates is unclear. Based on the chemical composition of the supernate (Hay 1997), the supernate density is estimated to be between 1.2 and 1.25 g/mL and the viscosity at 20°C is about 2.4 cP.

The shear strength of the waste heel is unknown but visual observations of the sample taken from near the heel surface imply that the strength of the sample was in excess of 0.5 kPa because the sludge did not flow or slump out of the sampler. Based on qualitative comparisons with sludge simulants, the shear strength of the Tank 19 sludge sample was also judged to have been at least 0.5 kPa. Based on the hot cell technician's observations that the Tank 19 sample felt "soft," the Tank 19 sample was probably not significantly stronger than 3.0 kPa (see footnote on page 5.23).

It is unknown whether the sample represented the bulk of the Tank 19 sludge. The sludge near the Tank 19 heel surface may be significantly stronger or weaker than the strength of the bulk sludge. Further, sample disruption and temperature changes that result from sampling can bias the sample strength either high or low depending on the nature of the sludge. Clearly, the strength of the sludge in Tank 19 is not known with sufficient accuracy to make defensible predictions for Tank 19 sludge mobilization mixing requirements.

5.3.2 Fast-Settling Particle Suspension Predictions for Full Scale

Based on the one-mixer tests in the 0.45-m and 1.8-m tanks, the P/V required for one mixer to suspend zeolite is $600 \pm 200 \text{ W/m}^3$. This value applies when the liquid-level-to-tank-diameter ratio is 0.39 and presumably when the tank diameter is between 0.45 m and 1.8 m.

Assuming that constant-P/V scaling can be applied to larger, geometrically scaled tanks, the all-particles-in-motion condition could probably be achieved for 20x50-mesh zeolite by supplying a P/V of $600 \pm 200 \text{ W/m}^3$ using a single Flygt mixer in the tank. The mixer would need to be of scaled dimensions (based on Phase A and B Test 1) and placed in the appropriate scaled location and orientation. Further, the liquid level would need to be adjusted to achieve a Z/T of 0.39.

None of these conditions can be met in the planned full-scale application. To meet these scaling conditions for SRS Tank 19, the mixer propeller diameter must be over 5 m, the liquid level must be 10 m, and the mixer hydraulic power must be 3200 kW (4300 hp). The mixers planned for use in Tank 19 have propeller diameters of 0.51 m, the liquid level will be maintained at 2 m or less, and each mixer will supply about 30 kW (40 hp) of hydraulic power.

As discussed in Section 5.1.3, it is not clear how to best account for differences in geometric scaling or quantify the multiple-mixer effect. If no correction is made for any of these effects, then attaining a P/V of $600 \pm 200 \text{ W/m}^3$ in Tank 19, which has an initial waste volume of 1050 m^3 (Goslen 1986), will require a total of $(600 \pm 200 \text{ W/m}^3)(1050 \text{ m}^3) = 630 \pm 210 \text{ kW}$ of hydraulic power. Each Model 4680 Flygt mixer supplies about 30 kW of power, so a total of 21 ± 7 mixers would be predicted using this approach.

Section 5.1.3 discusses speculative corrections for the effects of multiple mixers and liquid level. Applying these corrections reduces the predicted number of mixers required.

As mentioned earlier, the initial Z/T ratio is 0.078 in Tank 19 whereas the Phase A and B Test 1 data were collected at a Z/T of 0.39. Assuming that Figure 5.1 applies to tanks of all sizes (this is probably a poor assumption), the required P/V must be increased by roughly 40% to account for this difference in Z/T . Thus, a P/V of $840 \pm 280 \text{ W/m}^3$ is predicted to be required for a tank like Tank 19 with $Z/T = 0.078$. This estimate is the power intensity required for a *single* mixer to achieve the all-particles-in-motion-on-the-tank-floor condition in Tank 19.

Next, the correction for multiple mixers is applied. Assuming the hypothesized -0.5 power relationship applies, the number of mixers is calculated using $(P/V)_{req} = 840 \pm 280 \text{ W/m}^3$ in Equation (5.3). This calculation gives 9.5 ± 2.1 mixers.

A similar calculation can be performed assuming that the Tank 19 liquid level is 1 m instead of 2 m. Decreasing the liquid level results in an increase in the P/V supplied to the slurry, but the increase in the required P/V (from Figure 5.1) largely offsets this effect. Using $Z = 1 \text{ m}$ gives a prediction of 9.1 ± 2.0 mixers.

Even given the uncertainties involved in the predictions, more than three fixed-position Model 4680 Flygt mixers are likely required to achieve the desired all-particles-in-motion-on-the-tank-floor condition. However, retrieval of an acceptable quantity of zeolite from Tank 19 can likely be achieved at mixing intensities significantly lower than those required to reach the all-particles-in-motion condition. Solids can be retrieved using multiple pump-down cycles until the rate of solids recovery falls below a yet-to-be-specified minimum level.

P/V of roughly 280 W/m^3 in the 5.7-m tank with three mixers gave an assumed to be marginally acceptable zeolite retrieval rate (e.g., 15% recovery on the first pump-down test with the pump suction located 13 cm above the tank floor).^(a) The number of mixers required in

^(a)The solids recovery rate in this test was 15% from the first pump-down. Recovery rates from subsequent pump-downs are likely to be lower, but the magnitude of the decrease is not yet known. A 15% recovery rate is considered to be marginally acceptable on the basis that 14 complete pump-down cycles would be required to achieve removal of 90% of the initial quantity of rapidly settling solids, *assuming* that the recovery rate remains constant at 15% per cycle.

Tank 19 to achieve the same marginal performance can be estimated using the same approach as described above.^(a)

First, the 280 W/m³ P/V is adjusted from a three-mixer basis to a one-mixer basis by multiplying by the square-root of three, giving a required P/V of 485 W/m³. This number is adjusted for the difference in Z/T between the 5.7-m tank (Z/T = 0.175) and Tank 19 (Z/T = 0.078) using the extrapolation of Gladki's model in Figure 5.1. This correction increases the P/V to 640 W/m³. This value is substituted into Equation (5.3) and the predicted required number of mixers is 8. This prediction, again, is the number of fixed-position mixers expected to yield the minimum acceptable zeolite retrieval performance.

This analysis implies that the zeolite retrieval performance may degrade rapidly as the supplied mixer power intensity decreases from that required to reach the all-particles-in-motion condition. The 600-W/m³ power intensity found to be adequate for one mixer and Z/T = 0.39 implies that three mixers with Z/T = 0.175 (i.e., Test 9 in the 5.7-m tank) should reach the all-particles-in-motion condition at about $(600)(1.05)/(3^{0.5}) = 364 \pm 120$ W/m³. The Test 9 pump-down results imply that operating at roughly 75% of this value yields marginal zeolite retrieval performance. This implication is that the supplied P/V must be at least 75% of that required to reach the all-particles-in-motion condition to achieve an acceptable level of zeolite retrieval.^(b)

The mixer predictions for rapidly settling solids in Tank 19 are summarized in Table 5.4. Again, we must emphasize that the adjustments for the effects of multiple mixers and Z/T ratio are largely speculative and should not be considered quantitatively defensible. The *qualitative* indications, however, are that an impractical number of stationary mixers are probably required to achieve acceptable zeolite mixing in Tank 19. A combination of numerical modeling and experiment will likely be required to determine the accuracy of the three key assumptions in this analysis (i.e., that the required P/V varies with Z/T as shown in Figure 5.1, the required P/V varies with the number of mixers to the -0.5 power, and that constant-P/V scaling applies up to the Tank 19 size without regard to the lack of geometric similarity between the Phase A and B tests and the Tank 19 application.).

^(a)It must be stressed that these corrections are highly speculative and should be viewed with considerable skepticism. They are, however, the best corrections that can be made given the available data.

^(b)Some concerns exist that the retrieval pump suction was located too high above the tank floor in the 5.7-m tank tests. Had the suction been placed nearer to the floor, the retrieved fraction of solids might have been higher.

Table 5.4. Particle Suspension Mixer Predictions for Tank 19

Applied Correction	Mixing Condition	Required P/V on 1-mixer basis (W/m ³)	No. of Mixers (Flygt 4680)
None	All Particles in Motion Z = 2.0 m	600 ± 200	21 ± 7
Z/T Effect	All Particles in Motion Z = 2.0 m	840 ± 280	29 ± 10
Z/T and Multiple Mixers	All Particles in Motion Z = 2.0 m	840 ± 280	9.5 ± 2.1
Z/T and Multiple Mixers	All Particles in Motion Z = 1.0 m	1565 ± 520	9.1 ± 2.0
Z/T and Multiple Mixers	Marginal Retrieval Z = 2.0 m	485	8

From the above discussion, the required number of stationary mixers is probably prohibitively large. Three options for Tank 19 retrieval are 1) install Flygt mixers in Tank 19 along with a mechanism that allows the mixers to be continuously reoriented, 2) proceed with the baseline design of three or four mixers in fixed positions and operate them so the solids are periodically swept toward the retrieval pump suction,^(a) or 3) select an alternative mixing and retrieval approach for SRS Tank 19.

Because a variety of potential alternative approaches have already been considered, a more effective and efficient approach probably cannot be identified. Option 1 is likely to offer the greatest potential for success because it also allows for mixer operation according to Option 2.

Whether a relatively small number of Flygt mixers (i.e., 4 to 6) could be installed in Tank 19 so they can be continuously reoriented is under investigation. It is not yet known whether such an approach will result in acceptable solids retrieval, but a comparison of the Flygt mixer fluid jet characteristics with those of the previously used Tank 19 mixer pumps gives cause for optimism. The Phase A and B Flygt mixer test program has been focused exclusively on determining the performance of fixed-orientation mixers. Further experimentation and

^(a)The feasibility of this approach cannot be determined from existing test data. Further testing, modeling, and analysis are required before the potential of this approach can be accurately assessed.

perhaps numerical modeling will likely be required before the efficacy of variable orientation Flygt mixers can be accurately assessed.

5.3.3 Sludge Mobilization Predictions for Full Scale

The Phase A and B test results can also be used to predict the number of fixed-orientation Flygt Model 4680 mixers required to mobilize the sludge heel in SRS Tank 19. When taking 80% mobilization as the target fraction of sludge mobilized, ignoring the potential adverse scale-up effect discussed in Section 5.2, and ignoring the fact that the Tank 19 heel is not evenly distributed throughout the tank floor, the following predictions can be made.

The Tank 19 sludge strength is unknown, but a value between 0.5 and 3 kPa is reasonable based both on the observed behavior of samples taken from the Tank 19 heel and on shear strength measurements made on sludge samples from waste tanks at other DOE sites (Willingham 1994).^(a) For example, assume the Tank 19 sludge shear strength is 2 ± 1 kPa and the required average wall stress for 80% mobilization is 5% of this value, or 100 ± 50 Pa. The initial wetted surface area inside Tank 19 is about 690 m², so the initial required thrust (at the initial liquid level) is 69 ± 35 kN. Each Model 4680 mixer produces about 6.2 kN, so 11 ± 5 mixers would probably be required to reach 80% mobilization if the sludge has a shear strength of 2 ± 1 kPa. This approach does not take credit for the improved shear stress distribution that results as the number of mixers increases. The Phase A and B test data do not provide an adequate basis for quantifying the multiple-mixer effect for sludge mobilization.

^(a)The ability of the Tank 19 sludge sample chunks to hold their shape after being scraped out of the sampling cylinder was compared with that of sludge simulants of various strengths. This comparison implied a Tank 19 sludge strength of more than about 1 kPa. The technician who removed the Tank 19 sample from the sampler (using a lab spatula held by hot cell manipulators) reported that the solids did not feel hard, although it is unclear how accurately the technician can gauge small forces transmitted through the manipulators.

At one point during removal of the sample, a piece of sludge protruded several centimeters horizontally out from the mouth of the sampler without breaking free. An analysis of the forces acting on the sample as well as a comparison of this behavior with the behavior of sludge simulants imply that the sludge strength is probably 1 kPa or higher (Gauglitz and Aikin 1997 and Gauglitz et al. 1995).

The upper bound of 3 kPa is based on the hot cell technician's report that the solids were not hard and on the range of sludge strengths observed in other DOE waste tanks (Willingham 1994). The strength of the Tank 19 sludge may be higher than 3 kPa, but indications from the single available Tank 19 sample are that it is in the range of 0.5 to 3 kPa.

It must be emphasized that it is unknown if the strength of the Tank 19 sample is representative of the Tank 19 waste in general. Sampling or in situ testing of the Tank 19 sludge is required to address this issue rigorously.

Table 5.5 gives the number of Model 4680 mixers predicted to give 80% sludge mobilization in Tank 19 for a variety of assumed sludge shear strengths. For these calculations, the average shear stress required to achieve 80% sludge mobilization is assumed to be roughly 5% or 15% of the sludge shear strength and, in the second and third columns, no credit is taken for the expected beneficial effect of multiple mixers. In the fourth and fifth columns, the required average wall stress is assumed to vary with the inverse of the square-root of the number of mixers (i.e., the same relationship suggested from the particle suspension tests). Whether the square-root relationship is appropriate is not known, and the experimental data provide no support for this assumption (i.e., over the range of conditions tested, no beneficial effect of multiple mixers is evident, but the effect may have been hidden by changes in other test parameters).

The Phase A and B tests implied that the required wall shear stress (τ_o) is likely between 5% and 15% of the sludge shear strength (τ_s). Thus, the estimates based on 5%, though reasonable, are possibly nonconservative. The Table 5.5 estimates also do not account for the fact that the Tank 19 sludge is not evenly distributed throughout the tank or for the fact that the magnitude of the expected multiple-mixer effect is unknown. The effect of these simplifications on the results is unclear. All the calculations assume the wetted surface area is maintained at 690 m² during sludge mobilization. Performance is expected to improve as the liquid level is decreased, but this is probably a relatively minor effect (i.e., the applied τ_o increases by about 10% as the Tank 19 liquid level decreases from 2 m to 1 m).

Table 5.5. Predicted Number of Model 4680 Mixers for 80% Sludge Mobilization

Assumed Sludge Shear Strength (kPa)	N_{mix} Without Correction for Multiple Mixers $\tau_o = 5\% * \tau_s$	N_{mix} Without Correction for Multiple Mixers $\tau_o = 15\% * \tau_s$	N_{mix} With Correction for Multiple Mixers $\tau_o = 5\% * \tau_s / N_{mix}^{1/2}$	N_{mix} With Correction for Multiple Mixers $\tau_o = 15\% * \tau_s / N_{mix}^{1/2}$
0.1	0.6	1.8	0.7	1.4
0.5	2.8	8.4	2.0	4.1
1.0	5.6	17	3.1	6.5
2.0	11	33	5.0	10
5.0	28	84	9.2	19

Modifying the mixer supports to allow periodic or continuous reorientation is expected to significantly reduce the required number of mixers. Each Model 4680 mixer is expected to have an effective range of more than about 12 m when directed against a cohesive sludge with a shear

strength of 2 kPa.^(a) Each rotating Flygt mixer, then, could conceivably carve out a circular region with an effective cleaned radius of at least 12 m. With such an arrangement, three or four mixers could mobilize most of the Tank 19 sludge. Performance against a 0.5-kPa sludge is considerably better. An effective cleaned radius of more than 23 m is predicted for each pump if the sludge shear strength is 0.5 kPa.

Maintaining the rapidly settling solids in suspension and/or directing them to the retrieval pump inlet may still present a challenge, however. Further testing and/or modeling is required to determine if continuous reorientation of the mixers addresses the solids suspension issue as well as sludge mobilization.

Flygt mixers are planned for use in one of the Gunitite waste storage tanks at ORNL. These mixers are to be used to mobilize some of the sludge so it can be pumped from the tank as a slurry before the arm- and vehicle-based retrieval tools are deployed in the tank. Given an estimate for the sludge strength in the ORNL tank, the expected Flygt mixer performance can be predicted. The results of the ORNL operation will also serve as a useful check on the expected sludge mobilization scale-up relationship.

In summary, the Phase A and B data imply that fixed orientation Flygt mixers might not effectively mobilize and mix the SRS Tank 19 heel if they are used in the previously envisioned manner (i.e., three mixers in fixed positions) and if the sludge heel is as strong as it appears to be based on the single sample that has been taken. Acceptable performance may yet be achieved by designing the mixer stands to allow continuous reorientation and/or developing a strategy for turning pumps on and off so the rapidly settling solids preferentially accumulate near the retrieval pump inlet so they can be pumped from the tank.

5.4 Major Analysis Uncertainties

Sections 5.1, 5.2, and 5.3 mention uncertainties and complicating factors restricting the applicability of the Phase A and B test results to Flygt mixing in a full-scale tank such as SRS Tank 19. Many of these caveats are repeated below along with additional issues that are not explicitly discussed elsewhere in the report. This section gives an indication of where the

^(a)Powell et al. (1995a) presents a correlation between effective cleaned radius, submerged fluid jet characteristics, and sludge strength. Using this correlation and the reported performance of the Model 4680 Flygt mixers (Flygt 1998), an effective cleaned radius of 12.5 m is predicted for a 2-kPa sludge. The actual performance is expected to be better than this prediction because the liquid level in Tank 19 reduces the rate of jet momentum loss so jet velocities are likely higher than those assumed by the mixer pump performance correlation in Powell et al. (1995a). The magnitude of this improvement will be estimated based on the results of the full-scale (Phase C) Flygt mixer tests at SRS.

uncertainties are greatest and which results and analyses should be applied with considerable caution.

- **Geometric Scaling:** Approximate geometric scaling of tank diameter, mixer size, and liquid level were maintained between the Phase A 0.45-m tank and the Phase B 1.8-m tank. The three-mixer tests in the 5.7-m tank, however, did not represent appropriate geometric scaling of the envisioned three Model 4680 Flygt mixers in SRS Tank 19. In particular, the propeller diameter of the Model 4640 mixers used in the 5.7-m tank was a factor of 3.3 too large. Geometric scaling requires the propeller diameters in the 5.7-m tank to be 11.2 cm instead of 37 cm. This compromise was made because mixers with propeller diameters close to 11.2 cm with the requisite thrust were not available.
- **Dynamic and Kinematic Similarity:** The dynamic and kinematic similarity between tests at two scales implies that, on a dimensionless basis, all the flow streamlines are similar, all velocities are similar, and all forces are equal. Achieving full geometric, dynamic, and kinematic similarity can be quite difficult in practice, but if it can be done then the observations made in the scaled test will be directly applicable to the full-scale application. No attempt was made to apply dynamic and kinematic similarity principles to the Phase A and B Flygt mixer tests because of cost and schedule constraints. Consequently, considerable uncertainty exists in the applicability of some of the test results to full scale.
- **Applicability of Constant-P/V Scaling to Large Tanks:** Constant-P/V scaling is inferred to apply for tanks in the 0.45-m to 1.8-m size range. The results of the 5.7-m solids suspension tests are also consistent with constant-P/V scaling, but not conclusively so. However, the test data do not provide evidence that constant-P/V scaling applies to tanks as large as Tank 19. It is unknown whether the required P/V increases, decrease, or remains constant as the tank diameter increases to the scale of Tank 19 (i.e., 25.9 m).
- **Multiple Mixer Effect on Required P/V:** In Section 5.1.3, a -0.5 power relationship between the required P/V and the number of mixers is assumed. This relationship is consistent with the data from this test program, but the data are very limited so this relationship must be considered speculative.
- **Tank Liquid Level Effect on Required P/V and τ_o :** Figure 5.1 in Section 5.1.3 shows the effect of liquid level on required P/V based on an extrapolation of Gladki's (1997) solids suspension model. This relationship is highly speculative and gives only qualitative indications of the effect of liquid level. No attempt was made to account for the multiple-mixer effect in the analysis of the sludge mobilization data.
- **Scale-up of Sludge Mobilization Required τ_o :** A comparison of the τ_o required for kaolin clay in the different size tanks used for testing implies that the required τ_o may increase upon scale-up. An additional sludge mobilization test in the 0.45-m tank is needed to

determine whether the apparent scale-up effect is due to changes in the simulant composition between the Phase A and B tests.

- **Applicability of Pump-Down Test Results to Full Scale:** The results of the pump-down tests in the Phase A and B tests do not necessarily imply that similar results will be achieved at full scale. Efforts were not directed at developing an understanding of the pump-down process so scaling this process could be appropriately tested. Further work is needed to improve the understanding of the pump-down process so more accurate full-scale predictions can be made.
- **Properties of Tank 19 Supernate and Sludge Heel:** The properties of the Tank 19 heel were simulated using 20x50-mesh zeolite, kaolin clay, and water. In reality, the Tank 19 supernate is considerably more dense and viscous than water.^(a) Both of these effects will tend to decrease the settling velocity of the zeolite particles so solids suspension is more easily maintained in Tank 19 than in the Phase A and B tests. The Phase A and B tests used water to simulate the Tank 19 supernate because the results would be conservative and matching the Tank 19 density and viscosity would require the use of regulated solutions that would be costly to dispose of. The Tank 19 sludge was simulated by a layer of kaolin clay of uniform thickness. The actual Tank 19 sludge heel has an hourglass shape spanning the tank and has an unknown shear strength. Finally, roughly 40% of the Tank 19 heel is thought to be composed of salt crystals. It is unknown whether these salt crystals present a mixing challenge similar to that of the 20x50-mesh zeolite. The 20x50-mesh zeolite used in the Phase A and B tests was selected to model the zeolite known to be in the Tank 19 heel (roughly 40% of the heel is thought to be 20x50-mesh zeolite). It is unknown, however, whether the zeolite in Tank 19 has degraded in the two decades it has been inside of Tank 19. If such degradation has occurred, then the Tank 19 zeolite should be less challenging to mix than is implied by the Phase A and B tests.

^(a)Based on the supernate composition (Hay 1997), the supernate density is between 1.2 and 1.25 g/mL and the viscosity is about 2.4 to 2.5 cP.

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Appendix A

Phase B Test Plan

Appendix A: Phase B Test Plan

This appendix contains the Phase B test plan. The test plan was prepared before Phase B testing began and reflects the thinking of the test team at that time. The descriptions of the test procedures given in the test plan were adhered to except as noted in Section 3.0 of this report.

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

Test Plan - Phase B Tests at PNNL

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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 m³ (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. During fiscal year 1998, The U.S. Department of Energy (DOE) tasked staff from Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), SRS, and ITT Flygt Corporation to conduct a joint mixer testing program to evaluate the applicability of Flygt mixers to Tank 19 waste retrieval and waste retrieval in other DOE tanks. This test program consists of three phases. The first phase involved small-scale (0.45-m diameter tank) mixer testing at the ITT Flygt laboratory in Trumbull, Connecticut. The second phase involves larger-scale (1.8-m and 5.7-m diameter tanks) 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).

This test plan describes the mid-scale testing to be conducted at PNNL. A single 4-hp Flygt mixer will be tested in a 1.8-m (6-ft) diameter tank and up to three such mixers will be tested in a 5.7-m (18.75-ft) diameter tank. The specific tests that will be performed and the justification for these tests are provided herein.

Figure 1.1. Flygt Mixer

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

2.0 Scope and Objectives

Flygt mixer testing 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 to develop predictive Flygt mixer capabilities in DOE waste tanks so their effectiveness can be predicted for future applications. To meet these objectives, several issues must be addressed by combining small-scale tests, analysis, and then larger- and full-scale tests. This section discusses the scope and objectives of each phase of this test program. Emphasis is placed on the mid-scale (Phase B) tests in this test plan. The small-scale (Phase A) tests were conducted in March 1998 and are documented in Powell et al. (1999). The full-scale (Phase C) tests will be conducted at the SRS and described in a future test plan.

2.1 Phase A Tests at ITT Flygt

The Phase A tests were conducted at the ITT Flygt facility in Trumbull, Connecticut on March 16 to March 19, 1998. The results of the Phase A tests are summarized in Section 3.5. The objective of the Phase A tests was to provide a basis for selecting the mixer sizes to be tested in Phases B and C and to provide small-scale tank test data that will be used to correlate mixer performance to scale. One of the principal goals of this test program is to identify and verify Flygt mixer scale-up relationships for solids mixing.

2.2 Phase B Tests at PNNL

The second phase (Phase B) of Flygt mixer testing will be conducted at PNNL. Flygt mixers will be tested in a 1.83-m tank and a 5.7-m diameter tank containing pure water and water mixed with zeolite, crushed limestone, or sludge material. Based on Phase A test results, it is estimated that one mixer will be required in the 1.83-m tank, while three mixers will be required in the 5.7-m tank. Table 2.1 shows the Phase B test objectives. By comparing the results of Phase A and B tests, we hope that a scaling methodology can be developed to allow predictions of mixer performance at other scales. All tests should be performed with the full team present; in case the full team cannot be present, the tests have been prioritized. Tests 1, 4, 6, and 8 are deemed the highest priority; the full team must be present for these tests. Tests 3 and 4 are medium priority, and full team participation is desirable. Tests 2 and 7 are of lower priority; these tests can easily be performed without participation by the full team.

2.3 Phase C Tests at SRS

Full-scale tests will be performed at SRS in an 85-ft diameter (full-scale) tank. SRS staff 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 only one mixer will be used initially. 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. Velocity measurement locations will be limited to the access provided by a cross-walk that is being constructed, although a lightweight pole and roller structure could be used to span areas inaccessible by the cross-walk. As part of this testing, methods for deploying the Flygt mixers into Tank 19 will be evaluated. A separate test plan will be written for the Phase C tests.

Table 2.1. Phase B Test Objectives

Test No.	Scope Description	Test Objective
1	Three tests using 20x50-mesh zeolite particles in 1.8-m tank	Determine average wall stress and fluid velocity required to mix and maintain zeolite particles in suspension as a function of concentration and slurry depth
2	Four tests using 0.2-mm crushed limestone in 1.8-m tank	Determine average wall stress and fluid velocity required to mix and maintain crushed limestone particles in suspension as a function of concentration and slurry depth
3	Water velocity measurements	Determine the effect of solids on fluid velocity to provide technical basis for full- scale tests
4	One test using 500-Pa yield strength kaolin/water sludge simulant in 1.8-m tank	Determine average wall stress and fluid velocity required to mobilize sludge
5	One test using 1500-Pa yield strength kaolin/water sludge simulant in 1.8-m tank	Determine average wall stress and fluid velocity required to mobilize sludge
6	Three tests using 0.2-mm crushed limestone in 5.7-m tank	Determine average wall stress and fluid velocity required to mix and maintain crushed limestone particles in suspension as a function of slurry depth
7	Water velocity measurements in 5.7-m tank	Determine the effect of solids on fluid velocity to provide a technical basis for full- scale tests
8	One test using 500-Pa yield strength kaolin/water sludge simulant in 5.7-m tank	Determine average wall stress and fluid velocity required to mobilize sludge

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 to predict mixing. Thus, it is often necessary to develop empirical scaling relationships on a case-by-case basis using tests at smaller scales. This section discusses the theoretical framework used to guide the Flygt mixer tests.

3.1 Definition of Terms

Key terms used throughout this document are defined below:

Sludge - The layer of settled solids on the tank floor. Currently, Tank 19 is thought to contain roughly 125 m³ (33 kgal) of sludge, consisting of zeolite, salt crystals, and metal oxyhydroxide particles. This 125 m³ estimate includes the volume of interstitial liquid. Thus, the actual volume of solids (excluding interstitial liquid) is estimated to be 76 m³.

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:

$$F = N_f \rho N^2 D^4 = \frac{\pi}{32} \rho k^2 N^2 D^4 \quad (\text{A.3.1})$$

where N_f = empirical thrust affinity law proportionality constant, dimensionless
 ρ = slurry density, kg/m³
 N = propeller rotation speed, rotations per second
 D = propeller diameter, m
 k = empirical constant related to N_f — value of 1.49 for Model 4640 mixers.

According to this method, the value of τ_0 is independent of scale if the same solids and liquids 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 small-scale 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 This prediction is consistent with the observations made during the small-scale tests. The wetted area of the full-scale SRS tank (25.9-m diameter, 2.1-m waste depth) is approximately 700 m², so the predicted total thrust required to maintain Tank 19 solids in suspension is (20 Pa)(700 m²) = 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 and 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.

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.

^(a)Test 1 conditions are tank diameter = 0.46 m, particle size = 0.7 mm, particle density = 1660 kg/m³, propeller diameter = 7.8 cm, volume fraction solids = 0.015, liquid level = 18 cm and 25 cm. Test 2 conditions are the same except that particle size = 0.25 mm.

3.4 Sludge Mobilization

Sections 3.2 and 3.3 discussed the mixing intensity required to maintain solids in suspension. Of course, in Tank 19 the solids will 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. 1997b). 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, a problem that has been extensively studied by soil scientists.

Mobilization of 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 (τ_c) for erosion. 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 capable of generating 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 of soil erosion in general, but correlations for specific types of soils 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 being tested.

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 that either did not correlate with τ_c or were too difficult to measure accurately enough to be useful. Vane shear strength is measured by inserting a 4-bladed vane vertically into the sludge and measuring the torque required to begin rotating the vane. This is a standard technique in soil science for measuring shear strength (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 requiring drilling test cores and/or loading the sample into a viscometer inflict considerable strain on the sample. Samples that are sensitive to disruption will often give much lower strength measurements after being disturbed. This behavior has been observed in tank wastes at Hanford. 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 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. 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 versus 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 does not provide an adequate measure of the samples' 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 the difference is the disruption that occurs when the sample is loaded into the rheometer prior to measuring the static yield stress. Shear vanes reduce the extent of disruption prior to 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.

3.5 Phase A Tests at ITT Flygt

The key findings of the small-scale Flygt mixer tests, given in the summary section of Powell et al. (1999), 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 (Phase B) and in a full-scale tank at the SRS (Phase C) will be used to determine the applicability of these findings. The key findings from the Phase A tests were as follows:

- The average fluid velocities near the tank floor (1 cm above) required to maintain 20x50-mesh zeolite particles in motion are between 20 and 40 cm/s. Measurements indicated that similar velocities are required to maintain 50x100-mesh zeolite in motion, but the required velocities for the 50x100-mesh zeolite are expected to be somewhat lower than those for the 20x50-mesh zeolite.
- The zeolite suspension test results were consistent with previous particle suspension work (Gladki 1990, 1997) in a 1.5-ft tank using the same Flygt mixers except at higher particle concentrations less mixer thrust was required than is predicted by Gladki (1997). This difference is likely partially due to the fact that Gladki used the somewhat more demanding just-suspended criterion rather than the all-particles-in-motion criterion used for most of our testing.
- Sludge mobilization experiments revealed that, for the mixer configuration tested, the average wall shear stress required to achieve roughly 80% sludge mobilization was approximately 5% of the undisturbed sludge shear strength. 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 liquid volume required to reach the all-particles-in-motion criterion was typically between 150 and 200 W/m³ for the 20x50-mesh zeolite and between about 80 and 140 W/m³ for the 50x100-mesh zeolite. Some uncertainty exists in the basis for these power estimates. The actual power densities may have been up to twice these values. This possibility is under evaluation.
- At the end of the zeolite suspension tests, slurry was pumped from the tank while mixing continued until the propeller blade was exposed. 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.
- Tests using two mixers instead of one indicate that somewhat less total thrust may be required when two mixers are used. More uniform distribution of the mixer thrust is likely the cause.

Based on the findings from the small-scale tests, predictions for the mixing requirements in larger tanks were made. The accuracy of these predictions will be evaluated through larger-scale testing at PNNL and SRS. Some of the predictions that will be tested are as follows:

- The constant-wall-stress method for mixer sizing predicts that the 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 prediction corresponds to a mixer speed of roughly 315 ± 35 rpm.
- The constant-power-per-unit-volume method predicts that the Model 4640 mixer will need to run at 530 ± 50 rpm to achieve the predicted power density of 120 to 210 W/m³, which is the range of power densities required for the 1.5 vol% slurry of 20x50-mesh zeolite in Test 1A.
- Constant-wall-stress scaling predicts that 1.44 ± 0.3 modified 50-hp Model 4660 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 4660 mixers should be used in Tank 19.
- Constant-power-per-unit-volume predicts that 4.5 Model 4680 mixers will be required to achieve 120 W/m³ and 7.8 model 4680 mixers will be required to achieve 210 W/m³. The lack of geometric similarity between the small-scale tests and the planned Tank 19 operation will likely lead to higher power densities required at full-scale than were measured in the small-scale tank.
- 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 50-hp Model 4680 mixers required to mobilize 80% of the sludge with 100-, 1000-, and 2000-Pa shear strength is 0.44, 4.4, and 8.7 mixers, respectively.

Significant differences exist between the predicted numbers of mixers when different scale-up relationships are used. Further, it is unknown whether the average 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 given above should all be viewed as speculative until they are validated or refuted by the larger-scale tests.

Measurements made in the Phase A tests indicated, as mentioned above, that approximately 20 Pa of average wall stress is required to maintain 20x50-mesh zeolite solids in suspension. The wetted area of the Phase B 1.8-m tank is about 8.6 m² when filled to a depth of 1.08 m. Similarly, the wetted area of the Phase B 5.7-m tank is about 58 m² when filled to a depth of 1.8-m, which is the maximum depth likely to be tested. To achieve an average wall stress of 20 Pa in the 1.8-m tank, the supplied mixer thrust must be $(20 \text{ Pa})(8.6 \text{ m}^2) = 172 \text{ N}$. To achieve an average wall stress of 20 Pa in the 5.7-m tank, a total thrust of $(20 \text{ Pa})(58 \text{ m}^2) = 1160 \text{ N}$ is required. Each Model 4640 mixer selected for testing can supply a maximum of 810 N of thrust, so a single Model 4640 mixer will clearly meet the thrust requirements in the 1.8-m tank. The Model 4640 mixer was also attractive for testing in the 1.8-m tank because its 36.7-cm propeller diameter was close to geometrically scaled with respect to the 7.8-cm propeller mixer used for Phase A testing. Three of these mixers were selected for testing in the 5.7-m tank to ensure that sufficient thrust was available to perform sludge mobilization tests similar to those in Phase A where average wall stresses as high as 70 Pa were used. The maximum average wall stress in the 5.7-m tank that can be applied with the liquid at the 1.8-m level is about 42 Pa. With the liquid level decreased to its expected minimum (without mixer vortexing) of 1.0 m, the maximum applied average wall stress is about 56 Pa, which, based on the Phase A sludge mobilization tests, should be sufficient to mobilize a significant portion (if not all) of the 500-Pa sludge simulant.

4.0 Approach for Mid-Scale Tests

Flygt mixers will be installed in the PNNL Fluid Dynamics Laboratory, located in the 336 Building at the Hanford Site in Richland, Washington. The test matrix will include particle mobilization tests with zeolite and crushed limestone and sludge mobilization tests with clay-based sludge. Velocity measurements will also be taken during the mixing tests and during tests with clear water to provide a basis for full-scale tests at SRS. The test set-up, equipment, instrumentation, and simulants are discussed in the following sections.

4.1 Test Setup

Fluid velocity, particle suspension, and sludge mobilization tests will be conducted at two scales to help establish an accurate scaling methodology. One mixer will be placed in the bottom of a 1.8-m diameter tank, which includes a plexiglass (clear) bottom to view particle mobilization. Mixing tests will be conducted using a mixture of water with zeolite, crushed limestone, or kaolin sludge. Three mixers will also be placed in the bottom of a 5.7-m steel tank. This tank is a quarter-scale replica of a Hanford double-shell tank, and has been denoted the “quarter-scale tank.” Mixing tests will be conducted with a mixture of water and crushed limestone or kaolin sludge. Draw-down tests will be conducted at the end of all test series to observe the effect of low liquid level on mixing performance. An overview of the test setup in the 5.7-m tank is shown in Figure 4.1. Details of the test setup are included in the following section.

4.2 Test Equipment and Instrumentation

The following sections provide a description of the test equipment and instrumentation.

4.2.1 Flygt Mixer Model 4640

Three Model 4640 direct-drive mixers will be provided for the test program. At full load, the mixer motors provide 4 hp at the shaft and generate 810 N (182 lb) of thrust. The mixer propeller-blades are 37 cm in diameter and have a blade angle of 11 degrees. The blades are mounted inside a 52-cm outside diameter jet ring, which directs the flow of liquid through the blades. Each mixer will be mounted to a floor-mounted mixer stand consisting of angle brackets and a steel plate. The weight of the steel plate required to generate sufficient frictional force to resist the thrust of the mixers has been calculated to be 4305 N (968 lb). The steel pad dimensions chosen to achieve this weight are 61 cm wide, 122 cm long, and 7.6 cm thick (24 by 48 by 3 in.). Electric power will be supplied to each mixer through power cables. The cables will be connected to guide wires that will run from the tank top to the mixer housing. The cables will be inspected for signs of abrasion after tests are complete. To allow testing at a range of mixer speeds (from 0-860 rpm), the mixers will be controlled by variable-frequency drives.

The mixer configuration for tests in the quarter-scale tank is shown in Figure 4.2. The configuration corresponds to the expected deployment orientation in Tank 19 and is based on riser access limitations and the recommendation of ITT Flygt. Two of the mixers are positioned 180 degrees apart and are directed 30 degrees away from the diagonal line between them. The third mixer corresponds to

Figure 4.1. Flygt Mixers and PITBULL™ Pump Installed in the Quarter-Scale Tank

Figure 4.2. Flygt Mixers Orientation in the Quarter-Scale Tank

the southwest riser location of Tank 19 and is directed 10 degrees from a radial line. For tests in the 1.8-m diameter tank, one mixer will be mounted near the side of the tank, and the flow will be directed as shown in Figure 4.3. This is exactly the scaled location used during the Phase A zeolite suspension and fluid velocity tests.

4.2.2 Equipment

- **Quarter-Scale Tank:** This cylindrical tank is 5.72 m (18.75 ft) in diameter, 59 m³ (15625 gal), and constructed of stainless steel. The top of the tank can be enclosed by a tank dome. The dome contains access ports for installing test equipment. During the testing program, three-quarters of the tank dome will remain. An equipment bridge spans the tank-top, while a viewing platform surrounds one-quarter of the tank circumference.
- **Small Clear-Bottom Tank:** A small steel tank will be used for the zeolite and crushed limestone mixing tests. The tank is 183 cm in diameter and 137-cm deep. The tank bottom is constructed of Plexiglass to allow viewing of the particles during mixing.
- **Slurry Receipt Tank:** A large cone-bottom tank is available to receive slurry during sludge mobilization tests.

Figure 4.3. Flygt Mixer Orientation in Small Tank

- **PITBULL™ Pump:** A PITBULL™ pump will be used to transfer slurry from the quarter-scale tank to the slurry receipt tank at the end of the sludge mobilization tests. After the interior of the quarter-scale tank is inspected for unmobilized sludge, the pump will also be used to transfer slurry back into the quarter-scale tank. The pump is composed of a pump chamber, air lines, and a control panel. The pump uses two distinct strokes, fill and discharge, to perform its pumping action. During the fill stroke, a vacuum is applied to the pump chamber that draws liquid into the pump. When liquid reaches a sensing tube, the chamber is pressurized with compressed air to discharge the liquid out of the pump chamber. Check-valves are used at the pump chamber inlet and exit to control the direction of flow. A vacuum generator at the control panel generates a vacuum in the air line using compressed air. The chamber of this custom pump is cylindrical in shape to facilitate insertion through a tank riser and is 35.6 cm (14 in.) in diameter and 124-cm (49-in.) tall. The inlet to the pump is through a 12.7-cm (5-in.) check-valve located on the bottom of the pump. The pump is designed to pump sludge with a specific gravity of 1.2 to 1.3 at a rate of 378 lpm (100 gpm) with a 30.5-m (100-ft) equivalent discharge head. To eliminate flow obstruction, the pump will be removed from the tank during mixing. During draw-down, the pump will be placed in a low-velocity area to disrupt flow as little as possible.
- **Sump Pump:** A small sump pump will be used to pump slurry from the 1.8-m tank. The capacity of the pump is approximately 95 lpm (25 gpm)
- **Hoses:** A 5.08-cm inside diameter hose will be used to connect the PITBULL™ pump discharge to the slurry receipt tank or quarter-scale tank, depending on the mode of operation.
- **Lights:** High-intensity lights will be installed above both mixing tanks and below the small tank to enhance visualization of mixing.

4.2.3 Instrumentation

The instrumentation is briefly described below.

Slurry and Sludge Density Measurement: During the sludge mobilization tests, 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 digital 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 during the zeolite mobilization tests because the rapid settling velocities of the zeolite particles will likely result in a vertical concentration gradient within the tank. Visual indication through the clear-bottom tank will be used to determine the degree of mobilization. A similar approach will be used for the crushed limestone mixing tests. In addition to the visual observations, slurry density measurements will be made.

Liquid density will provide a relative measure of the level of mixing and also the gradation of solids in the liquid. Liquid density will be monitored during mixing tests with zeolite, crushed limestone, and sludge. The three separate density sensors described below will be used to monitor slurry density.

XL4 Density Meter from HR Wallingford: The XL4 Density Meter is based on an industrial oscillating tube probe that has been ruggedised for field use. The sensor consists of a short, completely sealed, tubular element which is made to resonate at its natural frequency using small, internally-mounted piezoelectric devices connected to a maintaining amplifier. The resonant frequency of the tubular element that depends on the mass of the fluid it displaces and this in turn is dependent on the fluid density. By measuring this frequency, the fluid density can be determined. The effects of temperature on the vibrational characteristics of the instrument are compensated for by the integral platinum resistance thermometer. The unit has a measuring range of 0 to 3 g/cm³ with an accuracy of ± 0.001 g/cm³.

Krohne Mass Flow Meter: This sensor is actually a single straight-tube, Coriolis-type mass flow meter that is also capable of measuring density. To measure density during the tests, a hose will be inserted into the slurry at an area of interest, and slurry will be pumped through the 3.81-cm diameter tube at low flow (less than 20 lpm). Slurry sampled in this way will be recycled to the tank.

Statham MD3018 Mud Density Transmitter s/nR6600: PNNL has a density meter that determines density by measuring the pressure differential between two points a fixed distance apart. The probe may be inaccurate in areas of high flow so may not be used near the mixers but will provide another source of density data.

Density measurements will be taken during all tests except the water series. During particle suspension tests, the density of the test slurry will be measured at each discrete motor speed using the Wallingford, Krohne, and Statham sensors. Density will be measured at mid-depth at three planar locations representative of high velocity, average velocity, and low velocity. During sludge mobilization tests, the density of the test slurry will be measured at each discrete motor speed every five minutes using all three density sensors. Density will be measured at mid-depth at three planar locations representative of high velocity, average velocity, and low velocity.

For conditions representing a fully mixed fluid, these measurements will be correlated with a density determined using a 100-mL calibrated density cup pycnometer. The sample will be taken from the average velocity location.

Slurry Temperature Measurement: Slurry temperature will be periodically measured during the tests using a hand-held thermocouple so that accurate values for water density and viscosity can be used when analyzing the test data.

Simulant Characterization: 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.

Characterization of the sludge simulant will include measurement of weight percent solids, vane shear strength, and yield stress. Sludge simulant weight percent solids will be measured by the observed

weight loss on drying at 150°C (or higher) for at least 24 hours. Vane shear strength will be measured using a Haake M5 Rotovisco viscometer with a shear vane attachment. Procedures for shear strength measurement are described in Powell et al. (1997a).

Fluid Velocity Measurements: Fluid velocities will be measured with a Model 511 Marsh-McBirney electromagnetic current meter. The sensor procured for this test program will be calibrated for two ranges: 0 to 61 cm/sec and 61 to 914 cm/sec to increase the sensors' accuracy at low and high velocity levels. The sensor probe is 3.81 cm in diameter; a stand-off tab maintains a minimum stand-off distance of at least 5.08 cm from the tank bottom to the sensor centerline. Thus, velocity can be measured no closer than 5.08 cm to the tank wall. The sensor measures fluid velocity in two directions and provides analog voltage output. During testing, the alignment of the probe will be recorded to determine direction of velocity. The output of the sensor will be sampled by the data acquisition system. The sensor data output rate is adjustable from 0.2 to 5 seconds, and the data acquisition system will sample the device at twice the 511 update rate. The sensor includes an 18.3-meter (60-ft) data cable. To insert the unit into the small tank, the sensor will be mounted to a unistrut fixture attached to the top of the tank. For the quarter-scale tests, the sensor will be mounted to a long pole and deployed through openings in the tank dome. The locations for measuring velocity in the quarter-scale tank will be limited by tank access provided by the large opening and the risers.

Data Acquisition System (DAS): The DAS will consist of a laptop computer running Strawberry Tree Work Bench PC DOS[®], version 2.4.0. All of the on-line measurements made during the tests will be recorded by the DAS at a frequency of 10 Hz. The analog outputs will be recorded to the data file without any time averaging. The raw data will be averaged and converted to engineering units for real-time display by the DAS system.

Monitoring Motor Parameters: The mixer variable frequency drives include the following analog gauges speed meter, speed potentiometer, voltage meter, and ammeter. These measurements will be monitored during the tests and manually recorded in the log book.

Slurry Tank Load Cells: The slurry receipt tank is mounted to three load cells, which will be used to determine the weight of material transferred during draw-down tests.

MicroMotion Coriolis Mass Flow Measurement System: The systems consists of a Coriolis sensor and an accompanying transmitter. The sensor will be MicroMotion Model DS300S15SU, and the transmitter will be Model RFT9739. The sensor/transmitter system has a minimum flow range of 0 to 350 lb/min and a maximum flow range of 0 to 7000 lb/min. The zero stability of the system is 0.70 lb/min. The accuracy of measurements for flow rate and density are $\pm 0.2\%$ of flow rate, $\pm$ the zero stability, and $\pm 0.001 \text{ g/cm}^3$, respectively. The Coriolis sensor outputs two frequency signals to the transmitter. The transmitter calculates the mass flow rate and density from the sensor output signals and provides two, 4-20 mA signals to the DAS. The signal averaging of the sensor will be set at one second. The density output will allow the density of the slurry to be monitored during draw-down tests in the quarter-scale tank with the PITBULL[™] pump.

4.3 Simulant Development

IE95 zeolite in the 20x50-mesh size range is being used for many of the particle suspension tests in Phase B. This material is appropriate for testing because IE95 zeolite in this size range constitutes a

significant fraction of the solids inside Tank 19 at SRS. The IE95 zeolite was tested as part of the Phase A test program. See Powell et al. (1999) for a further description of the basis for selecting IE95 zeolite and the zeolite concentrations for testing.

Crushed limestone (calcium carbonate with tradename Marble 30 from Specialty Minerals, Inc.) with a 50% passing size of approximately 0.2-mm was selected for testing as well. The density of this material is approximately 2.7 g/mL. Crushed limestone in this size range is expected to have a settling velocity nearly identical to that of the 20x50-mesh IE95 zeolite, so the mixing intensity required to maintain the crushed limestone in suspension will be similar to that required for the IE95 zeolite. An alternative to zeolite is needed to support the particle suspension testing in the 5.7-m diameter tank. Testing with zeolite in that tank would be prohibitively expensive at the solids concentration levels tested in Phase A and in the 1.8-m tank for Phase B. Both the IE95 zeolite and the 0.2-mm crushed limestone will be tested in the 1.8-m tank using a single Model 4640 mixer. These tests will allow a direct comparison of the relative mixing intensities required for these two materials. Only crushed limestone will be used for tests in the 5.7-m tank, but the comparison tests in the 1.8-m tank will allow an assessment to be made of the mixing intensity expected to be necessary to mix 20x50-mesh zeolite in the 5.7-m tank.

Sludge mobilization tests in the 1.8-m tank will use mixtures of EPK Pulverized kaolin clay from Feldspar Corporation (Edgar, Florida) and water. The mixtures are formulated to give shear strengths (and yield stresses) of about 500 Pa and 1500 Pa. Identical simulants will be tested in the small-scale tank used previously for Phase A testing. The 500-Pa kaolin simulant will be tested in the 5.7-m tank as well. The rationale for selecting sludge strengths in this range is based on the limited strength data available for sludge in tanks at SRS, ORNL, and Hanford. No direct measurements of the undisturbed strength of the Tank 19 sludge have been made, but visual indications from a sample-handling videotape imply that the sludge strength is in the >500-Pa range. The goal of the present testing, however, is not necessarily to mimic the Tank 19 sludge strength but rather to develop a correlation between sludge strength and mixer performance that can be used to predict the performance of Flygt mixers for sludge mobilization applications wherever reliable estimates for sludge strength can be obtained. For further discussion of the basis for selecting kaolin clay as a sludge simulant see Powell et al. (1997, 1999).

4.4 Test Procedure

The key elements of each test series planned for the Phase B tests at PNNL are described in this section. The planned tests are summarized in Table 4.1 below.

Table 4.1. Test Parameters and Key Data Expected

Test Phase	Test Focus	Test Parameters	Key Data Expected
Mixing Tests in 1.8-m Tank	Particle Suspension and Draw-Down (Tests 1, 2, 3)	<ul style="list-style-type: none"> ➤ One mixer - position and orientation as small-scale tests 1A, 1B, and 1C ➤ Motor speed ➤ 2 Slurry depths ➤ Volume fraction 0.015, 0.0108 ➤ Water only ➤ Water and 20x50-mesh IE95 zeolite ➤ Water and crushed limestone (0.2 mm) 	<ul style="list-style-type: none"> ➤ Determine mixer rpm required to suspend particles ➤ Visual indication of particle movement ➤ Velocity profile ➤ Minimum velocity required to suspend particles ➤ Fraction of material that can be pumped out
	Sludge Mobilization and Draw-Down (Tests 4, 5)	<ul style="list-style-type: none"> ➤ One mixer - position and orientation as small-scale tests 1A, 1B, and 1C ➤ Motor speed ➤ 1 Slurry depth ➤ 1 Sludge depth - 8 cm ➤ Kaolin/water sludge 	<ul style="list-style-type: none"> ➤ Percent mobilized versus mixer speed ➤ Slurry density ➤ Percent mobilized at full speed ➤ Fraction of material that can be pumped
Mixing Tests in Quarter-Scale Tank	Particle Suspension and Draw-Down (Tests 6, 7)	<ul style="list-style-type: none"> ➤ One, two, and three mixers ➤ Motor speed ➤ Mixer orientation (if deemed necessary) ➤ 3 Slurry depths: 0.762, 1.067, and 1.372 m ➤ Volume fraction 0.015 ➤ Water only ➤ Water and crushed limestone (0.2 mm) 	<ul style="list-style-type: none"> ➤ Determine mixer RPM required to suspend particles ➤ Slurry density ➤ Velocity profile ➤ Minimum velocity required to suspend particles ➤ Fraction of material that can be pumped during mixing
	Sludge Mobilization and Draw-Down (Test 8)	<ul style="list-style-type: none"> ➤ Three mixers - orientation provided by Flygt ➤ Motor speed ➤ Mixer orientation (if deemed necessary) ➤ 1 Slurry depth ➤ 1 Sludge depth - 8 cm ➤ Kaolin/water sludge 	<ul style="list-style-type: none"> ➤ Percent mobilized versus mixer speed ➤ Slurry density ➤ Percent mobilized at full speed ➤ Fraction of material that can be pumped during mixing

4.4.1 Test 1: Zeolite Suspension 0.3 to 0.85 mm (1.8-m Tank)

With a single Flygt mixer positioned within the 1.8-m diameter tank, 36.1 kg of Linde AW-500 zeolite (20x50-mesh) will be spread evenly on the tank floor. Water will be added to the tank in sufficient quantity to achieve a liquid depth 70.6 ± 1 cm above the tank floor. The quantity of zeolite will result in a 0.015 volume fraction of particles in the fully mixed slurry. 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 be activated and its speed slowly increased until all zeolite particles are in motion as observed through the clear tank bottom. The mixer speed will be increased slowly to allow time for erosion of the settled solids. As the mixer speed is increased, the extent of solids suspension will be observed and, if possible, photographed through the tank bottom. For each discreet motor speed, slurry density will be measured at mid-depth at three planar locations representative of high, medium, and low velocity. Density measurements will be made with the Wallingford, Krohne, and Statham sensors. The mixer speed required to suspend all the solids will be recorded, as well as the location of particles that were suspended last. At this motor speed, the slurry temperature will be measured and the slurry density will be measured with the three on-line sensors at the three locations described above. Density will also be measured with the pycnometer using a sample taken from the average velocity location. The velocity field of the fluid will also be measured, as described below.

Fluid velocity will be measured to compare it with data collected during small-scale Phase A tests and to support fluid computational modeling. Velocities will be measured with a Model 511 Marsh-McBirney electromagnetic current meter. During testing, the alignment of the probe will be recorded to determine the velocity direction. The output of the sensor will be sampled by the data acquisition system. The sensor data output rate will be set to 0.2 sec, and the data acquisition system will sample the device at twice this rate (0.1 sec). The sensor will be mounted to a unistrut fixture attached to the top of the tank. The locations that will be sampled include the points corresponding to the probe locations used in Phase A plus additional points, as depicted in Figure 4.4. The velocity should also be measured at the location of zeolite that was mobilized last. The probe height for each measurement will be 5.08 cm with one exception: the height of measurement location E will be the same as the height of the mixer-blade axis, which is consistent with the measurements taken during Phase A.

This test should be repeated using a circumferential orientation of the mixer per recommendations from Flygt personnel (Test 1A). After this test is completed, the mixer should be returned to the original position.

In addition to measuring motor speed and fluid properties at the just-suspended condition, slurry temperature, and fluid velocities will be measured at two distinct motor speeds for the radial mixer orientation only: 430 rpm (50% speed) and 860 rpm (100% speed). Prior to tests at these motor speeds, the mixer will be stopped and the zeolite will be redistributed evenly on the tank floor.

This procedure will be repeated for a higher liquid level in the tank. Additional water will be added to the tank to make the liquid level 103.8 cm and then the testing described above repeated. Then additional zeolite will be added to the tank and water removed as necessary to bring the water level to 103.8 cm. The tests will be repeated once again. The simulant compositions to be used for Test 1 are given in Table 4.2 below.

Figure 4.4. Velocity Measurement Locations in Small Tank

Table 4.2. Test 1 Simulant Compositions

Test No.	20x50 Zeolite (kg)	Water (kg)	Solids (wt%)	Volume Fraction (dimensionless)	Slurry Depth (cm)
1A	36.1	1823	1.94	0.015	70.6
1B	36.1	2693	1.32	0.0108	103.8
1C	50.1	2680	1.94	0.015	103.8

At the conclusion of Test 1C, water and zeolite will be pumped from the tank while the mixer is operating at the speed required to maintain the solids in suspension. The mixer will be turned off when 1) significant vortexing occurs or 2) when the liquid level falls to the point where the mixer blade is about to become exposed, whichever occurs first. Pumping will continue until slurry is no longer being withdrawn from the tank. The assessment of residual and transferred material will be based on the amount of zeolite and water left in the source tank.

After the initial pump-down is completed, clean water will be introduced into the tank to the same level as that used for Test 1C. The remaining zeolite will be redistributed to form a uniform layer. The simultaneous mixing and draw-down test will then be repeated. The assessment of residual and transferred material will be based on the amount of zeolite and water left in the source tank.

4.4.2 Test 2: Crushed Limestone Suspension 0.2 mm (1.8-m Tank)

With a single Flygt mixer positioned within the 1.8-m diameter tank, 76 kg of crushed limestone will be spread evenly on the tank floor. Water will be added to the tank in sufficient quantity to achieve a liquid depth 70.6 ± 1 cm above the tank floor. The quantity of crushed limestone will result in a 0.015 volume fraction of particles in the fully mixed slurry. If the crushed limestone is disturbed while adding water, efforts will be made to make the crushed limestone layer smooth and uniform.

The Flygt mixer will be activated and its speed slowly increased until all crushed limestone particles are in motion as observed through the clear tank bottom. The mixer speed will be increased slowly to allow time for the settled solids to erode. As the mixer speed is increased, the extent of solids suspension will be observed and, if possible, photographed through the tank bottom. For each discreet motor speed, slurry density will be measured at mid-depth at three planar locations representative of high, medium, and low velocity. Density measurements will be made with the Wallingford, Krohne, and Statham sensors. The mixer speed required to suspend all the solids will be recorded, as well as the location of the particles that were suspended last. At this motor speed, the slurry temperature and the slurry density will be measured with the three on-line sensors at the three locations described above. Density will also be measured with the pycnometer using a sample taken from the average velocity location. The velocity field of the fluid will also be measured as described in Section 4.4.1.

In addition to measuring motor speed and fluid properties at the just-suspended condition, slurry temperature and fluid velocities will be measured at two distinct motor speeds: 430 rpm (50% speed) and

860 rpm (100% speed). Prior to tests at these motor speeds, the mixer will be stopped, and the crushed limestone will be redistributed evenly on the tank floor.

This procedure will be repeated for a higher liquid level in the tank. Water will be added to the tank to make the liquid level 103.8 cm and then the test repeated. Additional crushed limestone will then be added and water removed as necessary so that the crushed limestone volume fraction is once again 0.015 at the 103.8-cm liquid level. This solids concentration will then be tested. Finally, additional crushed limestone will be added to the tank and water removed as necessary so that a test can be performed at the 0.06 volume fraction crushed limestone. The simulant compositions to be used for Test 2 are given in Table 4.3.

Table 4.3. Test 2 Simulant Compositions

Test No.	0.2-mm Crushed Limestone (kg)	Water (kg)	Solids (wt%)	Volume Fraction (dimensionless)	Slurry Depth (cm)
2A	76	1823	4.0	0.015	70.6
2B	76	2693	2.7	0.0108	103.8
2C	111.7	2680	4.0	0.015	103.8
2D	447	2558	14.9	0.060	103.8

Test 2D will be conducted at two mixer orientations: predominately radial (baseline) and circumferential. At the conclusion of Test 2D, the mixer will be returned to the baseline orientation.

At the conclusion of Test 2D, water and crushed limestone will be pumped from the tank while the mixer is operating at the speed required to maintain the solids in suspension. The mixer will be turned off when 1) significant vortexing occurs or 2) when the liquid level falls to the point where the mixer blade is about to become exposed, whichever occurs first. Pumping will continue until slurry is no longer being withdrawn from the tank. The assessment of residual and transferred material will be based on the amount of crushed limestone and water left in the source tank.

4.4.3 Test 3: Water Velocity Measurements (1.8-m Tank)

Following the tests with crushed limestone and zeolite, the tank will be emptied, cleaned, and filled with water. Velocity measurements and the slurry temperature will be taken at four motor speeds:

Mixer orientation

Speed

Baseline	430 rpm (50% speed)
Baseline	Speed required to suspend zeolite
Baseline	Speed required to suspend 0.2-mm crushed limestone
Baseline	860 rpm (100% speed)
Circumferential	860 rpm (100% speed)

For the last test, the mixer will be reoriented to discharge in a tangential manner to determine the effect of orientation. This series of the procedure will be repeated for water at two levels like the zeolite and crushed limestone tests. Thus, 10 sets of measurements will be taken. The location of the measurement will be the same as that used in the crushed limestone and zeolite tests.

4.4.4 Test 4: 500-Pa Yield Strength Sludge Mobilization (1.8-m Tank)

With a single Flygt mixer positioned within the 1.8-m diameter tank, an 8-cm-thick layer of 500-Pa shear strength, 500-Pa yield stress sludge simulant will be spread evenly on the tank floor. Three sludge samples will be taken at random locations from the simulant bed and tested for weight percent solids, vane shear strength, and yield stress. Water will be added to the tank in sufficient quantity to achieve a liquid depth 70.6 ± 1 cm above the tank floor. The water should be added slowly so the sludge will not be disturbed. Mixer speed will then be gradually increased until significant sludge mobilization is noted. The mixer speed will be kept constant and the slurry density will be measured every 5 minutes until no significant change is noted in the slurry density. Slurry density will be measured at mid-depth at three planar locations representative of high, medium, and low velocity. Density measurements will be made with the Wallingford, Krohne, and Statham sensors. The mixer speed will then be increased 25 rpm and the density measurements will be repeated. This process will be repeated until a) slurry density corresponds to a fully mixed tank or b) the maximum mixer speed is reached. At this motor speed, the slurry temperature and the slurry density will be measured with the three on-line sensors as at the three locations described above. Density will also be measured with the pycnometer using a sample taken from the average velocity location.

At the conclusion of Test 4, water and kaolin will be pumped from the tank while the mixer is operating at the speed required to mobilize the sludge. The mixer will be turned off when 1) significant vortexing occurs or 2) when the liquid level falls to the point where the mixer blade is about to become exposed, whichever occurs first. Pumping will continue until slurry is no longer being withdrawn from the tank. The assessment of residual and transferred material will be based on the amount of sludge and water left in the source tank.

4.4.5 Test 5: 1500-Pa Yield Strength Sludge Mobilization (1.8-m Tank)

With a single Flygt mixer positioned within the 1.8-m diameter tank, an 8-cm-thick layer of 1500-Pa shear strength, 1500-Pa yield stress sludge simulant will be spread evenly on the tank floor. Three sludge samples will be taken at random locations from the simulant bed and tested for weight percent solids, vane shear strength, and yield stress. Water will be added to the tank in sufficient quantity to achieve a liquid depth 70.6 ± 1 cm above the tank floor. The water should be added slowly so the sludge will not be disturbed. Mixer speed will then be gradually increased until significant sludge mobilization is noted. The mixer speed will be kept constant and the slurry density will be measured every 5 minutes until no significant change is noted in the slurry density. Slurry density will be measured at mid-depth at three planar locations representative of high, medium, and low velocity. Density measurements will be made with the Wallingford, Krohne, and Statham sensors. The mixer speed will then be increased 25 rpm and the density measurements repeated. This process will be repeated until a) slurry density corresponds to a fully mixed tank or b) the maximum mixer speed is reached. At this motor speed, the slurry temperature and the slurry density will be measured with the three on-line sensors at the three locations described above. Density will also be measured with the pycnometer using a sample taken from the average velocity location.

At the conclusion of Test 5, water and kaolin will be pumped from the tank while the mixer is operating at the speed required to mobilize the sludge. The mixer will be turned off when 1) significant vortexing occurs or 2) when the liquid level falls to the point where the mixer blade is about to become exposed, whichever occurs first. Pumping will continue until slurry is no longer being withdrawn from the tank. The assessment of residual and transferred material will be based on the amount of sludge and water left in the source tank.

4.4.6 Test 6: Crushed Limestone Suspension 0.2 mm (Quarter-Scale Tank)

Three Flygt Model 4640 mixers will be used for the tests in the quarter-scale tank. The initial position and orientation of the mixers, shown in Figure 4.2, was chosen based on prior tests and Flygt staff expertise. Any modification to the position or orientation of the mixers will be noted in the log book.

After the mixers are installed in the tank, 1055 kg of crushed limestone will be spread evenly on the tank floor. Water will be added to the tank in sufficient quantity to achieve a liquid depth 100 ± 2 cm above the tank floor. The quantity of crushed limestone will result in a 0.015 volume fraction of particles in the fully mixed slurry. If the crushed limestone is disturbed while adding water, efforts will be made to make the zeolite layer smooth and uniform.

The speed of the mixers will be increased simultaneously until the crushed limestone particles are in motion (just-in-motion criteria). Because this tank does not have a clear bottom, visual methods cannot be used to detect particle motion. Instead, density probes and sampling will be used to determine the average slurry density. The mixer speed will be increased slowly to allow time for the settled solids to erode. As the mixer speed is increased, the extent of solids suspension will be observed. For each discrete motor speed, slurry density will be measured at mid-depth at three planar locations representative of high, medium, and low velocity. Density measurements will be made with the Wallingford, Krohne, and Satham sensors. The mixer speed required to suspend all the solids will be recorded, as well as the location of particles that were last to become suspended. At this motor speed, the slurry temperature and the slurry density will be measured with the three on-line sensors at the three locations described above. Density will also be measured with the pycnometer using a sample taken from the average velocity location. The velocity field of the fluid will also be measured as described below.

Fluid velocity will be measured to compare it with data collected during small-scale Phase A tests and to support fluid computational modeling. Velocities will be measured with a Model 511 Marsh-McBirney electromagnetic current meter. During testing, the alignment of the probe will be recorded to determine the velocity direction. The output of the sensor will be sampled by the data acquisition system. The sensor data output rate will be set to 0.2 sec, and the data acquisition system will sample the device at twice this rate (0.1 sec). The sensor will be mounted to a unistrut fixture attached to the top of the tank. The tank dome will limit the locations that can be measured to those that are accessible through the large 90 degree opening and the four cylindrical openings. The mixer orientation within the tank should consider tank access limitations. The locations that will be sampled are shown in Figure 4.5. The velocity should also be measured at the location of crushed limestone that was mobilized last, if this location can be determined. The probe height for each measurement will be 5.08 cm.

Figure 4.5. Velocity Measurement Locations for the Quarter-Scale Tank

In addition to measuring motor speed and fluid properties at the just-suspended condition, slurry temperature and fluid velocities will be measured at two distinct motor speeds: 430 rpm (50% speed) and 860 rpm (100% speed). Prior to tests at these motor speeds, the mixer will be stopped, and the crushed limestone will be redistributed evenly on the tank floor (if practical).

If the mixer orientation is not ideal, the water will be pumped out of the tank and the mixers will be repositioned. The water will then be pumped back into the tank and the test repeated.

This procedure will be repeated for two higher liquid levels in the tank as shown in Table 4.4. Crushed limestone concentration will remain constant at 4.0 wt% (1.5 vol%) during these tests. The highest liquid level, 2.2 m, corresponds to the scaled height of Tests 1A and 2A in both Phase A tests in the 0.46-m tank and Phase B tests in the 1.8-m tank. The lowest liquid level, 1.0 m, is expected to be the lowest liquid level in which the mixers will operate without excessive vortexing.

At the conclusion of Test 6, water and crushed limestone will be pumped from the tank using the PITBULL™ while the mixer is operating at the speed required to mobilize the sludge. The PITBULL™ will be placed in a low-velocity zone within the tank to disrupt flow as little as possible. The mixer will be turned off when 1) significant vortexing occurs or 2) when the liquid level falls to the point where the mixer blade is about to become exposed, whichever occurs first. Pumping will continue until slurry is no longer being withdrawn from the tank. The assessment of residual and transferred material will be based on the amount of crushed limestone and water left in the source tank and the weight of material transferred to the slurry receipt tank.

Table 4.4. Test 6 Simulant Compositions

Test No.	0.2-mm Crushed Limestone (kg)	Water (kg)	Solids (wt%)	Volume Fraction (dimensionless)	Slurry Depth (m)
6A	1055	25,200	4.0	0.015	1.0
6B	1690	40,300	4.0	0.015	1.6
6C	2320	55,400	4.0	0.015	2.2

4.4.7 Test 7: Water Velocity Measurements (Quarter-Scale Tank)

Following tests with crushed limestone, the tank will be emptied, cleaned, and filled with water. Velocity measurements and the slurry temperature will be taken at four motor speeds:

<u>Mixer Orientation</u>	<u>Speed</u>
One radially oriented mixer	100% speed
Two tangential mixers	100% speed
Three mixers	430 rpm (50% speed)
Three mixers	Speed required to suspend 0.2-mm crushed limestone
Three mixers	860 rpm (100% speed)

This series of the procedure will be repeated for water at two levels like the crushed limestone tests. The location of the measurement will be the same as used in the crushed limestone and zeolite tests.

4.4.8 Test 8: 500-Pa Yield Strength Sludge Mobilization (Quarter-Scale Tank)

With three Flygt mixers positioned within the 5.7-m diameter tank, an 8-cm-thick layer of 500-Pa yield stress, 500-Pa shear strength sludge simulant will be spread evenly on the tank floor. Five sludge samples will be taken at random locations from the simulant bed and tested for weight percent solids, vane shear strength, and yield stress. Water will be added to the tank in sufficient quantity to achieve a liquid depth 220 ± 5 cm above the tank floor. The water should be added slowly so the sludge will not be disturbed. The speed of the three mixers will then be gradually increased until significant sludge mobilization is noted. The mixer speed will be kept constant and the slurry density will be measured every 5 minutes until no significant change is noted in the slurry density. Slurry density will be measured at mid-depth at three planar locations representative of high, medium, and low velocity. Density measurements will be made with the Wallingford, Krohne, and Statham sensors. The mixer speed will then be increased 25 rpm and the density measurements repeated. This process will be repeated until a) slurry density corresponds to a fully mixed tank or b) the maximum mixer speed is reached. At this motor speed, the slurry temperature will be measured and the slurry density will be measured with the three on-line sensors at the three locations described above. Density will also be measured with the pycnometer using a sample taken from the average velocity location. If all the sludge is not mobilized at full speed, the slurry will be removed using the PITBULL™ pump and the remaining sludge will be photographed. The depth and area of the remaining sludge will be measured to the extent possible to determine the fraction of sludge not mobilized.

At the conclusion of Test 8, water and kaolin will be pumped from the tank using the PITBULL™ while the mixer is operating at the speed required to mobilize the sludge. The PITBULL™ will be placed in a low-velocity zone within the tank to disrupt flow as little as possible. The mixer will be turned off when 1) significant vortexing occurs or 2) when the liquid level falls to the point where the mixer blade is about to become exposed, whichever occurs first. Pumping will continue until slurry is no longer being withdrawn from the tank. The assessment of residual and transferred material will be based on the amount of kaolin and water left in the source tank and the weight of material transferred to the slurry receipt tank.

5.0 Data Evaluation

All data records, calculations, and analyses reported from this test will be documented in a sufficient manner to be traceable from the primary data and the methods and equipment used, through the assumptions and/or interpretations made, to the corresponding reported results. This section outlines planned analyses and calculations, expected results, and a preferred system of units for reported values.

5.1 Planned Analyses

The first step in the data evaluation process will be to convert the raw data to engineering units for graphical display. Where applicable, instantaneous data and average results will be analyzed and compared. Analyses of test data will be conducted to obtain the following derived results:

- Mixer thrust
- Mixer power
- Average wall stress
- Sludge density versus average wall stress
- Zeolite particle size distribution
- Statistical velocity quantities (max, mean, min, RMS)
- Fluid velocity vectorized plots
- Density versus time and mixer speed(s) during tests with crushed limestone, zeolite, and sludge as measured by density meters and cross-checked with 100-mL calibrated density cup pycnometer.

5.2 Preferred Units

SI units will be adopted as the standard system of units. Many process control sensors are calibrated in terms of English units. The sensor ranges will be converted to an equivalent SI representation. Table 5.1 provides the preferred units for all anticipated reported values.

5.3 Hand Calculations

When calculations, like those done using a spreadsheet computer program, are used to evaluate or calculate new data, the calculation is prepared in accordance with PNL-MA-70, Good Practices Standard - 4.0 Work Performance, Section 4.5, "Hand Calculations."

Table 5.1. Preferred Units for Reported Values

Measurement	Preferred Unit
High Pressure	MPa
Low Pressure (water, air)	kPa
Volumetric Flow Rate	liters/min
Mass Flow Rate	kg/s
Particle Size	mm
Pipe Diameter	mm
Pipe Length	m
Stand-Off Distance	mm
Density	kg/m ³
Air Velocity	m/s
Mass	kg
Force	newton
Shear Strength	MPa

6.0 Project Record System

6.1 Software and Control

Most of the data will be collected with the computer data acquisition equipment and saved to hard disk. Portions of this data will be converted to EXCEL format for data manipulation and display. Other data, such as current atmospheric data, will be taken manually and recorded in the laboratory record book.

A test summary database will be maintained to capture the essential aspects of each test. This database will, as a minimum, record the following information:

- Date
- Start Time
- End Time
- Test Description (including test parameters if part of a test matrix)
- Reference Test Instruction of Procedure
- Laboratory Record Book Page (starting)
- Excel Data File Name(s)
- Excel Data File Archive Name and Location
- Raw Data File Name(s)
- Raw Data File Archive Name and Location
- Notes.

Data files will be double-archived to optical disk. Copies of the archive disks will be stored in remote locations. Test data archives will be included in the project Record Inventory and Disposition Schedule (RIDS) as set forth in PNL-MA-68 Records Management and Document Control.

6.2 Use of Laboratory Record Books

All laboratory data, general observations, and details of the activities performed per this test plan will be documented in a Laboratory Record Book (LRB). Laboratory Record Books may also be used to document other research activities. When LRBs are used, the LRB procedures must be applied as set forth in PNL-MA-68 Records Management and Document Control, Section 6.0, "Research Project Records System" and PNL-MA-70, Part 2, Good Practices Standard, Section 5.0, "Information and Records Management."

6.3 Calibration Records

Calibration records of all instruments used to generate reported data will be maintained in the project files.

7.0 Facility and Safety Considerations

The testing program outlined in this document will be conducted in the Fluid Dynamics Laboratory located at the 336 Building at the Hanford Site. The following sections provide an overview of the 336 Building systems that will be used in the tests and a review of safety and personnel training considerations.

7.1 Electrical Supply

The mixers will be supplied with power from individual variable-frequency drives, which will be connected to facility power. The drives require 460 volt, three-phase power and include an internal breaker set to 30 amps. Power cables will be supplied with the mixers to connect the mixers to the variable-frequency drives.

7.2 Water

Water is supplied from a 1.5-in. line on the ground floor of the building. The pressure is approximately 90 psi. The water will be used to prepare simulants and fill the tank prior to mixing.

7.3 Compressed Air

Compressed air from the facility will be used to power the PITBULL™ pump. The system is capable of generating at least 100 SCFM at 100 psi for an indefinite period of time, and will be more than adequate for the pump.

7.4 Safety Precautions

PNNL's Industrial Hygiene, Occupational Safety, and Fire Protection Manual (PNNL-MA-43) and Standards-Based Management System (SBMS) Subject Areas provide the minimum requirements for routine operations. In reviewing the planned testing program, potential hazards were identified along with steps to mitigate or eliminate hazards. The results of the job hazards assessment are provided in Table 7.1

Table 7.1. Job Hazards Assessment Results

Sequence of Basic Job Work Activity	Hazards Present	How to Eliminate Hazards
Operation of low-pressure water system	Water leakage	Isolate water sources when not in use. Monitor water inside the test area and discontinue operation if significant uncontrolled water is generated. Prepare containment using absorption materials and tarps if required.
Assembly, testing, and operation of compressed air	Stored energy release	Secure hoses at appropriate points and intervals. Compressed air is not to be used for housekeeping.
	Noise	Post appropriate warnings. Wear hearing protection during operation of the PITBULL™ pump.
Mixer operation	Cable entering blades	A structural stand-cable will be installed between each mixer and the tank structure. Mixer power cables will be attached to the strand-cable to keep power cables clear of the blades. An emergency stop will be included in the electric circuit so that all mixers can be stopped using a single switch.
	Mixer movement	The mixer base plates will be secured with permanent magnets selected to provide sufficient friction to prevent sliding. Calculations will assume wet conditions a safety factor of 2 against sliding.
General activities in the high-bay	Low obstacles Flying debris	Wear safety glasses and hard hats while in the high-bay area.
	Confined space	The quarter-scale tank is a confined space. A permit will be obtained prior to entering the tank. Personnel entering the tank shall adhere to rules governing confined space.
Simulant preparation	Irritation (desiccation)	Wear respirators when handling dry materials, eye protection, gloves, and coveralls when handling simulant materials. Provide eyewash station, maintain housekeeping. Respirators will include HEPA cartridges with prefilters.
	Manual lifting	Use proper lifting procedures.
Simulant disposal	Moving equipment	Post observer as required to guide forklift or truck operator and keep personnel clear.

7.5 Training and Qualification Requirements

Personnel training for operating test equipment will be done using a combination of briefings, equipment walk-throughs, site hazard orientation, and on-the-job training in accordance with the PNNL Training and Qualification Manual PNL-MA-04. Briefings of operational and test procedures will be conducted by the author of the procedure being discussed. Equipment walk-throughs and on-the-job training shall be conducted by experienced operations personnel. Attendance for all training activities will be documented using training attendance forms.

7.6 Waste Minimization and Management

Waste disposal procedures have been developed with the cooperation of the PNNL Environmental, Safety, and Health (ES&H) department for all materials that will be used in this test program.

8.0 References

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Appendix - Data Sheets

Data Sheet for Fluid Velocity Measurements

Test Number: _____ Date: _____ Start Time: _____

Mixer Settings to Match Test: _____

Mixer(s) Location and Orientation: _____

Mixer rpm Setting(s): _____

Water Level (cm): _____

Water Temperature (deg C): _____

Data Acquisition System Filename: _____

[illegible]

Data Sheet for Density Measurements

Start Time: _____

Simulant Composition: _____

AA.2

Data Sheet for Sludge Characterization Measurements

Test Number: _____ Date: _____ Start Time: _____

Test Number	Sample Location	wt% solids	Vane Shear Strength	Yield Stress

Appendix B

Phase B Test 3 Water Velocity Data (1.8-m Tank)

Appendix B: Phase B Test 3 Water Velocity Data (1.8-m Tank)

The data contained in this appendix were gathered according to the procedures described for Phase B Test 3 in Appendix A and Section 3.0 of this report. All the data presented in this appendix were collected in the 1.8-m diameter tank filled with water. See Appendix C for water velocity data collected in the 5.7-m tank.

Velocity measurements were made in the 1.8-m tank for mixer speeds of 430, 720, and 860 rpm, liquid levels of 70.6 cm and 103.4 cm, and two mixer orientations. The first mixer orientation represented the scaled mixer position corresponding to that used for water velocity tests in Phase A. Velocity measurements were made for all three mixer speeds and both liquid levels for this mixer orientation. See Figure 4.3 in the body of this report for a sketch showing this mixer orientation. Figures B.1 through B.26 apply to the first orientation. The second mixer orientation, referred to as "Test 1D" or "circumferential orientation," was attained by relaxing a mixer restraint cable so that instead of discharging due south it discharged about 20 degrees to the east of due south. Figures B.27 and B.28 apply to the Test 1D orientation.

Figure 4.3 shows the positions where the velocity measurements were made. Velocities were measured at a total of 11 different positions for each set of conditions. All measurements were made with the probe centerline 5 cm above the tank floor with the except measurements at points B9 and E9 where the probe centerline was 28 cm above the floor (i.e., at the same level as the mixer propeller axis). Note that there is no Location D.

For each permutation of tank liquid level, mixer orientation, mixer speed, and velocity probe position, two values have been calculated from the raw data. First, the average velocity was calculated by averaging the magnitudes of the measured velocities at each location under each set of conditions. The temporal velocity readings were sampled at 10 Hz for 15 to 25 sec in each position. Thus, roughly 150 to 250 velocity values were collected for each probe position and each set of conditions. The average of each set of values is taken to represent the time-averaged velocity at each location in the tank. These average velocities are plotted in the following figures (B.1 to B.28). The error bars on the average velocity values represent the root-mean-square fluctuating velocity component.

The second value plotted in the figures below is the average 1-second peak velocity. Each 15 to 25 sec velocity measurement was divided into segments, each 1-sec long. The maximum velocity in each segment was determined and then all of these maximum velocities were averaged. This average value represents the average peak velocity experienced at each probe position every second. The 95% confidence intervals were calculated for the average 1-sec peak velocity values. The error bars on the plots below reflect the 95% confidence intervals.

The raw velocity data from these tests are available from the authors upon request.

Figure B.1. Location A in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.2. Location B in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.3. Location C in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.4. Location E in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.5. Location F in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.6. Location G in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.7. Location H in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.8. Location I in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.9. Location J in 1.8-m Tank at 70.6-cm Liquid Level

Figure B.10. Location B9 in 1.8-m Tank at 70.6-cm Liquid Level
(Position B9 is along propeller axis above point B)

Figure B.11. Location E9 in 1.8-m Tank at 70.6-cm Liquid Level
(Location E9 is along propeller axis above position E)

Figure B.12. Location A in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.13. Location B in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.14. Location C in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.15. Location E in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.16. Location F in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.17. Location G in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.18. Location H in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.19. Location I in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.20. Location J in 1.8-m Tank at 103.4-cm Liquid Level

Figure B.21. Effect of Z on V_{avg} in 1.8-m Tank at 430 rpm

Figure B.22. Effect of Z on V_{peak} in 1.8-m Tank at 430 rpm

Figure B.23. Effect of Z on V_{avg} in 1.8-m Tank at 720 rpm

Figure B.24. Effect of Z on V_{peak} in 1.8-m Tank at 720 rpm

Figure B.25. Effect of Z on V_{avg} in 1.8-m Tank at 860 rpm

Figure B.26. Effect of Z on V_{peak} in 1.8-m Tank at 860 rpm

Figure B.27. Effect of Z on V_{avg} in 1.8-m Tank at 860 rpm (with mixer in Test 1D orientation)

Figure B.28. Effect of Z on V_{peak} in 1.8-m Tank at 860 rpm (with mixer in Test 1D orientation)

Appendix C

Phase B Test 7 Water Velocity Data (5.7-m Tank)

Appendix C: Phase B Test 7 Water Velocity Data (5.7-m Tank)

The data contained in this appendix were gathered according to the procedures described for Phase B Test 7 in Appendix A and Section 3.0 of this report. All the data presented in this appendix were collected in the 5.7-m diameter tank filled with water. See Appendix B for water velocity data collected in the 1.8-m tank. The raw velocity data from these tests are available from the authors upon request.

For each permutation of tank liquid level (Z), mixer orientation, mixer speed, and velocity probe position, two values have been calculated from the raw data. First, the average velocity (v_{avg}) was calculated by averaging the magnitudes of the measured velocities at each location under each set of conditions. The temporal velocity readings were sampled at 10 Hz for 15 to 25 sec in each position. Thus, roughly 150 to 250 velocity values were collected for each probe position and each set of conditions. The average of each set of values is taken to represent the time-averaged velocity at each location in the tank. These average velocities are plotted in the following figures (C.1 - C.129). The error bars on the average velocity values represent the root-mean-square fluctuating velocity component.

The second value plotted in the figures below is the average 1-second peak velocity (v_{peak}). Each 15 to 25 sec velocity measurement was divided into segments, each 1-sec long. The maximum velocity in each segment was determined and then all of these maximum velocities were averaged. This average value represents the average peak velocity experienced at each probe position every second. The 95% confidence intervals were calculated for the average 1-sec peak velocity values. The error bars on the following plots reflect the 95% confidence intervals. The sketch below shows the relative locations of the angles and radial positions used for the velocity measurements plotted in this appendix. In the sketch, V_y points due north.

C.1

Figure C.1. Effect of Z on v_{avg} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.2. Effect of Z on v_{peak} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.3. Effect of Z on v_{avg} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.4. Effect of Z on v_{peak} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.5. Effect of Z on v_{avg} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.6. Effect of Z on v_{peak} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.7. Effect of Z on v_{avg} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.8. Effect of Z on v_{peak} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.9. Effect of Z on v_{avg} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.10. Effect of Z on v_{peak} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.11. Effect of Z on v_{avg} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.12. Effect of Z on v_{peak} in 5.7-m Tank (860 rpm Mixer Speed)

Figure C.13. Effect of Z on v_{avg} in 5.7-m Tank

Figure C.14. Effect of Z on v_{peak} in 5.7-m Tank

Figure C.15. Effect of Z on v_{avg} in 5.7-m Tank

Figure C.16. Effect of Z on v_{peak} in 5.7-m Tank

Figure C.17. Effect of Z on v_{avg} in 5.7-m Tank

Figure C.18. Effect of Z on v_{peak} in 5.7-m Tank

Figure C.19. Effect of Z on v_{avg} in 5.7-m Tank

Figure C.20. Effect of Z on v_{peak} in 5.7-m Tank

Figure C.21. Effect of Z on v_{avg} in 5.7-m Tank

Figure C.22. Effect of Z on v_{peak} in 5.7-m Tank

Figure C.23. Effect of Z on v_{avg} in 5.7-m Tank

Figure C.24. Effect of Z on v_{peak} in 5.7-m Tank

Figure C.25. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.26. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.27. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.28. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.29. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.30. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.31. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.32. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.33. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.34. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.35. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.36. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.37. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.38. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.39. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.40. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.41. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.42. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.43. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.44. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.45. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.46. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.47. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.48. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.49. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.50. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.51. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.52. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.53. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.54. Fluid Velocity vs. Tank Level. (860 rpm Mixer Speed)

Figure C.55. Fluid Velocity vs. Tank Level.

Figure C.56. Fluid Velocity vs. Tank Level.

Figure C.57. Fluid Velocity vs. Tank Level.

Figure C.58. Fluid Velocity vs. Tank Level.

Figure C.59. Fluid Velocity vs. Tank Level.

Figure C.60. Fluid Velocity vs. Tank Level.

Figure C.61. Fluid Velocity vs. Tank Level.

Figure C.62. Fluid Velocity vs. Tank Level.

Figure C.63. Fluid Velocity vs. Tank Level.

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Figure C.65. Fluid Velocity vs. Tank Level.

Figure C.66. Fluid Velocity vs. Tank Level.

Figure C.67. Fluid Velocity vs. Tank Level.

Figure C.68. Fluid Velocity vs. Tank Level.

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Figure C.72. Fluid Velocity vs. Tank Level.

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Figure C.80. Fluid Velocity vs. Tank Level.

Figure C.81. Fluid Velocity vs. Tank Level.

Figure C.82. Fluid Velocity vs. Tank Level.

Figure C.83. Fluid Velocity vs. Tank Level.

Figure C.84. Fluid Velocity vs. Tank Level.

Figure C.85. Fluid Velocity vs. Mixer Speed

Figure C.86. Fluid Velocity vs. Mixer Speed

Figure C.87. Fluid Velocity vs. Mixer Speed

Figure C.88. Fluid Velocity vs. Mixer Speed

Figure C.89. Fluid Velocity vs. Mixer Speed

Figure C.90. Fluid Velocity vs. Mixer Speed

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Figure C.92. Fluid Velocity vs. Mixer Speed

Figure C.93. Fluid Velocity vs. Mixer Speed

Figure C.94. Fluid Velocity vs. Mixer Speed

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Figure C.98. Fluid Velocity vs. Mixer Speed

Figure C.99. Fluid Velocity vs. Mixer Speed

Figure C.100. Fluid Velocity vs. Mixer Speed

Figure C.101. Fluid Velocity vs. Mixer Speed

Figure C.102. Fluid Velocity vs. Mixer Speed

Figure C.103. Fluid Velocity vs. Mixer Speed

Figure C.104. Fluid Velocity vs. Mixer Speed

Figure C.105. Fluid Velocity vs. Mixer Speed

Figure C.106. Fluid Velocity vs. Mixer Speed

Figure C.107. Fluid Velocity vs. Mixer Speed

Figure C.108. Fluid Velocity vs. Mixer Speed

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Figure C.110. Fluid Velocity vs. Mixer Speed

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Figure C.120. Fluid Velocity vs. Mixer Speed

Figure C.121. Fluid Velocity vs. Mixer Speed

Figure C.122. Fluid Velocity vs. Mixer Speed

Figure C.123. Fluid Velocity vs. Mixer Speed

Figure C.124. Fluid Velocity vs. Mixer Speed

Figure C.125. Fluid Velocity vs. Mixer Speed

Figure C.126. Fluid Velocity vs. Mixer Speed

Figure C.127. Fluid Velocity vs. Mixer Speed

Figure C.128. Fluid Velocity vs. Mixer Speed

Figure C.129. Fluid Velocity vs. Mixer Speed

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