WSRC-TR-2004-00436
REVISION 0

EVALUATION OF MIXING IN THE SLURRY MIX EVAPORATOR AND MELTER FEED TANK (U)

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August 2004

Immobilization Technology Section
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Prepared for the U.S. Department of Energy Under Contract Number DEAC09-96SR18500

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy.

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Key Words:
DWPF, Mixing,
Vortex, Xanthan Gum,
Scaling Mixing Tanks

Retention:
Permanent

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EXECUTIVE SUMMARY

The Savannah River National Laboratory (SRNL) performed 1/6th scale mixing tests using Xanthan Gum and Frit 418 slurries to evaluate the impact of removing the helical cooling coils from the Melter Feed Tank, and to evaluate the minimum agitator speed necessary in the Slurry Mix Evaporator (SME) tank and the Melter Feed Tank (MFT) to maintain solids suspension and fluid motion throughout the tank. Testing was conducted with three slurries having Bingham Plastic yield stresses of Five, Ten, and Twenty Pascals.

Testing was performed at three different tank levels, 6 gallons (full scale equivalent: 1500 gallons), 25 gallons (6000 gallons), and 40 gallons (9500 gallons). Each slurry was tested at each tank level with the helical coils in the vessel and with the helical coils removed from the vessel. Each test consisted of various agitation speeds, including 220 revolutions per minute (RPM), 330 RPM, and 420 RPM (full scale equivalent: 67, 103, and 130 RPM, respectively using the Ekato sizing correlation).

Conclusions

Vortex formation increased significantly when the coil was removed, especially for the 5 Pa test fluid. Vortex formation can cause process upsets by entraining air into the process[1] and can cause uneven mechanical loading on the agitator shaft and subsequent failure. It should be noted that scaling of the vortex phenomena is extremely uncertain and the 1/6th scale results may not accurately reflect the severity of the problems that will occur in the full scale tank. However, removal of the coil did improve surface motion and solids distribution.

The 1/6th scale test results showed good surface motion for the 5 Pa and 10 Pa fluids at 25 gallons for the 330 RPM tests (scales to 6000 gallons and 103 RPM), but the 20 Pa fluid indicated borderline results with small areas of stagnation around the wall. Cavern formation was noted for all fluids at 40 gallons (9500 gallons) at this speed, both with the coils in and out. Sample results from the homogeneity samples did not indicate that the 5 Pa fluid was uniform at 40 gallons and 330 RPM with the coils in the tank.

The power per unit volume sizing method yielded significant cavern formation at higher volumes and at lower volumes with high yield stress materials. Comparisons between the 1/6th Scale SRAT and the Full Scale homogeneity study indicate that Equal Tip Speed may be a more appropriate scaling method. Utilizing Equal Tip Speed as a scaling method would lead to significant changes in the results given the much higher agitator speeds required.

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[1] Stone, M.E., Marinik. A.R., Small Scale Mixing Tests for the DWPF Chemical Process Cell Vessels (U). March 2004. WSRC-TR-2004-00074.

The DWPF MFT agitator is currently configured at a high speed setting of 103 RPM with no operational difficulties noted to date. Sample results from the MFT have agreed with sample results from the SME, indicating that adequate mixing has been maintained in the MFT at the lower agitator speed.

Recommendations

A plan should be developed to address vortex formation prior to removal of the MFT coil assembly.

The CFD models developed for the MFT and SME vessels should be validated versus the 1/6th scale results. Validation of the model will lead to improved results from the model and will allow better representation of the DWPF process by the model.

The rheological properties of actual DWPF process slurries should be measured. A flow curve would be ideal, but even a single point measurement of apparent viscosity could lead to valuable insight into process conditions and aid in the evaluation of process upsets. The amount of variability in the process could be determined if the analysis is performed on routine process samples.

The MFT and SME agitators should not operate continuously at the low speed setting (67 RPM) when the vessels are above 6000 gallons to reduce the potential for cavern formation.

Alternative means of reducing the erosion rate on the cooling/heating coils due to the irregular shaped frit are:

- Conversion of irregular shaped frit to spherical shaped frit which is processed from the irregular shaped frit.
- Raising the lower section of the cooling/heating coils above the discharge of the bottom impeller. Raising the coils would likely improve mixing in the vessel.

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LIST OF ACRONYMS

ACTL	Aiken County Technology Laboratory
CFD	Computational Fluid Dynamics
CPC	Chemical Process Cell
DWPF	Defense Waste Processing Facility
HLW	High Level radioactive Waste
MFT	Melter Feed Tank
RPM	Revolutions Per Minute
SME	Slurry Mix Evaporator
SRAT	Sludge Receipt and Adjustment Tank
SRNL	Savannah River National Laboratory
SRS	Savannah River Site

1.0 INTRODUCTION AND BACKGROUND

The Defense Waste Processing Facility (DWPF) vitrifies High Level radioactive Waste (HLW) currently stored in underground tanks at the Savannah River Site (SRS). The HLW currently being processed is a waste sludge composed primarily of metal hydroxides and oxides in caustic slurry. These slurries are typically characterized as Bingham Plastic fluids.

The HLW undergoes a pretreatment process in the Chemical Process Cell (CPC) at DWPF. The processed HLW sludge is then transferred to the Sludge Receipt and Adjustment Tank (SRAT) where it is acidified with nitric and formic acid then evaporated to concentrate the solids. Reflux boiling is utilized to strip mercury from the waste and then the waste is transferred to the Slurry Mix Evaporator tank (SME). Glass formers are added as a frit slurry to the SME to prepare the waste for vitrification. This mixture is evaporated in the SME to the final concentration target. The frit slurry mixture is then transferred to the Melter Feed Tank (MFT) to be fed to the melter.

The irregular shaped frit slurry is extremely abrasive and is currently causing failure of the heating and cooling coil assembly in the SME vessel after approximately two years of continuous operations. The agitator on the SME has two speed settings: 130 revolutions per minute (RPM) and 67 RPM. The higher speed is used by DWPF to maintain homogeneity in the SME. Operating at the higher speed increases the erosion rate, therefore DWPF is evaluating reducing this speed to 103 RPM.

The MFT contains a coil assembly similar to the coil assembly in the SME, but the coils are not currently required to maintain tank temperatures. DWPF is evaluating the removal of the coil assembly from the MFT to reduce the maintenance required on the tank.

DWPF Engineering has developed a Computational Fluid Dynamics (CFD) model of the SRAT, SME and MFT to evaluate the above proposed process changes. Small-scale mixing tests were conducted by the Savannah River National Laboratory (SRNL) to evaluate the proposed process changes and to verify the results of the CFD model. The tests were conducted in response to a Technical Task Request[2] from DWPF Engineering and conducted in accordance with a Task Technical and Quality Assurance Plan.[3]

[2] Technical Task Request, “Develop Scale Model Testing of the SME and MFT Mixing Process.” HLW/DWPF/TTR-2004-0009

[3] Technical Task Plan, “Scale Model Testing of the SME and MFT Mixing Process (U).” WRSC-RP-2004-00407.

2.0 EXPERIMENTAL SETUP

2.1 Simulant Development

Physical simulants were developed to provide rheological properties similar to the actual waste having Bingham Plastic yield stresses of 5, 10, and 20 Pascals (Pa). The simulants contained 30 weight percent (wt %) Frit 418. Xanthan Gum solutions were used in place of precipitated hydroxide simulants because the Xanthan Gum solutions are more cost effective, somewhat transparent and yield the necessary rheological properties. Kathon CG-ICP was utilized as a preservative for the Xanthan Gum solutions. The frit and Kathon CG-ICP concentrations were held constant while the Xanthan Gum concentrations were varied to obtain the targeted yield stresses. The particle size distribution of the Frit 418 used during this study met the requirements specified for use in DWPF: greater than 70 wt % of Frit will be between 80 and 140 mesh, less than 2 wt % Frit will be greater than 80 mesh, and less than 10 wt % Frit less than 200 mesh. The rheology of Xanthan Gum / Kathon CG-ICP / Frit 418 slurries were measured using the rheometer at the Aiken County Technology Laboratory (ACTL) and the rheological properties evaluated for suitability based upon engineering judgment.

2.2 Frit 418 Settling Test

Initially a settling test was performed to determine the settling characteristics of the different slurries, indicating the approximate time required for complete settling. Seven graduated cylinders were setup according to SRT-GPD-2004-00075 (as seen in Appendix F) and shown in Figure 2-1. The composition of the slurry in each cylinder is described in Table 2-1. Frit was added to Tests 1.1 through 2.3 just as testing began, however, the Frit had already been added to the slurries in Tests 3.1 through 3.3 prior to testing. Therefore, cylinders for each test were shaken vigorously just prior to testing. The entire test was recorded by time lapse video.

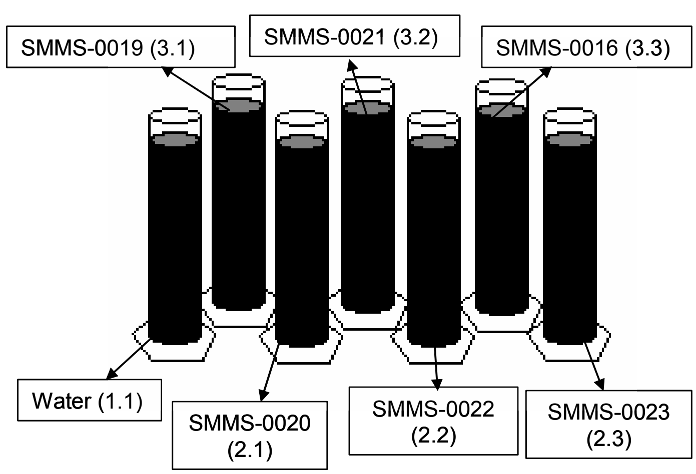

Figure 2-1. Experimental Setup

The water test (Test 1.1) showed all the frit settling in less than 10 seconds. The 5 Pa Xanthan Gum 1% Frit (Test 2.1) completely settled in approximately 43 hours. The 10 Pa Xanthan Gum 1% Frit (Test 2.2) showed very little settling during the five day test. The 20 Pa Xanthan Gum 1% Frit (Test 2.3) showed no settling during the five day test. The 20 Pa Xanthan Gum (Test 2.3) contained air bubbles that were entrained in the slurry during the addition of the Xanthan Gum slurry to the cylinder prior to testing. This entrained air remained stagnant in the cylinder throughout the testing. Test 1.1 through Test 2.3 cylinders, after testing was complete, are shown in Figure 2-2.

Table 2-1 Settling Test Simulant Makeup

Test #	Frit 418 (wt%)	Frit 418 (g)	Slurry Yield Stress	Slurry Mass (g)	Sample #
1.1	1.0	0.5	0 Pa	50	Water
2.1	1.0	0.5	5 Pa	50	SMMS-0020
2.2	1.0	0.5	10 Pa	50	SMMS-0022
2.3	1.0	0.5	20 Pa	50	SMMS-0023
3.1	30	N/A[4]	5 Pa	50	SMMS-0019
3.2	30	N/A[4]	10 Pa	50	SMMS-0021
3.3	30	N/A[4]	20 Pa	50	SMMS-0016

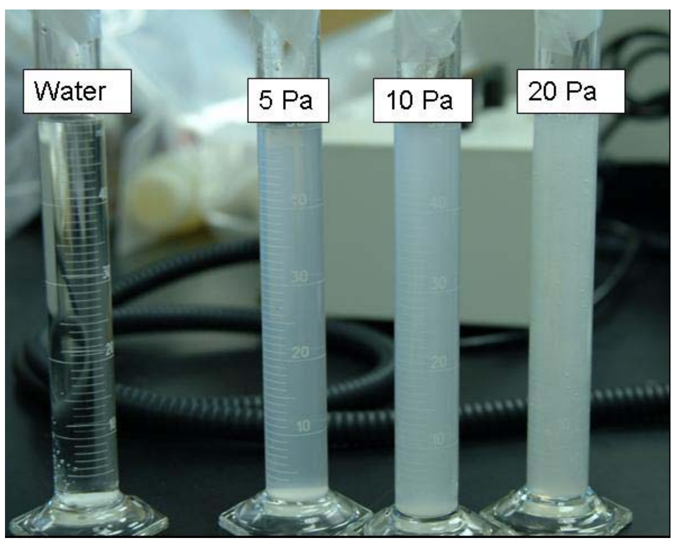

Figure 2-2. Settling of One Wt % Frit After 5 Days of Settling

The 5 Pa Xanthan Gum 30% Frit (Test 3.1) clearly showed settling within 43 hours and is shown in Figure 2-3. The 10 Pa Xanthan Gum 30% Frit (Test 3.2) showed some settling of the larger frit particles, however, most of the frit remained suspended in the slurry.

[4] Frit was already added to these slurries.

The 20 Pa Xanthan Gum 30% Frit (Test 3.3) showed no settling during the entire five days of testing. Figure 2-3 shows the amount of settling for Test 3.1 through Test 3.3.

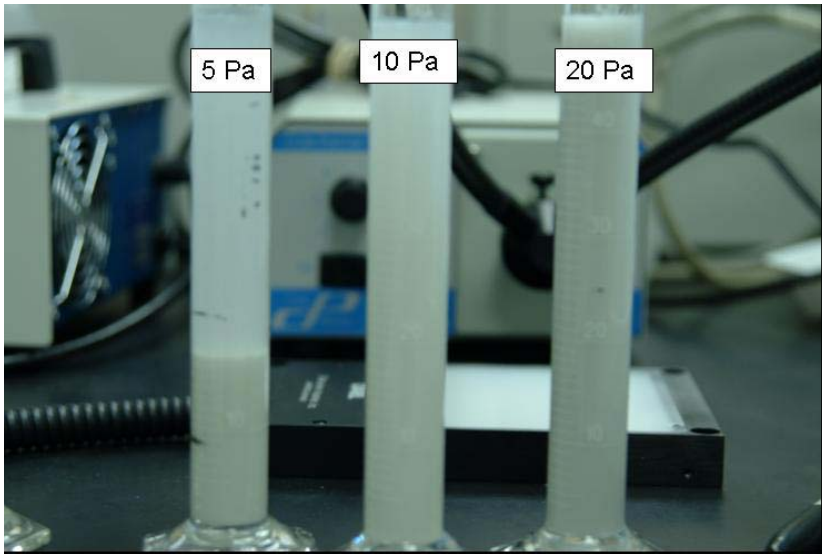

Figure 2-3. Settling of Thirty Wt % Frit After 43 hrs

As a result of the very slow settling nature of the 10 Pa and 20 Pa fluids, it was unlikely that either would settle during the mixing tests. The decision of whether or not to perform solids sampling was made during the mixing portion of this testing.

2.3 Simulant Target Rheology

It was important during testing that the rheological properties of the simulants were representative of the rheology in the SME and MFT. Since the SME and MFT have an operating range of rheological properties, the targeted rheological property was that of the bounding conditions in the SME and MFT.[3] Initial simulant preparation was based on previous mixing studies utilizing Xanthan Gum.[5] Each simulant was prepared with Xanthan Gum, Frit 418, Kathon CG-ICP, and Deionized water. The Xanthan Gum concentration was varied to achieve the targeted yield stress.

Simulant development required determining the Xanthan Gum concentrations for simulants that have yield stresses of 5, 10, and 20 Pascals. Eighteen test solutions were prepared and analyzed rheologically using the Haake RS600 Rheometer. The Z38 bob/cup (concentric cylinder geometry) was used to produce the flow curves. After adjustments to the test solutions were finalized to determine the blending ratios of the additives required for the targeted yield stresses, the batching quantities for the mixing tests for the 5, 10 and 20 Pa mixing simulants were determined and the results are shown in Table 2-2. The rheogram and the Bingham Plastic regression for each of the test simulants are in Appendix C.

[5] Stone, M.E., Marinik. A.R., Small Scale Mixing Tests for the DWPF Chemical Process Cell Vessels (U). March 2004. WSRC-TR-2004-00074.

Table 2-2 Batching Quantities of Xanthan Gum/Frit 418 for Mixing Tests

Simulant Yield Stress Target	Batching Quantities				Calculated Solids Content	Sample #
	Xanthan Gum	Frit 418	Kathon CG-ICP	Water		
	Grams	Kilograms	Grams	Kilograms	Wt%	
5 Pa	585.5	73.8	344.4	171.3	30.4	SMMS-0024
10 Pa	947.2	73.8	344.4	170.9	30.5	SMMS-0025
20 Pa	1550.0	73.8	344.4	170.3	30.8	SMMS-0026

2.3.1 Rheological Model Fits

Slow settling slurries can be modeled as a single phase fluid. This produces certain simplifications over dealing with a two-phase solid-liquid transport model in the analysis of pumps, pipeline flow, and tank mixing. Various empirical and semi-theoretical models have been proposed to relate the shear stress and the shear rate of non-Newtonian slow settling slurries. One of the simplest of these rheological models is the Bingham Plastic fluid, which is generally used when characterizing SRS waste slurries. This is a two parameter model that is used to relate shear stress and shear rate data and is shown below.

$$\tau = \tau_{BP} + \mu_{\infty} \cdot \dot{\gamma}$$

where: τ = shear stress (Pa)

τ_{BP} = Bingham Plastic yield stress (Pa)

μ_{∞} = Bingham Plastic consistency or infinite viscosity (Pa·sec)

$\dot{\gamma}$ = shear rate (sec^{-1})

The two fitted parameters are the yield stress and consistency and both are constants for a given sample that is time-independent. The Bingham Plastic model or any other rheological model must be fitted to only the laminar region of a flow curve. The Bingham Plastic model is a linear fit of the rheological data, where the intercept is the yield stress, and the slope is the consistency. If the yield stress is zero, then the fluid is a Newtonian fluid and the consistency is equivalent to the viscosity of a Newtonian fluid. When the yield stress is not zero, the consistency is no longer analogous to the viscosity of a Newtonian fluid. The difference between a Newtonian and non-Newtonian fluid is that the non-Newtonian fluid is shear rate dependent. This shear rate dependence can be expressed as the apparent viscosity of the non-Newtonian fluid and is calculated by taking the ratio of the shear stress to shear rate and is shown below for a Bingham Plastic fluid:

$$\mu_{apparent} = \frac{\tau}{\dot{\gamma}} = \frac{\tau_{BP} + \mu_{\infty} \cdot \dot{\gamma}}{\dot{\gamma}} = \frac{\tau_{BP}}{\dot{\gamma}} + \mu_{\infty}$$

where: $\mu_{apparent}$ = Apparent viscosity (Pa·sec)

The apparent viscosity of a Bingham Plastic fluid decreases with increasing shear rate and approaches that of the infinite viscosity as shown above. This type of rheological behavior is called shear thinning. The apparent viscosity goes to infinity as the shear rate goes to zero. The apparent viscosity of other non-Newtonian models can also be calculated in this fashion.

The Bingham Plastic properties are presumed to be time independent. Not all slurries are time independent. Time-dependence is a potential issue when dealing with slurries containing colloidal solid particles. Colloidal solids are in the range of 1 micron in diameter.[8] Colloidal solids can exhibit unusual behavior because the size of the particles is small enough that the inter-particle surface forces can become an appreciable fraction of the total force acting on a given particle. SRS waste slurries and corresponding simulants contain particles in this size range. The Bingham Plastic model is not appropriate for fluids that are highly time-dependent. DWPF frit particles are larger than a majority of the sludge particles. An issue with SME product frit slurries is keeping the frit uniformly suspended, so that the slurry can be classified as slow settling[6] at the point of rheological measurement.

[6] Koopman, D.C., A Comparison of Rheology Data for Radioactive and Simulant Savannah River Site Waste (U). March 2004. WSRC-TR-2004-00044.

2.4 Mixing Tests

2.4.1 Instrumentation and Equipment Setup

The 1/6th scale SRAT/SME/MFT vessel has an internal diameter of 23.19 inches and has coils, impellers, pump dip legs, and a bubbler geometrically scaled from the full scale vessel. The agitator motor and other equipment installed during the mixing tests are listed in Appendix D. A diagram of the tank and installed equipment is shown in Figure 2-4.

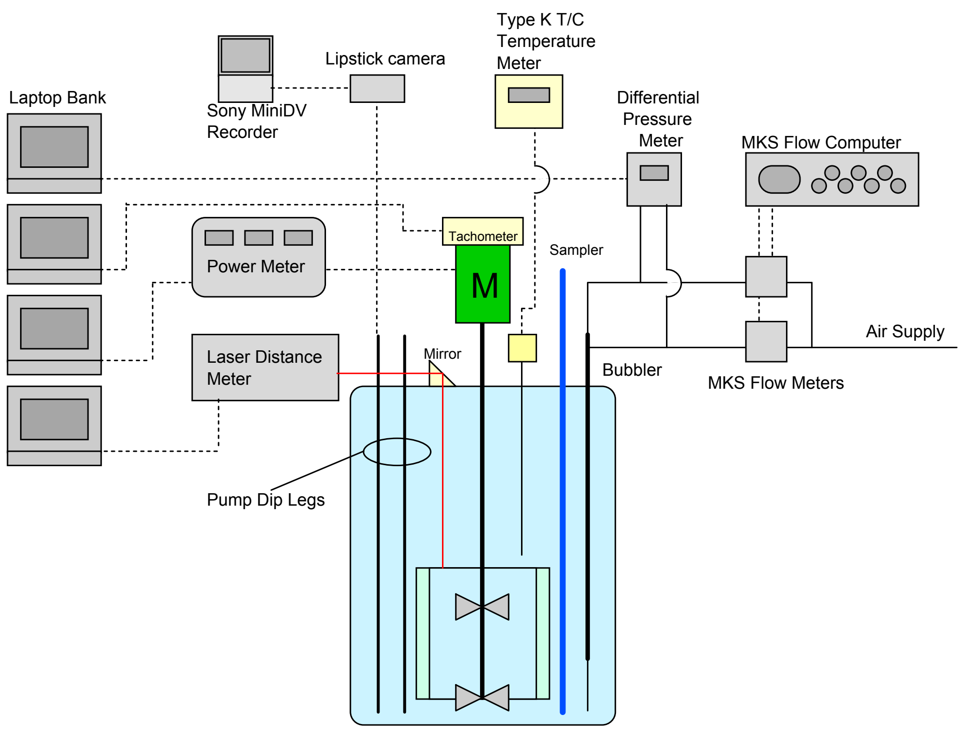

Figure 2-4. 1/6th Scale SRAT/SME/MFT Diagram

The 1/6th scale SRAT/SME/MFT vessel was fitted with a variety of instruments to monitor each test. These instruments measured agitator speed, vessel temperature, slurry density, agitator power, and vortex depth. In addition, video cameras recorded surface phenomena (e.g. motion) during the test and were used to monitor the tank bottom for settled solids. Details of the instruments used during the testing are provided in Appendix D. Three different motors were used for agitation during this testing. Originally a direct drive motor was used (Lightnin EV1P50M), however, it failed during the Five Pascal fluid testing. Secondly, a motor using a gear reducer was used (Lightnin EV5P50M), which limited the rotational speed. Therefore, a third motor was used (Caframo BDC3030), however , it was only capable of limited duration tests, and thus was only used to agitate at high speeds (i.e. 360 RPM - 450 RPM). Figure 2-5 shows the 1/6th Scale Vessel, Coils, and Agitator Blades. Agitator speeds tested and the subsequent data collected are located in Appendix A.

Figure 2-5. 1/6th Scale Mixing Tank, Coil and Agitator

3.0 RESULTS

3.1 Five Pascal Tests

40 Gallon Test Coils In
The minimum agitator speed required to suspend solids was 76 RPM as evident through the Lipstick Camera, which is located ¼" off the bottom of the tank. Surface motion was not evident at 220 RPM, however, slight motion was observed at 300RPM. Full surface motion without vortexing occurred at 378 RPM. Full motion and vortexing occurred at 420 RPM.

40 Gallon Test Coils Out
Mixing at 200 RPM showed no surface motion, however, mixing at 330 RPM produced surface movement nearly to the tank wall. Complete surface motion occured at 360 RPM and a vortex existed, but did not reach the bottom impeller. At 420 RPM full surface motion and vortexing was observed, as well as, a constant gurgling noise from the vortex, indicating that the vortex had reached the lower impeller.

25 Gallon Test Coils In
Slight surface movement occurred at 60 RPM with areas along the wall being stagnant. The surface movement was more pronounced at 150 RPM. At 220 RPM a slight vortex occurred, and surface movement is nearly to the wall. There is full surface motion and a pronounced vortex above the upper impeller hub when mixing at 330 RPM. Mixing at 390 RPM, the surface motion was completely to the tank wall moving towards the center in a swirling fashion. The vortex at 390 RPM was slightly deeper than that of 330 RPM, and oscillated around the agitator shaft rather than centrally located about the shaft.

25 Gallon Test Coils Out

Minimum agitator speed required for movement at a distance of ¼" from the bottom (as seen through the Lipstick Camera) was 98.2 RPM, however, there was no visible surface motion at this speed. Relatively no surface motion and no vortex were observed while mixing at 150 RPM. Full surface motion was evident, with the vortex reaching and air entrainment occurring at the upper impeller blade at 220 RPM. At 330 RPM an extreme vortex impacting the upper impeller and significant surface motion occurred. The vortex exposed the upper impeller hub, and periodically the upper impeller itself as shown in Figure 3-1. Significant amounts of air were entrained at this agitator speed and the surface was in a swirling motion. Visually there was little change at 360 RPM, an extreme vortex entrained air and full surface movement continued in a swirling motion with no stagnant areas. At 420 RPM, there was a large vortex with rapid fluid motion throughout the tank.

Figure 3-1. 25 Gallon, 5 Pa, Visible Upper Impeller Hub at 330 RPM with Coils Out

6 Gallon Test Coils In

Incomplete surface movement was observed at 150 RPM with stagnant areas near the tank walls. Full surface movement and significant air entrainment occurred at 220 RPM. At 330 RPM the surface was obscured by bubbles as the agitator entrained air at an extremely high rate. There was very little change at 420 RPM, due to the high volume of air being entrained and the surface continued to be obscured by bubbles. The vigor at which the slurry was thrown from the impellers increased significantly.

6 Gallon Test Coils Out

Minimum agitator speed required for movement at a distance of ¼" from the bottom (as seen through the Lipstick Camera) was 154 RPM. At 220 RPM, surface motion is complete with a vortex revealing the lower impeller. Surface motion increases at 330 RPM violently throwing the slurry onto the tank walls.

3.2 Ten Pascal Tests

40 Gallon Test Coils In
With agitator speeds of 75 RPM, 100 RPM, 150 RPM, 200 RPM, and 250 RPM, no surface motion occurred. At speeds of 275 RPM, 300 RPM, 330 RPM, and 350 RPM, surface motion was limited to that with immediate contact to the agitator shaft. No surface motion was observed at 420 RPM with the exception of slight oscillations around the agitator shaft.

40 Gallon Test Coils Out
Surface motion was again limited in this test for 220 RPM, 330 RPM, and 348 RPM to the area immediately contacting the agitator shaft. At 420 RPM, significant surface motion was observed, however, no vortexing occurred.

25 Gallon Test Coils In
Surface motion was limited to the interior of the coils at speeds of 75 and 150 RPM. However, at 200 RPM the surface motion was observed outside of the coils as well as inside, but not extending to the tank walls. Surface motion outside the coils was more pronounced at 220 RPM, again with stagnant areas at the tank walls. Surface motion was nearly to the walls at 300 RPM, and completely to the walls at both 330 (Figure 3-2) and 352 RPM. A slight vortex was observed at both 330 RPM and 352RPM. At 420 RPM, the vortex increased and surface motion continued throughout the tank.

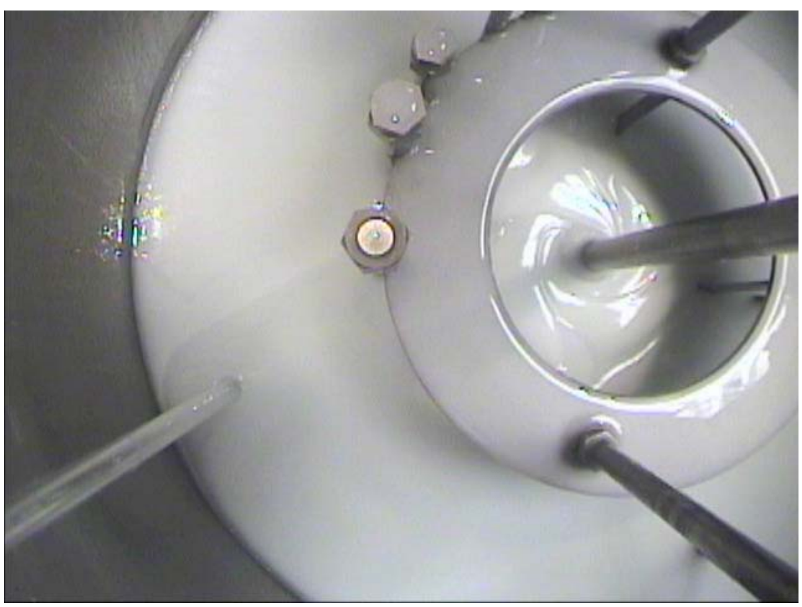

Figure 3-2. 25 Gallon, 10 Pascal Fluid Mixing at 330 RPM with Coils In

25 Gallon Test Coils Out
Surface motion, at 150 RPM, was observed extending to approximately three inches from the tank wall. Some surface motion was noted at 220 RPM, however, the surface areas near the wall remained stagnant, and there was no vortex. Full surface motion with the exception of some small stagnant areas at the tank wall occurred at 330 RPM with a vortex slightly off-centered. At 360 RPM, the off-centered vortex remained, and full surface motion was observed. Both surface motion and the vortex increased at 420 RPM with the vortex revealing the upper impeller.

6 Gallon Test Coils In
Slight surface motion was observed outside the coils at 220 RPM with only a slight increase in motion near the tank wall. Mixing at 275 RPM produced a large amount of bubbles pushing toward the tank wall with greater vigor than previously seen. Both 300 RPM, and 330 RPM showed increase bubble production outside the coils, and surface motion increased slightly towards the tank wall as speed increased. There was little difference between 330 RPM and 354 RPM with respect to visual appearance of bubbles and surface motion. Mixing at speeds of 275 RPM and greater produced obvious air entrainment, however, coils and agitator blades obscured view of actual vortex depth.

6 Gallon Test Coils Out
Agitation at 75 RPM produced surface movement approximately five inches in diameter centered around the agitator shaft. A slight depression around the shaft formed at 75 RPM. Some surface motion was noted at 150 RPM, however, no motion occurred within two inches of the tank wall. Full mixing occurred at 220 RPM with complete surface motion throughout the tank. Rapid and irregular surface motion occurred at 330 RPM, the slurry was thrown to the tank wall as evident in Figure 3-3.

Figure 3-3. 6 Gallons, 10 Pa, Extreme Surface Motion At 330 RPM with Coils Out

3.3 Twenty Pascal Tests

40 Gallon Test Coils In
No surface motion was visible with the exception of the area directly contacting the agitator shaft through out this entire test. Tests were conducted at 75 RPM, 100 RPM, 150 RPM, 200 RPM, 220 RPM, 250 RPM, 275 RPM, 300 RPM, 330 RPM, 420 RPM, and 450 RPM.

40 Gallon Test Coils Out
Testing was conducted at 75 RPM, 100 RPM, 150 RPM, 200 RPM, 220 RPM, 250 RPM, 300 RPM, 330 RPM, 350 RPM, 420 RPM, and 450 RPM. No surface motion was observed at any speed other than a slight oscillatory motion and no vortexing at 450 RPM.

25 Gallon Test Coils In
There was no surface movement outside the coils at both 75 RPM and 100 RPM. Significant motion occurred inside the coils at 150 RPM, with slight motion on the outside of the coils moving towards the tank center. Significant surface motion extended beyond the coils at 220 RPM, however, the wall areas remained stagnant. Also, no vortex was observed at 220 RPM. A slight vortex did appear around 275 RPM, although surface motion did not change significantly from that of 220 RPM. At approximately 288 RPM the vortex reversed from a depression in the slurry surface to an elevation. The flow around the agitator reversed and began pumping up and away from the agitator shaft rather than towards the shaft and down, see Figure 3-4. Significant motion occurred inside the coils at 330 RPM with some surface motion outside the coils, however, the wall areas remained stagnant. Again, at 330 RPM, a reverse vortex was pumping slurry up the center and away from the agitator shaft.

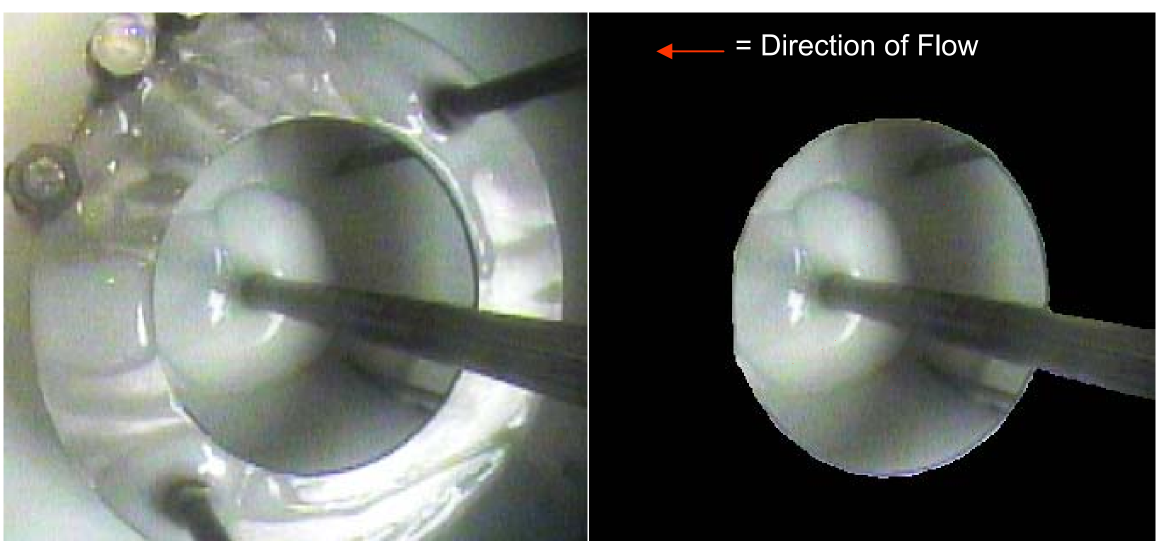

Figure 3-4. 25 Gallons, 20 Pa Reverse Vortex With Coils

25 Gallon Test Coils Out

Surface motion is evident at 200 RPM, however, the outer perimeter of the tank remained stagnant. Motion increased slightly at 220 RPM, but motion ceased approximately four inches from the tank wall. At 330 RPM surface motion increased in both area and velocity. A small depression existed at 330 RPM, but the tank wall areas were still stagnant. There was very little change in surface motion characteristics when speed was increased to 345 RPM. There was very good motion over the whole surface at 420 RPM, and a very deep vortex.

6 Gallon Test Coils In

There was significant surface motion inside the coils at 75 RPM, 100 RPM, 150 RPM, and 200 RPM, but there was no notable movement outside the coils at these speeds. At 220 RPM, surface motion remained significant inside coils, and began oscillating outside the coils. At 300 RPM and 330 RPM the oscillatory motion outside the coils increased, but neither speed showed any swirling motion or lateral movement on the surface.

6 Gallon Test Coils Out

Cavern mixing occurred at 75 RPM, 100 RPM, 150 RPM, and 200 RPM with surface motion centered about the agitator, and no motion within six inches of the tank wall. Surface motion became more pronounced at 220 RPM with no vortex and nearly four inches from the tank wall was stagnant. At 275 RPM there was complete surface motion. Surface motion was more violent at 330 RPM with a deep vortex exposing the lower impeller hub and slurry slung to the tank wall.

3.4 Discussion

3.4.1 Impact of Coils on Solids Suspension

While mixing at specific agitator speeds during the Five Pascal Tests samples were taken with a Coliwasa (Composite Liquid Waste Sampler) at three different locations within the mixing vessel. All three locations were sampled in quadruplicate as designated in the technical task plan governing this study.[4] The three sampling locations in the tank are; just below the surface of the slurry (Surface Level), at the measured depth equivalent to that of the surface level when mixing at 25 Gallons (25 Gallon Level), and at approximately three inches off the tank bottom (Tank Bottom). During the Five Pascal Testing, sampling was done after mixing for two hours at 220 RPM, and again after mixing at 330 RPM for two hours both with the coils in and with the coils removed. Sampling locations were maintained by a shaft guide fixed to the lid of the tank allowing very little room for movement, and only movement in a vertical direction. Markers on the side of the Coliwasa were used to designate the point at which sampling was to be done.

After sampling was completed, the individual samples were analyzed for weight percent total solids and density. The mixing vessel was considered homogeneous if each set of samples (surface level, 25 gallon level and tank bottom) were within 5% of the average value[3] of all samples extracted at a specific agitation speed. Table 3-1 contains the density, the weight percent total solids, and sample information for the samples taken prior to mixing with the Five Pascal fluid.

Table 3-1 Results for Initial Five Pascal Fluid Samples

Sample	Location	Wt.% Total Solids	Agitator Speed (RPM)	Coils	Density (g/mL)	% Deviation Total Solids
SMMS-0027-A	Tank Bottom	53.07	0	In	1.44	95.90
SMMS-0027-B	Tank Bottom	54.66	0	In	1.44	101.77
SMMS-0028-A	25 Gallon Level	20.74	0	In	1.12	-23.44
SMMS-0028-B	25 Gallon Level	23.24	0	In	1.14	-14.21
SMMS-0029-A	Surface Level	4.22	0	In	1.00	-84.42
SMMS-0029-B	Surface Level	6.61	0	In	1.03	-75.60

Figure 3-5 is a graphical representation of the results for sampling at 220 RPM and at 330 RPM during the 5 Pa tests. The solids distribution was unevenly distributed at both 220 RPM with coils in and coils out and 330 RPM with coils in the mixing vessel, indicating that the vessel was not homogenous. However, with the coils removed and mixing at 330 RPM, the solids distribution was within the $\pm$ 5% uniformity requirement. As stated previously, during the Five Pascal Test, complete surface motion was not observed at 220 RPM with the coils in or out of the vessel.

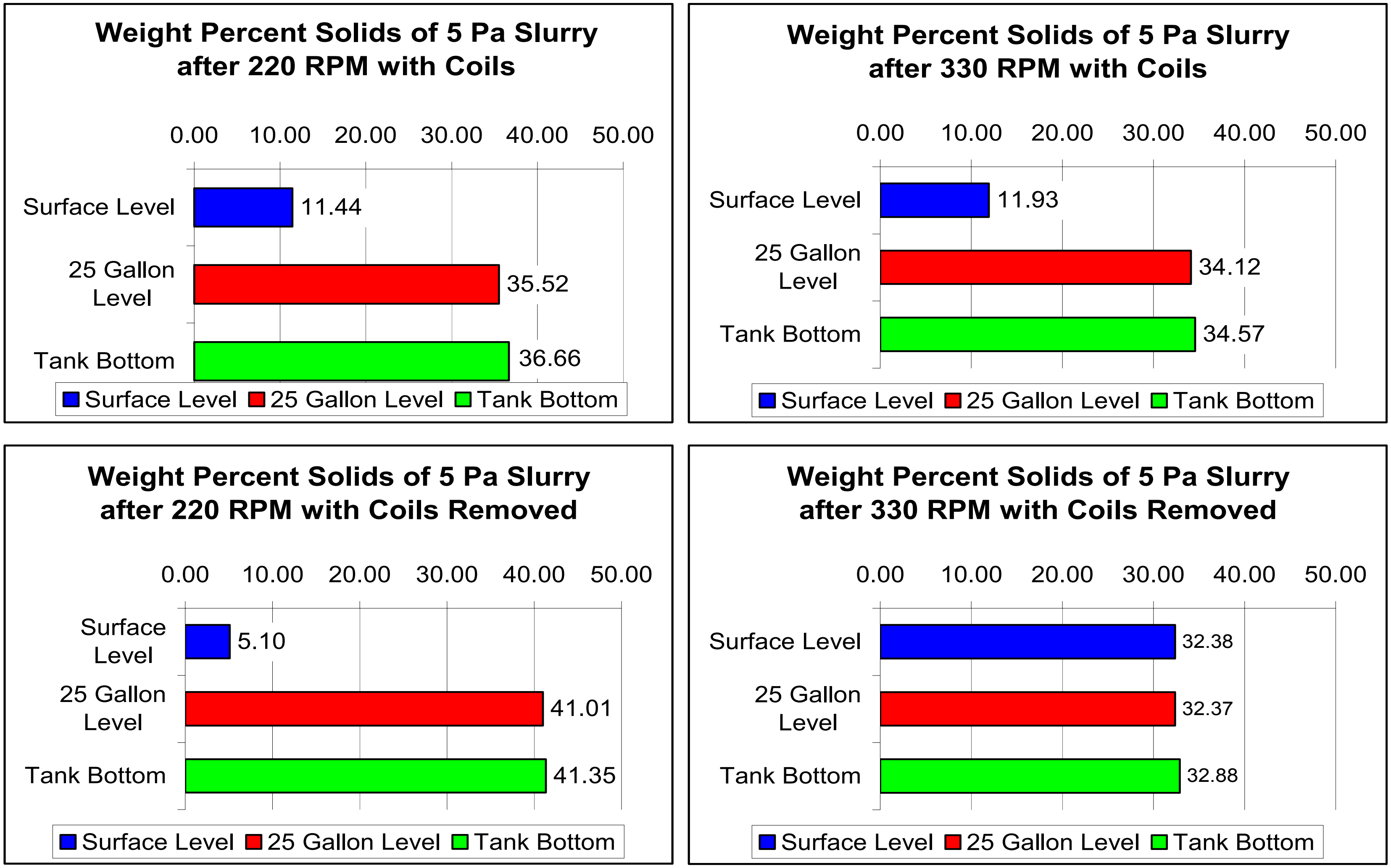

Figure 3-5. Histogram of Wt% TS Distribution for Five Pascal Mixing Tests at 40 Gallons

Table 3-2 contains all sample information and results of density and weight percent solids analysis for samples extracted after mixing at both 220 revolutions per minute and 330 revolutions per minute.

Table 3-2 Physical Properties from the 40 Gallon Five Pascal Fluid Mixing Tests

Sample	Location	Wt.% Total Solids	Agitator Speed (RPM)	Coils	Density (g/mL)	% Deviation Total Solids
SMMS-0030-A	Surface Level	7.63	220	In	1.04	72.63
SMMS-0030-B	Surface Level	6.98	220	In	1.03	74.96
SMMS-0030-C	Surface Level	18.00	220	In	1.08	35.42
SMMS-0030-D	Surface Level	13.16	220	In	1.07	52.79
SMMS-0031-A	25 Gallon Level	35.25	220	In	1.27	-26.46
SMMS-0031-B	25 Gallon Level	35.63	220	In	1.23	-27.83
SMMS-0031-C	25 Gallon Level	35.42	220	In	1.24	-27.07
SMMS-0031-D	25 Gallon Level	35.77	220	In	1.24	-28.33
SMMS-0032-A	Tank Bottom	37.31	220	In	1.25	-33.86
SMMS-0032-B	Tank Bottom	35.97	220	In	1.24	-29.05
SMMS-0032-C	Tank Bottom	36.82	220	In	1.25	-32.10
SMMS-0032-D	Tank Bottom	36.54	220	In	1.26	-31.09
SMMS-0033-A	Surface Level	11.34	330	In	1.08	57.80
SMMS-0033-B	Surface Level	11.90	330	In	1.06	55.72
SMMS-0033-C	Surface Level	12.56	330	In	1.05	53.26
SMMS-0033-D	Surface Level	11.92	330	In	1.06	55.64
SMMS-0034-A	25 Gallon Level	33.83	330	In	1.25	-25.89
SMMS-0034-B	25 Gallon Level	34.21	330	In	1.23	-27.30
SMMS-0034-C	25 Gallon Level	34.22	330	In	1.22	-27.34
SMMS-0034-D	25 Gallon Level	34.21	330	In	1.24	-27.30
SMMS-0035-A	Tank Bottom	34.75	330	In	1.24	-29.31
SMMS-0035-B	Tank Bottom	34.58	330	In	1.22	-28.68
SMMS-0035-C	Tank Bottom	34.35	330	In	1.19	-27.83
SMMS-0035-D	Tank Bottom	34.60	330	In	1.24	-28.76
SMMS-0036-A	Surface Level	6.94	220	Out	1.02	76.19
SMMS-0036-B	Surface Level	6.94	220	Out	1.03	76.19
SMMS-0036-C	Surface Level	3.32	220	Out	1.01	88.61
SMMS-0036-D	Surface Level	3.18	220	Out	1.01	89.09
SMMS-0037-A	25 Gallon Level	40.77	220	Out	1.31	-39.86
SMMS-0037-B	25 Gallon Level	41.35	220	Out	1.30	-41.85
SMMS-0037-C	25 Gallon Level	40.92	220	Out	1.29	-40.38
SMMS-0037-D	25 Gallon Level	40.98	220	Out	1.32	-40.58
SMMS-0038-A	Tank Bottom	41.08	220	Out	1.30	-40.93
SMMS-0038-B	Tank Bottom	41.02	220	Out	1.32	-40.72
SMMS-0038-C	Tank Bottom	41.97	220	Out	1.31	-43.98
SMMS-0038-D	Tank Bottom	41.33	220	Out	1.32	-41.78
SMMS-0039-A	Surface Level	32.62	330	Out	1.26	-0.23
SMMS-0039-B	Surface Level	32.20	330	Out	1.24	1.06
SMMS-0039-C	Surface Level	32.97	330	Out	1.24	-1.31
SMMS-0039-D	Surface Level	31.73	330	Out	1.23	2.50

Table 3-2 Physical Properties from the 40 Gallon Five Pascal Fluid Mixing Tests

Sample	Location	Wt.% Total Solids	Agitator Speed (RPM)	Coils	Density (g/mL)	% Deviation Total Solids
SMMS-0040-A	25 Gallon Level	32.48	330	Out	1.23	0.20
SMMS-0040-B	25 Gallon Level	32.18	330	Out	1.23	1.12
SMMS-0040-C	25 Gallon Level	32.27	330	Out	1.22	0.84
SMMS-0040-D	25 Gallon Level	32.56	330	Out	1.23	-0.05
SMMS-0041-A	Tank Bottom	33.80	330	Out	1.23	-3.86
SMMS-0041-B	Tank Bottom	32.88	330	Out	1.23	-1.03
SMMS-0041-C	Tank Bottom	32.66	330	Out	1.24	-0.35
SMMS-0041-D	Tank Bottom	32.19	330	Out	1.22	1.09

It was expected that the Ten Pascal fluid would not settle throughout the duration of the agitator test, based on the settling tests performed in section 2.2. However, samples were taken during the 40 gallon, Ten Pascal Test. Each sample was analyzed for weight percent total solids and density. Solids sampling was not done, with the coils in or with the coils out, until the following day. Table 3-3 summarizes the physical properties of the Ten Pascal Test samples.

Table 3-3 Physical Properties from the 40 Gallon Ten Pascal Fluid Mixing Tests

Sample	Location	Wt.% Total Solids	Agitator Speed (RPM)	Coils	Density (g/mL)	% Deviation Total Solids
SMMS-0042-A	Surface Level	31.35	330	Out	1.18	1.12
SMMS-0042-B	Surface Level	29.57	330	Out	1.19	6.73
SMMS-0042-C	Surface Level	30.75	330	Out	1.20	3.01
SMMS-0042-D	Surface Level	30.04	330	Out	1.19	5.25
SMMS-0043-A	25 Gallon Level	32.05	330	Out	1.22	-1.09
SMMS-0043-B	25 Gallon Level	32.28	330	Out	1.22	-1.82
SMMS-0043-C	25 Gallon Level	32.1	330	Out	1.22	-1.25
SMMS-0043-D	25 Gallon Level	31.71	330	Out	1.22	-0.02
SMMS-0044-A	Tank Bottom	32.54	330	Out	1.22	-2.64
SMMS-0044-B	Tank Bottom	33.4	330	Out	1.22	-5.35
SMMS-0044-C	Tank Bottom	32.73	330	Out	1.22	-3.24
SMMS-0044-D	Tank Bottom	31.93	330	Out	1.22	-0.71
SMMS-0045-A	Surface Level	31.04	330	In	1.20	1.20
SMMS-0045-B	Surface Level	30.81	330	In	1.21	1.92
SMMS-0045-C	Surface Level	30.58	330	In	1.20	2.65
SMMS-0045-D	Surface Level	30.89	330	In	1.20	1.67
SMMS-0046-A	25 Gallon Level	31.78	330	In	1.23	-1.14
SMMS-0046-B	25 Gallon Level	31.58	330	In	1.21	-0.51
SMMS-0046-C	25 Gallon Level	31.63	330	In	1.21	-0.67
SMMS-0046-D	25 Gallon Level	31.49	330	In	1.20	-0.22
SMMS-0047-A	Tank Bottom	31.85	330	In	1.22	-1.36

Table 3-3 Physical Properties from the 40 Gallon Ten Pascal Fluid Mixing Tests

Sample	Location	Wt.% Total Solids	Agitator Speed (RPM)	Coils	Density (g/mL)	% Deviation Total Solids
SMMS-0047-B	Tank Bottom	31.61	330	In	1.21	-0.60
SMMS-0047-C	Tank Bottom	31.88	330	In	1.21	-1.45
SMMS-0047-D	Tank Bottom	31.89	330	In	1.21	-1.49

Three samples taken from the Ten Pascal slurry with coils-removed fell outside of the 5% uniformity requirement. Sampling did not occur until 12 hours after the Ten Pascal Test was completed, which is a time lapse of greater than what is expected of normal DWPF operations. All sampling locations were identical to those of the Five Pascal Test samples. Samples were taken in quadruplicate for the Ten Pascal Test as well, and showed, as expected, very little variation in distribution. Figure 3-6 and Figure 3-7 is a graphical representation of solids distribution during the Ten Pascal Tests. Additionally, based on these results, mixing with the coils in seemed to provide a more homogenous distribution than that with the coils out. This could be due to the higher shear rates (bulk) which could have reduced the apparent viscosity to a point were the larger frit particles have settled and are not easily re-suspended through the mixing tank.

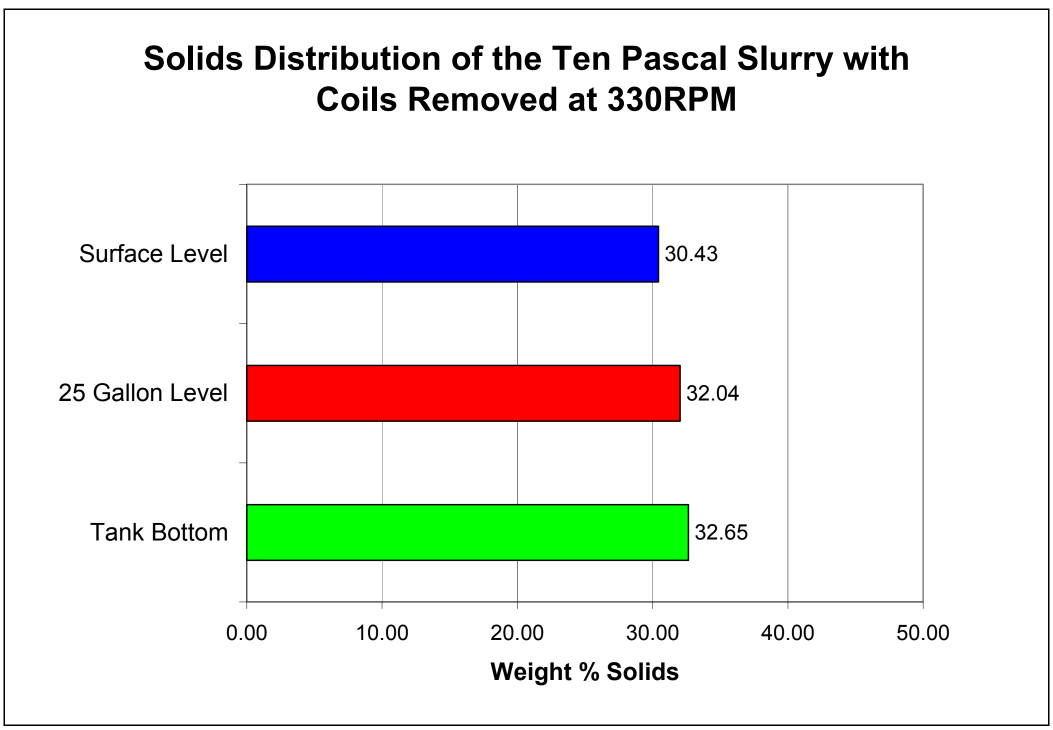

Figure 3-6. Histogram of Wt% TS Distribution for Ten Pascal Mixing Tests with Coils Out at 40 Gallons

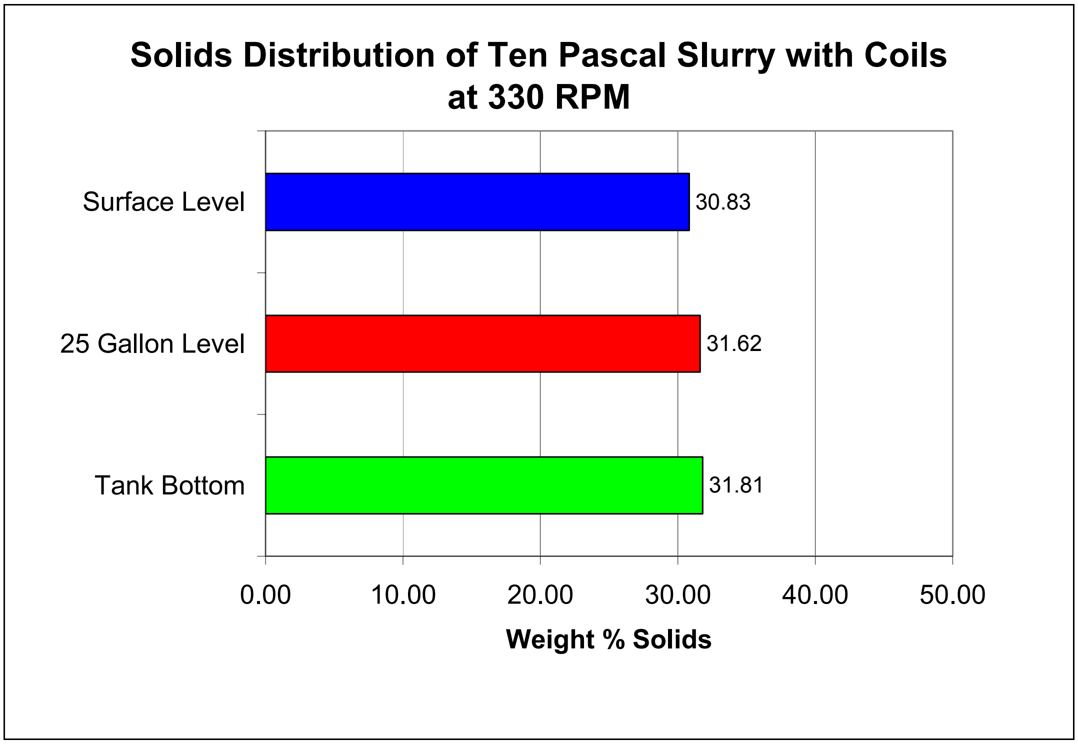

Figure 3-7. Histogram of Wt% TS Distribution for Ten Pascal Mixing Tests with Coils In at 40 Gallons

Given that the frit in the Ten Pascal slurry settles faster than the frit in the Twenty Pascal slurry, coupled with the fact that the Ten Pascal slurry exhibited a fairly decent wt.% solids distribution even after mixing cessation for over twelve hours, it was decided that no solids distribution sampling will be performed during testing with the Twenty Pascal slurry.

3.4.2 Surface Phenomena

To quantify the surface phenomena a Lieco Disto Pro 4[a] Laser Distance Meter was used to measure the surface to tank lid distance. Measurements were taken from Tank edge towards the tank middle at several measured increments creating a *surface profile*.

Surface profiles quantify the shape of the vortex and can be used to show the differences in the size of the vortex for a given agitator speed, with and without the coils. During testing of the Five Pascal slurry, significant vortex formation was noted at the 6 gallon level, the 25 gallon level, and the 40 gallon level, with the coils removed. For the 5 Pascal slurry a vortex was present with the coils in and with the coils out, at 220 RPM at the 25 gallon level. However, the vortex was slightly deeper with the coils out than with the coils in, as seen in Figure 3-8. When the coils were in, they seem to provide some natural baffling or the overall flow produced by the impellers is smaller with the coils in as compared to with the coils out.

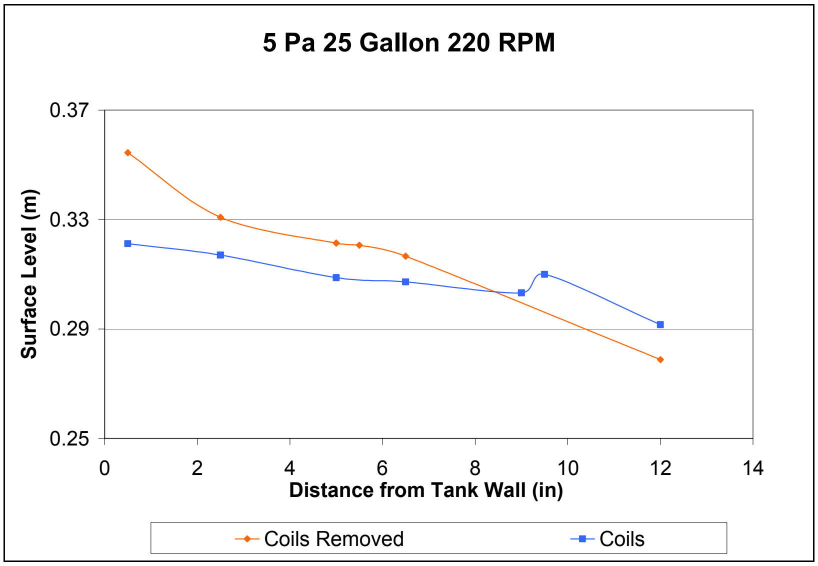

Figure 3-8. Impact of Coils on Vortex Depth at 220 RPM For 25 Gallon 5 Pa Slurry

While testing at the 40 gallon levels with the 5 Pascal slurry, a significant vortex was present when mixing at 360 RPM with the coils out and at 420 RPM with the coils in. No vortexing occurred during the 40 gallon tests with the 10 Pascal or the 20 Pascal slurries. Figure 3-9 shows, the vortex during the 25 gallon test of the Ten Pascal slurry was greater with the coils removed.

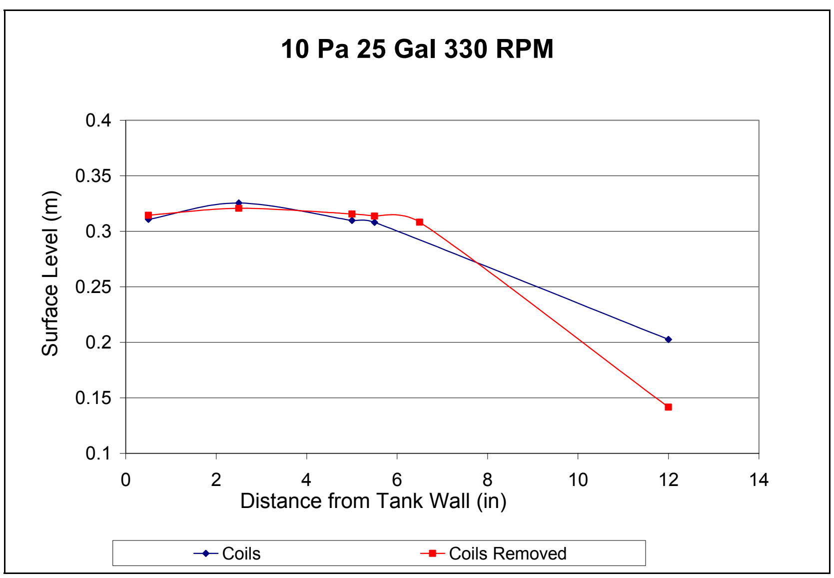

Figure 3-9. Impact of Coils on Vortex Depth at 330 RPM For 25 Gallon 10 Pa Slurry

The 20 Pascal slurry had very little vortexing for all test conditions. A slight vortex occurred in both the 25 Gallon test with and without the coils. However, as previously discussed, during the 25 Gallon test with the coils in, the center of the vortex was higher than the surrounding areas. The cause of this phenomenon was not investigated. During the 6 Gallon test with coils in, there was a slight vortex, however, with the coils out there was a deep vortex revealing the lower impeller hub.

The overall trend during testing was that the depth of the vortex increased for a given agitator speed with the coils out as compared with the coils in. Agitator speed also impacted the size and depth of the vortex in a proportionate manner, which has not been quantified in this task. In general, as the agitator speed increased for a given test condition, so did the size and depth of the vortex.

Several qualifiers must be mentioned with respect to the surface profile measurements. When the coils were in the vessel, the plate at the top of the coils assembly blocked the laser from measuring surface level between the 13 through 17 half-inch marks. The direct drive motor, and the gear reduced motor prevented measurements beyond the 15 half-inch mark. Another issue with measuring the vortex center (11.6 inches from the tank wall) was the tendency for the vortex to oscillate (the vortex would slightly collapse and then grow again), thus increasing the variance of surface level measurements taken near the agitator shaft. This caused very erratic readings, and when graphed the error bars increased significantly as measurements moved towards the center of the vortex. The inconsistency inherent in the data because of the above issue required that the data be treated in context with other information such as visual observations to accurately reflect test results.

Previous testing showed very similar results with respect to homogeneity of solids when mixing, and the ability to mix well at given speeds and volumes.[7, 8] Full mixing was noted at the 5Pa test with 25 gallons at 220 RPM, which compared well with the results seen in a full scale test of a 7 Pa fluid at 6000 gallons and 67 RPM performed during the Homogeneity Study. Although, the results in this report compare well with the results of that previous testing, the comparison is limited to mid-level and low level volumes. There was no apparent comparison for high volume testing (approximately 9500 gallons) done on mixing in the SME or the MFT.

[7] Jenkins, W.J., MFT Homogeneity Study at TNX – Preliminary Report on the High Weight Percent Solids Concentration (U). September 2, 1993. WSRC-RP-93-1229.
[8] Jenkins, W.J., MFT Homogeneity Study at TNX – Final Report on the Low Weight Percent Solids Concentration (U). September 21, 1993. WSRC-RP-93-1271.

4.0 SCALING METHODS

There are many different methods available for scaling agitator speeds, each geared towards a specific aspect of mixing. Equal solids suspension and equal power per unit volume consumption are two examples of desired results that yield two different methods of scaling. It is important in agitator speed scaling (either up or down) that geometric similarity exists between the pilot scale vessel and the full scale vessel. However, even with geometrically similar vessels, scaling mixing processes can be unpredictable due to dynamic and kinematic dissimilarities. Scaling using dynamic/kinematic similarities for unique mixing conditions further complicates the problem, due to lack of available technical references supporting the use of the similarity. This problem can be further complicated, if multiple mixing requirements (equal solids suspension, similar surface phenomena, etc.) are required. When scaling mixing processes, it is pertinent to evaluate all the available scaling methods with regards to a specific situation (i.e. the 1/6th Scale vessel to the DWPF Full Scale vessel) and use engineering judgment as to which method or hybrid of methods will result in the desired mixing process.

Ekato performed the initial testing to determine the speed and power requirements for the current DWPF vessels. The Ekato results were presented as a log-log plot of agitator speed versus vessel diameter.[9] This diagram was the primary method for determining the scaled agitator speeds for this testing. As mentioned, there are many different ways to scale mixing tanks, however, each contains different limiting aspects depending on the intended outcome.

The agitator speed can be scaled using a geometric property, such as impeller diameter, tank diameter or volume. Geometric properties that have the same degree of freedom can be interchanged, for example, one can use tank diameter in place of impeller diameter, without causing a change in the exponents shown in equation 4.0, but would change the value of the constant K_j. The different scaling methods provided below can be represented in the form of:

$$n_i^v \cdot D^w = K_j \qquad (4.0)$$

Where: n_i = agitator speed (revolutions/second)
K_j = constant for a given condition (having units of $n_i^v \cdot D^w$)
D = impeller diameter (m)
v = speed exponent (unitless)
w = diameter exponent (unitless)

Note that Kj is assumed constant when scaling between the two different sized scaled processes. For two different scales, where "1" denotes the full scale and "2" denotes the pilot scale, the above equation reduces to:

[9] Located in Appendix E.

$$\frac{n_2}{n_1} = \left(\frac{D_2}{D_1}\right)^{-\frac{w}{v}} \tag{4.1}$$

4.1 Equal Reynolds Number

A sizing method yielding one of the largest changes in agitator speed from one scale to another is equal Reynolds Number. The Reynolds Number (N_{RE}) for a power-law fluid can be calculated using the following equation[10]:

$$N_{RE} = \frac{\rho n^{2-n'} D^2}{K\left(k_s\right)^{n'-1}} \tag{4.2}$$

Where: ρ = Density (Kg/m^3)
n = Rotational Speed (Revolutions/Second)
D = Impeller Diameter (m)
k_s = Effective Shear Rate Constant (unitless)
n' = Flow Behavior Index of a Power Law Fluid (unitless)
K = Power Law Coefficient (Pa-sec$^{n'}$)

Reconfiguring equation (4.2) into equation (4.1) and using equation (4.2) yields the following sizing correlation:

$$\frac{n_2}{n_1} = \left(\frac{D_2}{D_1}\right)^{\frac{-2}{2-n'}} \tag{4.3}$$

Note that equation (4.3) is dependent on the flow behavior index (hence is fluid dependent) and in the case where the fluid is Newtonian (n' = 1), equation (4.4) reduces to the Newtonian case, as expected. Using the DWPF Full Scale vessel low speed setting (67 RPM) and the 10 Pa slurry model as a Power Law fluid (where n' = 0.3576, K =7.162 Pa·sec$^{0.3576}$), the agitator speed for the 1/6th Scale vessel is shown below. Table 4-1 contains all the results for the 5, 10 and 20 Pa fluids fitted with a Power Law model.

$$n_2 = 67RPM\left(\frac{5.8}{36}\right)^{-1.2177} = 619 \;\; RPM$$

[10] Wilkens, R.J., Henry, C., Gates, L.E., "How to Scale-Up Mixing Processes in Non-Newtonian Fluids", Chem. Eng. Prog., 100 (5), pp.44-52. May 2003.

Table 4-1 Scaling Agitator Speeds Using Equal Reynolds Number

Full Scale Agitator Speed (RPM)	Yield Stress (Pa)		
	5	10	20
	K =1.057 Pa sec$^{n'}$ n' =0.4133	K = 2.774 Pa sec$^{n'}$ n' =0.3576	K = 7.162 Pa sec$^{n'}$ n' =0.273
67	669	619	555
103	1029	952	853
134	1338	1240	1110

4.2 Equal Cavern Diameter Ratio

The cavern (area which has active mixing) can be estimated and the method for determining the cavern diameter ratio can be used for sizing. The size of the cavern diameter (D_c) can be estimated using the impeller diameter, power number, fluid density, agitator speed, and the yield stress of the fluid.[11, 12] The cylindrical cavern relationship[11, 12], equation (4.4) will be used. This correlation can be used to estimate the speed or impeller diameter for a required cavern size between the impeller and tank walls. Past this point, the cavern grows (in the z direction) directly proportional to the agitator speed.

$$\left(\frac{D_c}{D}\right)^3 = \left(\frac{1.36N_P}{\pi^2}\right)\left(\frac{\rho n^2 D^2}{\tau_y}\right) \tag{4.4}$$

Where: D_c= Cavern Diameter (m)
N_P = Power Number (unitless)
τ_y = Yield Stress (N/m^2)

Reconfiguring equation (4.4) into equation (4.1) and using equation (4.2) yields the following (this assumes that the power number, density, and yield stress do not change):

$$\frac{n_2}{n_1} = \left(\frac{D_2}{D_1}\right)^{-1} \tag{4.5}$$

To properly utilize these equations, a baseline condition must be determined (such as when the cavern reaches the tank wall D_c = T) to determine an agitator speed. In this case, $D_C/D = T/D = 4$. Using a power number of 6[13], yield stress of 10 Pa and a density of 1200 kg/m^3 for the DWPF full scale vessel, the agitator speed is:

[11] Solomon, J., Elson, T.P., Nienow, A.W., and Pace, G.W., Chemical Engineering Com. Vol. 11 pp143, 1981.
[12] Elson, T.P., Cheesman, D.J., Nienow, A.W., Chemical Engineering Science. Vol.41, No 10, pp.2555-2562, 1986.
[13] Power number taken from Ekato report, see Appendix E.

$$n_1 = \sqrt{\left(\frac{D_c}{D}\right)^3 \left(\frac{\pi^2 \cdot \tau_y}{1.36 N_P \cdot \rho \cdot D^2}\right)} = \sqrt{\left(\frac{12}{3}\right)^3 \cdot \frac{\pi^2 \cdot 10 Pa \cdot \left(\frac{kg \cdot m}{Pa \cdot s^2}\right)}{1.36 \cdot 6 \cdot 1200 \frac{kg}{m^3} \cdot (0.9144)^2}}$$

$$= 0.8784 \frac{rev}{\sec} = 52.7 RPM$$

For the 1/6th Scale vessel agitator speed to have the same cavern condition (to the wall of the tanks), is:

$$n_2 = 52.7 \left(\frac{5.8}{36}\right)^{-1} = 327 \ RPM$$

The agitator speeds for the other fluids are shown in Table 4-2. Note the exponent using equal cavern diameter is -1.0, slightly less than that of the Reynolds Number method for a given fluid. In general, the calculated N_{RE} speeds are much higher than that of the equal cavern method.

Table 4-2 Scaling Agitator Speed Using Equal Cavern Diameter Method To Reach the Wall of the Mixing Tank

Process	Tank Diameter (inches)	Yield Stress (Pa)		
		5	10	20
1/6th Scale	5.8	231 RPM	327 RPM	463 RPM
DWPF Scale	36	37.3 RPM	52.7 RPM	74.5 RPM

Note that this is the agitator speed required to have mixing to the walls of the tank, not necessarily throughout the vessel. The agitator speed past this point increases linearly after the cavern reaches the wall[11, 12], but is not calculated in this report. Note, that the minimum operating speed (67 RPM) for the full scale DWPF process with a 20 Pa fluid, there would be a cavern that does not reach the tank walls.

4.3 Equal Tip Speed

The impeller tip speed, S_t, is a relatively common method for scaling. Tip Speed scaling is generally associated with shear sensitive mixing phenomena, such as particle or droplet size control. [10] Tip Speed can be calculated by:

$$S_t = \pi n D \tag{4.6}$$

Reconfiguring equation (4.8) into equation (4.1) and using equation (4.2) yields the following:

$$\frac{n_2}{n_1} = \left(\frac{D_2}{D_1}\right)^{-1} \tag{4.7}$$

Note that tip speed, equation (4.6), is independent of any physical property. The exponent for both the equal cavern diameter ratio and equal tip speed are the same. In reality, the speed for complete mixing as determined by the cavern method would yield a larger agitator speed, since the above equal cavern diameter ratio does not take into consideration additional speed for complete tank mixing. Equal Tip Speed should be used for scale-up only when small-scale studies have definitively shown that required process performance correlates with Tip Speed. Equal Tip Speed has been calculated for the 1/6th Scale vessel at 67 RPM DWPF Full Scale and is shown below. Results for the other speeds are provided in Table 4-3.

$$n_2 = 52.7\left(\frac{5.8}{36}\right)^{-1} = 327 \;\; RPM$$

Table 4-3 Scaling Agitator Speed Using Equal Tip Speed Method

Agitator Speed (RPM) DWPF Scale	1/6th Scale
67	416
103	639
134	832

4.4 Equal Power Per Unit Volume

Scale-up utilizing the Power Per Unit Volume (P/V) is one of more common and acceptable methods for sizing. The advantage to P/V scaling is three fold; this method is well established and documented, easily measured on a pilot scale, and typically conservative (providing adequate mixing in the full scale processes) when scaling from pilot to full scale equipment. To calculate P/V in turbulent flow, the following equation can be used:

$$\frac{P}{V} = \frac{\left(N_p \rho n^3 D^5\right)}{\left(\frac{\pi T^2 Z}{4}\right)} \tag{4.8}$$

Where: P = Impeller Power (W)
V = Volume (m^3)
T = Tank Diameter (m)
Z = Depth of Liquid in Vessel (m)

From geometric similarities, equation (4.8) can be written as:

$$\frac{P}{V}\alpha\frac{N_p\rho n^3D^5}{D^3}=N_p\rho n^3D^2 \qquad (4.9)$$

Reconfiguring equation (4.9) into equation (4.1) and using equation (4.2) yields the following:

$$\frac{n_2}{n_1}=\left(\frac{D_2}{D_1}\right)^{-\frac{2}{3}} \qquad (4.10)$$

Power per Unit Volume is generally used for scale-up unless there are specific agitation requirements such as particle dispersion, solids distribution, or surface phenomena. Unlike tip speed, power per unit volume is dependent on many variables. Equal P/V has been calculated for the 1/6th Scale vessel at 67 RPM DWPF Full Scale and is shown below. Results for the other DPWF agitator speeds are provided in Table 4-4.

$$n_2=67\left(\frac{5.8}{36}\right)^{-\frac{2}{3}}=226\ \ RPM$$

Table 4-4 Scaling Agitator Speed Using Equal Power Per Unit Volume

Agitator Speed (RPM)	
DWPF Scale	**1/6th Scale**
67	226
103	348
134	453

4.5 Ekato Method

Ekato was the agitator vendor who performed the original agitator testing to determine the agitator speed, motor size, and agitator shaft for the DWPF processes. Ekato used two different scales and then interpolated the test results to determine the agitator speed that would provide adequate mixing, given the dimensions of the full scale mixing processes at DWPF. The Ekato test conditions and results are shown in Appendix E. A summary of their testing is provided below:

- The fluids used had the following approximate fluid properties: yield stress of 7 Pa, and consistency of 0.025 Pa·s.
- The top of the bottom flat blade impeller was located just below the draft tube, discharging its flow into the bulk of the tank. This is different from that of the DWPF and the 1/6th scale, where the bottom impeller partially discharges some of its flow directly into the coils.
- The two scales used by Ekato are not geometrically similar.

The small vessel and pilot vessel results that provided adequate visual mixing (speed and tank diameter) and the speed recommended by Ekato for DWPF are shown in Figure 4-1.

These three data points were fitted to a power law model and the exponent of -0.6386 was determined and shown in Figure 4-1.

The Ekato speed has been calculated for the 1/6th Scale vessel at 67 RPM DWPF Full Scale and is shown below. Results for the other DPWF agitator speeds are provided in Table 4-5. The results are very similar to the power per unit volume results in the previous section.

$$n_2 = 67\left(\frac{5.8}{36}\right)^{-0.6386} = 215 \;\; RPM$$

Table 4-5 Scaling Agitator Speed Using Ekato Method

Agitator Speed (RPM) DWPF Scale	Agitator Speed (RPM) 1/6th Scale
67	215
103	330
134	420

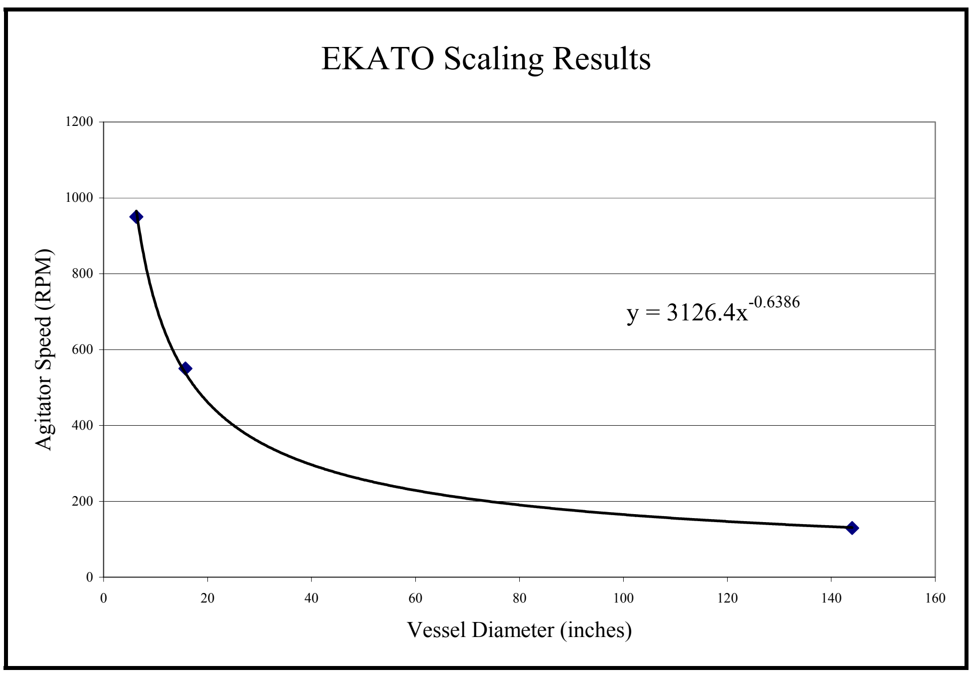

Figure 4-1. Ekato Test Results

4.6 Equal Froude Number

The Froude Number method, N_{Fr}, is among the most conservative of scale up methods. Often Equal Froude Number is disregarded because it results in a high (in some cases, impossibly high) rotational speed at full scale conditions. The N_{Fr} is defined as the ratio of the inertial force over the gravitational force of agitation in a mixing vessel:

$$N_{Fr} = \frac{n^2 D}{g} \tag{4.11}$$

Where: g = gravity, m/s^2

Reconfiguring equation (4.11) into equation (4.1) and using equation (4.2) yields the following:

$$\frac{n_2}{n_1} = \left(\frac{D_2}{D_1}\right)^{-\frac{1}{2}} \tag{4.12}$$

The Froude Number is most appropriate for scaling when trying to maintain similar surface phenomena as it accounts for gravitational effects with respect to significant vortexing.[14] Equal Froude number has been calculated for the 1/6th scale vessel at 67 RPM DWPF full scale and is shown below. Results for the other DPWF agitator speeds are provided in Table 4-6. Note that the results in Table 4-6 assume that a visual verification of the phenomena occurred, which is not the case, since there is no data to state the condition of the agitated surface and to compare this to the scaled system.

$$n_2 = 67\left(\frac{5.8}{36}\right)^{-\frac{1}{2}} = 167 \ \ RPM$$

Table 4-6 Scaling Agitator Speed Using Equal Froude Number

Agitator Speed (RPM)	
DWPF Scale	**1/6th Scale**
67	167
103	257
134	324

4.7 Comparison of 1/6th Scaled Mixing to TNX Homogeneity Study

A comparison was made between the 1/6th Scaled mixing vessel test results and the Homogeneity Studies.[7,8] At 6000 Gallons and 100 RPM the Homogeneity Studies showed complete mixing with uniform solids suspension. Complete mixing and solids suspension was seen in the 1/6th Scale tests at 25 Gallons (6000 gallon equivalent) and 330 RPM. The rheology of the fluids used in both test were similar, but not identical. The fluid used in the homogeneity testing was approximately 7 Pascals, where as, the comparable fluid in the 1/6th Scale testing was 5 Pascals. Utilizing those two points a power-law regression was performed and the results are shown in Figure 4-2. Thus, the

[14] Skelland, A.H.P., Non-Newtonian Flow and Heat Transfer. pp.310-311, 1967. John Wiley & Sons, Inc. New York.

Power per Unit Volume method may be too conservative (not yielding adequate agitator speed) when scaling from the 1/6th Scale vessel to the DWPF Full Scale vessel. However, error is inherent with just two points, and therefore the results should be used with caution.

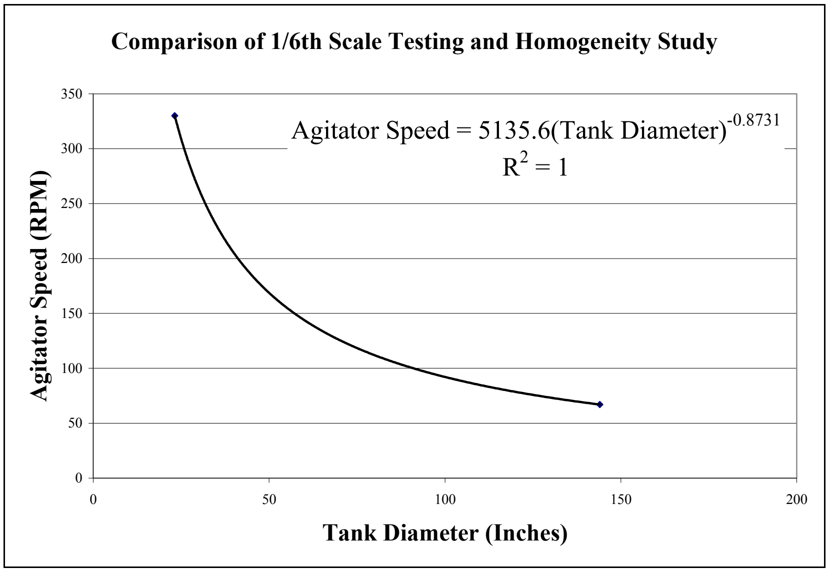

Figure 4-2. Comparison to TNX Homogeneity Study

Given the DWPF scale, the 1/6th Scale dynamic/kinematic properties used in the above sections were calculated for the three different fluids and the 67 RPM and 130 RPM Full Scale speeds and the results are shown in Table 4-7 through Table 4-12. In all these calculations, it was assumed that the power number is constant for the condition of flow and the effective shear rate constant is applicable throughout all Reynolds numbers. Using the DWPF design parameters to determine the mixing properties of the 1/6th Scale clearly indicate that N_{RE} predicts the highest agitator speed and the N_{Fr} predicts the lowest. The Reynolds number indicates that if other scaling methods are used other than equal N_{RE}, the Reynolds number for the 1/6th Scale could be an order of magnitude lower than that of the DWPF scale, resulting in inappropriate utilization of the power number. If Cavern mixing exists on the 1/6th Scale, it may not necessarily exist on the Full Scale. In most cases the cavern ratio for the Full Scale is greater than those of the 1/6th Scale, indicating that there would be less of a chance to have cavern mixing.

The scaling methods discussed here are based upon scaling of vessels of standard mixing geometries that are geometrically similar and are not all inclusive. These scaling methods do not account for mixing vessels that have heating and cooling coils surrounding the impellers nor do they consider having the bottom impeller located very near the bottom of the mixing vessel. These issues add more uncertainty when sizing. Another issue, such as wall surface area per volume has a greater effect on a small scale mixing vessel than it would on a large scale mixing vessel. Finally, the number of coils columns in the mixing vessel could also impact sizing.

Table 4-7 Dynamic/Kinematic Properties of 1/6th Scale Using Various Sizing Methods – 5 Pa Fluid, 130 RPM

Input Data

Fluid Density:	1200.0	kg/m^3
Yield Stress:	5	Pa (N/m^2)
Power Law Coef:	1.057	Pa·s$^{n'}$
Flow index:	0.4133	unitless
Impeller shear ratio:	11	unitless
Impeller Power Number:	6	unitless

	Full Scale	Pilot	Units
Tank Dia.:	144	23.2	inches
Tank Vol.:	9500	40	gallons
Impeller Dia.:	36	5.8	inches

Property	Units	Full Scale	Scaling Method Used To Determine Pilot Scale Properties				
			N_{RE}	Cavern / N_{TS}	P/V	Ekato	N_{Fr}
Rotational Speed	RPM	130	1298	807	439	382	324
N_{RE}	unitless	211488	211488	99447	37865	30315	23365
Cavern Ratio	unitless	9.20	12.63	9.20	6.13	5.59	5.01
Tip Speed	m/s	6.22	10.01	6.22	3.39	2.94	2.50
Power	Watts	46859	5065	1216	196	129	79
PV	W/m^3	1303	33458	8034	1294	850	520
Froude Number	unitless	0.44	7.03	2.72	0.80	0.61	0.44

Table 4-8 Dynamic/Kinematic Properties of 1/6th Scale Using Various Sizing Methods – 5 Pa Fluid, 67 RPM

Input Data

Fluid Density:	1200.0	kg/m^3
Yield Stress:	5	Pa (N/m^2)
Power Law Coef:	1.057	Pa·s$^{n'}$
Flow index:	0.4133	unitless
Impeller shear ratio:	11	unitless
Impeller Power Number:	6	unitless

	Full Scale	Pilot	Units
Tank Dia.:	144	23.2	inches
Tank Vol.:	9500	40	gallons
Impeller Dia.:	36	5.8	inches

Property	Units	Full Scale	Scaling Method Used To Determine Pilot Scale Properties				
			N_{RE}	Cavern / N_{TS}	P/V	Ekato	N_{Fr}
Rotational Speed	RPM	67	669	416	226	197	167
N_{RE}	unitless	73880	73880	34740	13227	10590	8162
Cavern Size	unitless	5.91	8.12	5.91	3.94	3.59	3.22
Tip Speed	m/s	3.21	5.16	3.21	1.75	1.52	1.29
Power	Watts	6415	693	167	27	18	11
PV	W/m^3	178	4580	1100	177	116	71
Froude Number	unitless	0.12	1.87	0.72	0.21	0.16	0.12

Table 4-9 Dynamic/Kinematic Properties of 1/6th Scale Using Various Sizing Methods – 10 Pa Fluid, 130 RPM

Input Data

Fluid Density:	1200.0	kg/m^3
Yield Stress:	10	Pa (N/m^2)
Power Law Coef:	2.774	$Pa{\cdot}s^{n'}$
Flow index:	0.3576	unitless
Impeller shear ratio:	11	unitless
Impeller Power Number:	6	unitless

	Full Scale	Pilot	Units
Tank Dia.:	144	23.2	inches
Tank Vol.:	9500	40	gallons
Impeller Dia.:	36	5.8	inches

Property	Units	Full Scale	Scaling Method Used To Determine Pilot Scale Properties				
			N_{RE}	Cavern / N_{TS}	P/V	Ekato	N_{Fr}
Rotational Speed	RPM	130	1201	807	439	382	324
N_{RE}	unitless	96153	96153	50053	18423	14635	11177
Cavern Size	unitless	7.30	9.52	7.30	4.87	4.43	3.97
Tip Speed	m/s	6.22	9.26	6.22	3.39	2.94	2.50
Power	Watts	46859	4008	1216	196	129	79
PV	W/m^3	1303	26474	8034	1294	850	520
Froude Number	unitless	0.44	6.01	2.72	0.80	0.61	0.44

Table 4-10 Dynamic/Kinematic Properties of 1/6th Scale Using Various Sizing Methods – 10 Pa Fluid, 67 RPM

Input Data

Fluid Density:	1200.0	kg/m^3
Yield Stress:	10	Pa (N/m^2)
Power Law Coef:	2.774	$Pa{\cdot}s^{n'}$
Flow index:	0.3576	unitless
Impeller shear ratio:	11	unitless
Impeller Power Number:	6	unitless

	Full Scale	Pilot	Units
Tank Dia.:	144	23.2	inches
Tank Vol.:	9500	40	gallons
Impeller Dia.:	36	5.8	inches

Property	Units	Full Scale	Scaling Method Used To Determine Pilot Scale Properties				
			N_{RE}	Cavern / N_{TS}	P/V	Ekato	N_{Fr}
Rotational Speed	RPM	67	619	416	226	197	167
N_{RE}	unitless	32372	32372	16851	6202	4927	3763
Cavern Size	unitless	4.69	6.12	4.69	3.13	2.85	2.55
Tip Speed	m/s	3.21	4.77	3.21	1.75	1.52	1.29
Power	Watts	6415	549	167	27	18	11
PV	W/m^3	178	3624	1100	177	116	71
Froude Number	unitless	0.12	1.60	0.72	0.21	0.16	0.12

Table 4-11 Dynamic/Kinematic Properties of 1/6th Scale Using Various Sizing Methods – 20 Pa Fluid, 130 RPM

Input Data

Fluid Density:	1200.0	kg/m^3
Yield Stress:	20	Pa (N/m^2)
Power Law Coef:	7.162	$Pa{\cdot}s^{n'}$
Flow index:	0.273	unitless
Impeller shear ratio:	11	unitless
Impeller Power Number:	6	unitless

	Full Scale	Pilot	Units
Tank Dia.:	144	23.2	inches
Tank Vol.:	9500	40	gallons
Impeller Dia.:	36	5.8	inches

Property	Units	Full Scale	Scaling Method Used To Determine Pilot Scale Properties				
			N_{RE}	Cavern / N_{TS}	P/V	Ekato	N_{Fr}
Rotational Speed	RPM	130	1077	807	439	382	324
N_{RE}	unitless	48702	48702	29586	10343	8120	6116
Cavern Size	unitless	5.80	7.03	5.80	3.86	3.52	3.15
Tip Speed	m/s	6.22	8.31	6.22	3.39	2.94	2.50
Power	Watts	46859	2891	1216	196	129	79
PV	W/m^3	1303	19095	8034	1294	850	520
Froude Number	unitless	0.44	4.84	2.72	0.80	0.61	0.44

Table 4-12 Dynamic/Kinematic Properties of 1/6th Scale Using Various Sizing Methods – 20 Pa Fluid, 67 RPM

Input Data

Fluid Density:	1200.0	kg/m^3
Yield Stress:	20	Pa (N/m^2)
Power Law Coef:	7.162	$Pa{\cdot}s^{n'}$
Flow index:	0.273	unitless
Impeller shear ratio:	11	unitless
Impeller Power Number:	6	unitless

	Full Scale	Pilot	Units
Tank Dia.:	144	23.2	inches
Tank Vol.:	9500	40	gallons
Impeller Dia.:	36	5.8	inches

Property	Units	Full Scale	Scaling Method Used To Determine Pilot Scale Properties				
			N_{RE}	Cavern / N_{TS}	P/V	Ekato	N_{Fr}
Rotational Speed	RPM	67	555	416	226	197	167
N_{RE}	unitless	15502	15502	9418	3292	2585	1947
Cavern Size	unitless	3.73	4.52	3.73	2.48	2.26	2.03
Tip Speed	m/s	3.21	4.28	3.21	1.75	1.52	1.29
Power	Watts	6415	396	167	27	18	11
PV	W/m^3	178	2614	1100	177	116	71
Froude Number	unitless	0.12	1.28	0.72	0.21	0.16	0.12

5.0 CONCLUSIONS

Vortex formation increased significantly when the coil was removed, especially for the 5 Pa test fluid. Vortex formation can cause process upsets by entraining air into the process[15] and can cause uneven mechanical loading on the agitator shaft and subsequent failure. It should be noted that scaling of the vortex phenomena is extremely uncertain and the 1/6th scale results may not accurately reflect the severity of the problems that will occur in the full scale tank. However, removal of the coil did improve surface motion and solids distribution.

The 1/6th Scale test results showed good surface motion for the 5 Pa and 10 Pa fluids at 25 gallons for the 330 RPM tests (scales to 6000 gallons and 103 RPM), but the 20 Pa fluid indicated borderline results with small areas of stagnation around the wall. Cavern formation was noted for all fluids at 40 gallons (9500 gallons) at this speed. Sample results from the homogeneity samples did not indicate that the 5 Pa fluid was uniform at 40 gallons and 330 RPM with the coils in the tank.

Laboratory Scale test utilizing power per unit volume as the scaling parameters had significant cavern formation at higher volumes and at lower volumes with high yield stress materials. Comparisons of sizing methods indicate a variety of results, where sizing using the Reynolds number or Froude number are not recommended. The other sizing methods discussed may be suitable, however, additional testing may be required.

It should be noted that the DWPF MFT agitator is currently configured with a high speed setting of 103 RPM and that no operational difficulties have been noted. Sample results from the MFT have agreed with sample results from the SME, indicating that adequate mixing has been maintained in the MFT at the lower agitator speed. In addition, scale up of the 1/6th scale mixing test results to full scale process is very difficult and a variety of different methods that yield very different results are available.

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[15] Stone, M.E., Marinik. A.R., Small Scale Mixing Tests for the DWPF Chemical Process Cell Vessels (U). March 2004. WSRC-TR-2004-00074.

6.0 RECOMMENDATIONS

A plan should be developed to address vortex formation prior to removal of the MFT coil assembly.

The CFD models developed for the MFT and SME vessels should be validated versus the $1/6^{th}$ scale results. Validation of the model will lead to improved results from the model and will allow better representation of the DWPF process by the model.

The rheological properties of actual DWPF process slurries should be measured. A flow curve that would allow yield stress and consistency to be determined would be ideal, but even a single point measurement of apparent viscosity would lead to valuable insight into process conditions and aid in the evaluation of process upsets. The amount of variability in the process could be determined if the analysis is performed on routine process samples.

The MFT and SME agitators should not operate continuously at the low speed setting (67 RPM) when the vessels are above 6000 gallons to reduce the potential for cavern formation.

Alternative means of reducing the erosion rate on the cooling/heating coils due to the irregular shaped frit are:

- Conversion of irregular shaped frit to spherical shaped frit which is processed from the irregular shaped frit.
- Raising the lower section of the cooling/heating coils above the discharge of the bottom impeller. Raising the coils would likely improve mixing in the vessel.

APPENDIX A. Mixing Data for all Tests

Coils

5 Pascal

Time	Agitator Speed	Tank Level	Density Meter	Temperature	Air Flow	Agitator Power	Power/Volume
	RPM	Gallons	IN H20	Celsius	mL/min	Watts	watts/gallon
1405	76	40	98.79	22	10	11.4	0.285
1407	100	40	9.64	22	10	15.9	0.398
1408	150	40	9.76	22	10	30.3	0.758
1409	200	40	9.62	22	10	56.2	1.405
1410	220	40	9.5 - 9.8	22	10	70.4	1.760
1411	250	40	8.9 - 9.5	22	10	92.4	2.310
1414	275	40	8.9 - 9.6	22	10	117.3	2.933
1416	300	40	8.8 - 9.7	22	10	145.1	3.628
1417	325	40	8.8 - 9.9	22	10	181.2	4.530
1418	350	40	8.3 - 10.0	22	10	222	5.550
1420	378	40	8.11 - 9.71	22	10	272	6.800
1453	220	40	8.9 - 9.6	22	10	71.7	1.793
1500	0	40	9.53 - 9.92	22	10	0	-
1500	220	40	9.2 - 9.74	22	10	69.7	1.743
800	0	25	10.4	23	10	-	
926	60	25	9.6	23	10	8.7	0.35
947	150	25	9.6	23	10	29.9	1.20
951	220	25	9.49	23	10	63.5	2.54
800	300	25	8.7 - 9.5	22	10	188.7	7.55
954	330	25	8.8 - 10.0	23	10	171.6	6.86
959	390	25	8.8 - 9.9	23	10	275	11.00
1626	75	6	0.89	22	-	7.5	1.250
1628	150	6	0.86	22	-	17.3	2.883
1630	220	6	0.72	22	-	26.9	4.483
1632	330	6	0.71	22	-	52.5	8.750
1635	420	6	1.02	22	-	75.3	12.550
1637	800	6	1.4	22	-	235	39.167

Time	Agitator Speed	Tank Level	Density Meter	Temperature	Air Flow	Agitator Power	Power/Volume
	RPM	Gallons	IN H20	Celsius	mL/min	Watts	watts/gallon
1050	74	25	9.7	21	10	25.9	1.04
1051	100	25	9.7	21	10	36.7	1.47
1052	150	25	9.62	21	10	60.9	2.44
1054	175	25	9.52	21	10	75.1	3.00
1055	200	25	9.5	21	10	92.1	3.68
1059	220	25	9.56	21	10	107.2	4.29
1105	300	25	9.69	21	10	178.5	7.14
1107	330	25	9.45	21	10	207	8.28
1110	345	25	9.45	21	10	218	8.72
1124	75	25	9.43	21	10	13.5	0.54
1125	100	25	9.83	21	10	15.8	0.63
1126	150	25	9.5	21	10	23.1	0.92
1127	200	25	9.6	21	10	36.8	1.47
1129	220	25	9.81	21	10	43.3	1.73
1131	250	25	9.55	21	10	55.5	2.22
1133	300	25	9.26	21	10	85.4	3.42
1135	330	25	9.03	21	10	111	4.44
1139	375	25	8.88	21	10	162	6.48
1140	400	25	10.51	21	10	196	7.84
1141	420	25	8.54	21	10	226	9.04
1145	445	25	10.6	21	10	267	10.68

Time	Agitator Speed	Tank Level	Density Meter	Temperature	Air Flow	Agitator Power	Power/Volume
	RPM	Gallons	IN H20	Celsius	mL/min	Watts	watts/gallon
1445	75	38	9.38	21	10	12.5	0.33
1449	100	38	9.37	21	10	14.8	0.39
1450	150	38	9.44	21	10	22.7	0.60
1451	200	38	9.52	21	10	37.6	0.99
1452	220	38	9.2	21	10	46	1.21
1500	250	38	9.12	21	10	59.6	1.57
1501	300	38	8.49	21	10	92.43	2.43
1502	330	38	8.67	21	10	117.4	3.09
1508	375	38	9.22	21	10	169.9	4.47
1509	400	38	8.99	21	10	199	5.24
1510	420	38	8.4	21	10	226	5.95
1514	437	38	6.54	21	10	261	6.87

10 Pascal

Time	Agitator Speed	Tank Level	Density Meter	Temperature	Air Flow	Agitator Power	Power/Volume
	RPM	Gallons	IN H20	Celsius	mL/min	Watts	watts/gallon
1432	220	40	9.65	21	10	111.7	2.7925
1455	220	40	9.57	22	10	104.5	2.6125
1456	75	40	9.64	22	10	24	0.6
1457	100	40	9.49	22	10	33.2	0.83
1500	150	40	9.83	22	10	56.6	1.415
1501	200	40	9.52	22	10	86.2	2.155
1502	250	40	9.07	22	10	124.5	3.1125
1502	275	40	9.52	22	10	147.5	3.6875
1503	300	40	9.3	22	10	174.5	4.3625
1503	330	40	8.59	22	10	202	5.05
1504	350	40	10.81	22	10	227	5.675
1347	220	25	9.57	22	10	111	4.44
1410	220	25	9.72	22	10	100.3	4.012
1417	220	25	9.55	22	10	97.3	3.892
1421	75	25	9.83	22	10	22.5	0.9
1425	100	25	9.38	22	10	31.6	1.264
1426	150	25	9.74	22	10	53.6	2.144
1427	200	25	9.54	22	10	82.6	3.304
1428	250	25	9.65	22	10	119.2	4.768
1429	275	25	9.49	22	10	140	5.6
1430	300	25	9.43	22	10	166.6	6.664
1431	330	25	9.3	22	10	195.3	7.812
1432	352	25	8.88	22	10	215	8.6
1023	75	6	3.66	20	10	27.8	4.63
1023	100	6	3.81	20	10	39	6.50
1024	150	6	3.59	20	10	60.5	10.08
1025	200	6	3.61	20	10	86.3	14.38
1026	220	6	3.75	20	10	97.9	16.32
1027	250	6	3.73	20	10	116.1	19.35
1028	275	6	3.94	20	10	129.8	21.63
1029	300	6	3.67	20	10	143.5	23.92
1030	330	6	3.72	20	10	160.2	26.70
1031	354	6	3.81	20	10	175.2	29.20

Time	Agitator Speed	Tank Level	Torque	Temperature	Air Flow	Agitator Power	Power/Volume
	RPM	Gallons	N-cm	Celsius	mL/min	Watts	watts/gallon
1438	330	40	196	21	10	120	3
1440	360	40	232	21	10	153	3.825
1441	420	40	324	21	10	235	5.875
1508	330	25	182	21	10	114	4.56
1514	420	25	295	21	10	217	8.68
1517	450	25	342	21	10	270	10.8

20 Pascal

Time	Agitator Speed	Tank Level	Density Meter	Temperature	Air Flow	Agitator Power	Power/ Volume
	RPM	Gallons	IN H20	Celsius	mL/min	Watts	Watts/Gallon
1634	75	40	9.69	22	10	20.9	0.52
1635	100	40	9.22	22	10	29.9	0.75
1636	150	40	9.29	22	10	48.9	1.22
1637	200	40	9.39	22	10	77.7	1.94
1638	220	40	10.01	22	10	91.2	2.28
1639	250	40	9.68	22	10	114.2	2.86
1640	275	40	9.44	22	10	135.6	3.39
1641	300	40	9.02	22	10	161.1	4.03
1642	330	40	9.79	22	10	193.6	4.84
1643	352	40	9.5	22	10	214	5.35
931	75	25	10.08	21	10	24.2	0.97
934	100	25	9.92	21	10	33.9	1.36
936	150	25	9.53	21	10	56.3	2.25
938	200	25	9.25	21	10	87	3.48
926	222	25	9.66	21	10	108	4.32
940	251	25	9.23	21	10	125.7	5.03
942	275	25	9.79	21	10	147.8	5.91
944	300	25	9.44	21	10	172.6	6.90
948	330	25	9.28	21	10	195	7.80
951	347	25	9.88	21	10	209	8.36
1358	75	6	4.79	21	10	26.2	4.37
1400	100	6	4.83	21	10	36.9	6.15
1402	150	6	4.84	21	10	59.6	9.93
1403	200	6	4.88	21	10	85.6	14.27
1404	220	6	4.46	21	10	97.5	16.25
1405	250	6	4.7	21	10	115.7	19.28
1406	275	6	4.84	21	10	130.7	21.78
1407	300	6	5.04	21	10	148.3	24.72
1408	330	6	4.59	21	10	162.5	27.08
1409	357	6	5.09	21	10	184	30.67

Time	Agitator Speed	Tank Level	Torque	Temperature	Air Flow	Agitator Power	Power/ Volume
	RPM	Gallons	N-cm	Celsius	mL/min	Watts	Watts/Gallon
1222	420	40	300	22	10	220	5.5
1227	450	40	338	22	10	265	6.625
1300	330	40	189	22	10	113	2.825
1310	420	40	313	22	10	228	5.7

Time	Agitator Speed	Tank Level	Torque	Temperature	Air Flow	Agitator Power	Power/Volume
	RPM	Gallons	N-cm	Celsius	mL/min	Watts	watts/gallon
1438	330	40	196	21	10	120	3
1440	360	40	232	21	10	153	3.825
1441	420	40	324	21	10	235	5.875
1508	330	25	182	21	10	114	4.56
1514	420	25	295	21	10	217	8.68
1517	450	25	342	21	10	270	10.8

Coils Removed

5 Pascal

Time	Agitator Speed RPM	Tank Level Gallons	Density Meter IN H20	Temperature Celsius	Air Flow mL/min	Agitator Power Watts	Power/Volume Watts/Gallon
1205	0	6	3.25	25	10	0.2	0.03
1215	150	6	3.4	23	10	59.0	9.83
1218	220	6	3.3	23	10	88.3	14.72
1224	330	6	3.4	23	10	151.6	25.27
1226	190	6	3.4	23	10	68.7	11.45
1437	98	25	9.8	22	10	34.1	1.36
1440	150	25	9.5	22	10	59.0	2.36
1504	150	25	9.4	22	10	49.2	1.97
1444	220	25	9.35	22	10	100.4	4.02
1449	330	25	9.3	22	10	179.2	7.17
1457	360	25	9.2	22	10	186.9	7.48
754	0	40	10.4	22	10	0.1	0.00
810	220	40	10.0	22	10	112.9	2.82
1010	220	40	9.9	22	10	85.8	2.15
1027	330	40	10.0	22	10	166.5	4.16
1220	360	40	9.4	23	10	185.0	4.63

10 Pascal

Time	Agitator Speed RPM	Tank Level Gallons	Density Meter IN H20	Temperature Celsius	Air Flow mL/min	Agitator Power Watts	Power/Volume Watts/Gallon
1014	0	6	6.34	21	10	-0.2	-
1049	75	6	3.76	22	10	23.2	3.87
1050	150	6	3.71	22	10	51.9	8.65
1054	190	6	3.68	22	10	66.6	11.10
1017	220	6	3.75	22	10	92.2	15.37
1028	220	6	3.87	22	10	90.6	15.10
1047	220	6	3.73	22	10	82.7	13.78
1051	330	6	3.69	22	10	143.3	23.88
1318	100	25	9.62	22	10	31.3	1.25
1319	150	25	9.54	22	10	51.6	2.06
1247	220	25	9.5	22	10	105.2	4.21
1322	330	25	8.7	22	10	187.5	7.50
1326	360	25	9.3	22	10	199.0	7.96
827	220	40	9.71	22	10	113.0	2.83
855	220	40	9.82	22	10	101.6	2.54
917	220	40	9.98	22	10	92.0	2.30
924	220	40	9.7	22	10	96.9	2.42
924	330	40	8.64	22	10	189.6	4.74
925	348	40	8.37	22	10	204.0	5.10

Time	Agitator Speed RPM	Tank Level Gallons	Torque N-cm	Temperature Celsius	Air Flow mL/min	Agitator Power Watts	Power/Volume Watts/Gallon
1540	330	25	154	20	10	100.0	4.00
1545	420	25	227	20	10	170.0	6.80
1550	450	25	242	20	10	200.0	8.00
1608	420	40	283	20	10	208.0	5.20
1609	330	40	182	20	10	113.0	2.83
1610	350	40	201	21	10	130.0	3.25
1612	380	40	243	21	10	162.4	4.06
1613	420	40	282	21	10	205.0	5.13
1615	450	40	309	21	10	243.0	6.08

20 Pascal

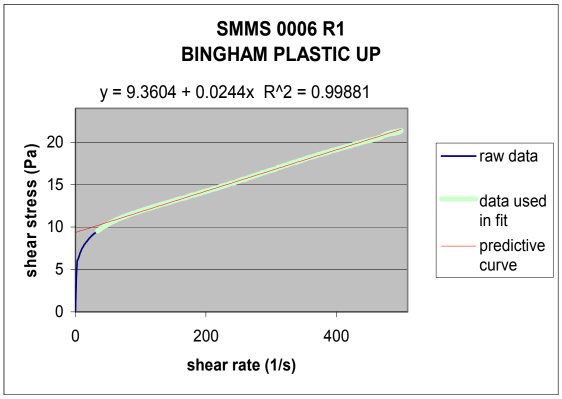
Time	Agitator Speed RPM	Tank Level Gallons	Density Meter IN H20	Temperature Celsius	Air Flow mL/min	Agitator Power Watts	Power/Volume Watts/Gallon
817	75	6	4.39	21	10	28.4	4.73
819	100	6	4.54	21	10	40.0	6.67
820	150	6	4.52	21	10	64.8	10.80
821	200	6	4.49	21	10	92.5	15.42
823	220	6	4.42	21	10	104.9	17.48
825	250	6	4.51	21	10	116.1	19.35
826	275	6	4.82	21	10	131.5	21.92
827	300	6	4.72	21	10	146.8	24.47
827	330	6	4.59	21	10	167.9	27.98
829	350	6	4.50	21	10	176.7	29.45
924	75	25	9.63	21	10	28.1	1.12
925	100	25	9.5	21	10	38.8	1.55
926	150	25	9.52	21	10	61.8	2.47
928	200	25	9.48	21	10	95.0	3.80
929	220	25	9.32	21	10	109.7	4.39
931	250	25	9.22	21	10	132.1	5.28
933	275	25	9.64	21	10	153.1	6.12
934	300	25	10.03	21	10	180.4	7.22
936	330	25	9.14	21	10	207.0	8.28
938	346	25	9.47	21	10	217.0	8.68
941	330	25	-	21	10	196.0	7.84
942	345	25	9.74	21	10	210.0	8.40
1155	75	40	9.94	21	10	23.2	0.58
1159	100	40	9.64	21	10	31.7	0.79
1159	150	40	9.57	21	10	54.9	1.37
1200	200	40	10.04	21	10	82.1	2.05
1201	220	40	10.08	21	10	94.7	2.37
1203	250	40	9.92	21	10	115.8	2.90
1204	275	40	9.32	21	10	138.3	3.46
1205	300	40	9.42	21	10	163.0	4.08
1206	330	40	10	21	10	197.0	4.93
1209	351.8	40	9.87	21	10	217.0	5.43

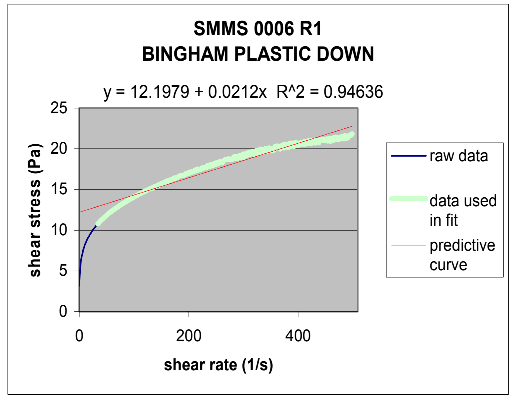
Time	Agitator Speed RPM	Tank Level Gallons	Torque N-cm	Temperature Celsius	Air Flow mL/min	Agitator Power Watts	Power/ Volume Watts/Gallon
1010	420	25	288	21	10	213.0	8.52
1017	330	25	166	21	10	102.0	4.08
1035	330	40	170	21	10	111.0	2.78
1037	420	40	310	21	10	210.0	5.25
1043	450	40	310	21	10	250.0	6.25

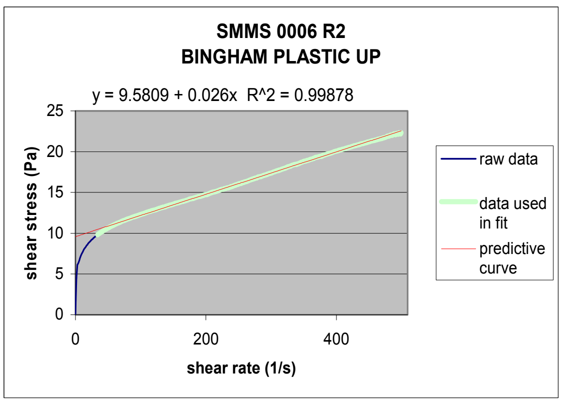
APPENDIX B. Composition of Simulant Samples

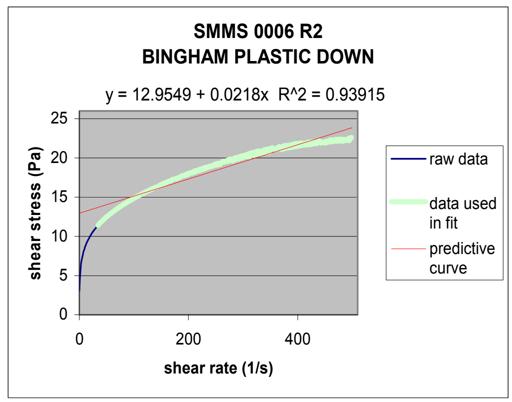
	5 Pascals		10 Pascals		10 Pascals	20 Pascals	
Firt 418 (g)	75.00	0.00	75.00	0.00		75.00	0.00
Xanthan Gum (g)	0.88	1.25	2.63	3.75		3.50	5.00
Kathon (g)	0.35	0.50	0.35	0.49		0.35	0.49
DI H2O (g)	173.78	248.25	172.03	245.76		171.15	244.51
Sample Number	SMMS-0006	SMMS-0007	SMMS-0008	SMMS-0009		SMMS-0010	SMMS-0011
Firt 418 (g)	75.03	0.00	75.00	0.00	0.00	75.00	0.00
Xanthan Gum (g)	0.44	0.63	1.05	1.75	3.75	1.58	3.25
Kathon (g)	0.36	0.51	0.36	0.50	0.00	0.35	0.50
DI H2O (g)	174.22	248.90	173.61	247.80	246.23	173.11	246.30
Sample Number	SMMS-0012	SMMS-0013	SMMS-0014	SMMS-0015	SMMS-0018	SMMS-0016	SMMS-0017
Frit (g)	75.00	0.00	75.00	0.00		0.00	
X.G. (g)	0.60	0.98	0.96	1.63		3.00	
Kathon (g)	0.35	0.50	0.35	0.50		0.50	
Water (g)	174.10	248.50	173.70	247.90		246.50	
Sample Number	SMMS-0019	SMMS-0020	SMMS-0021	SMMS-0022		SMMS-0023	

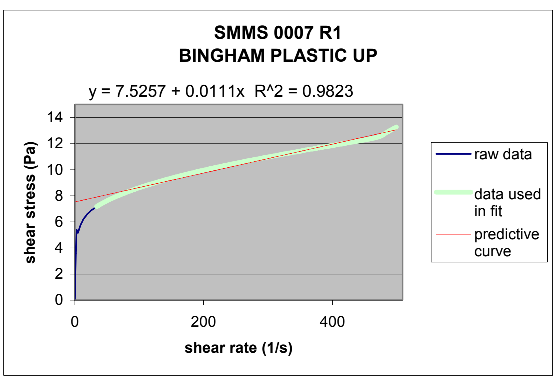
APPENDIX C. Rheograms of Simulant Preparation

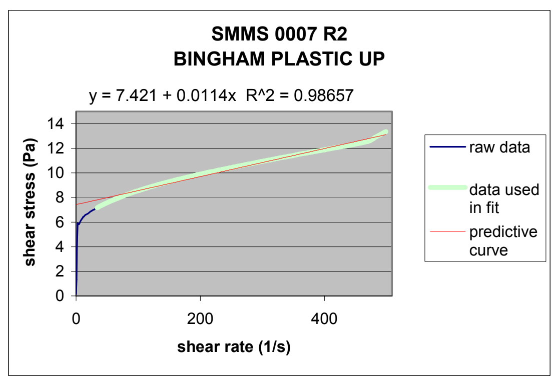


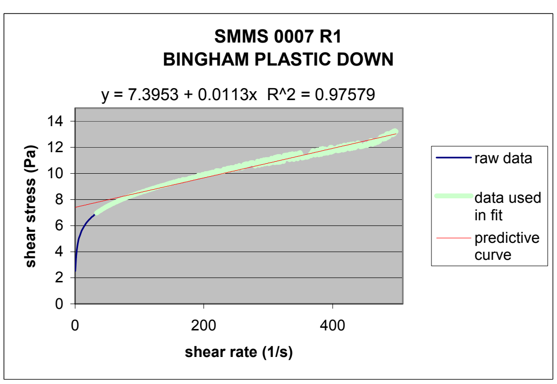


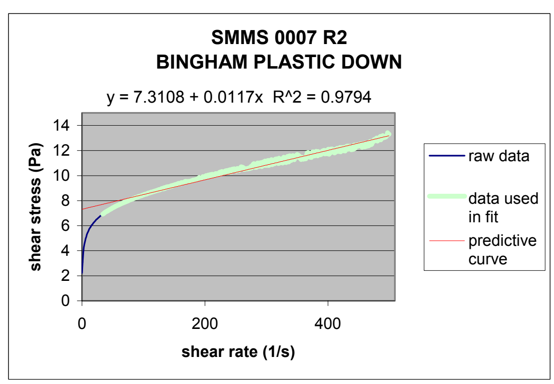


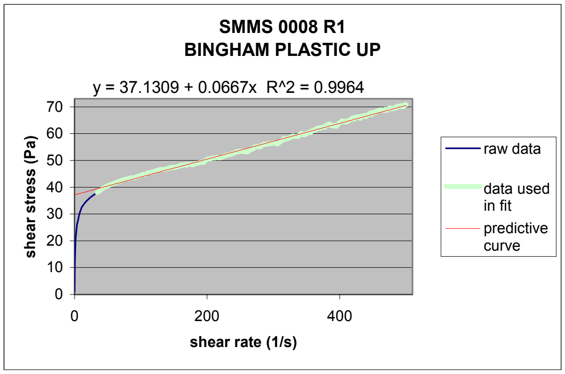


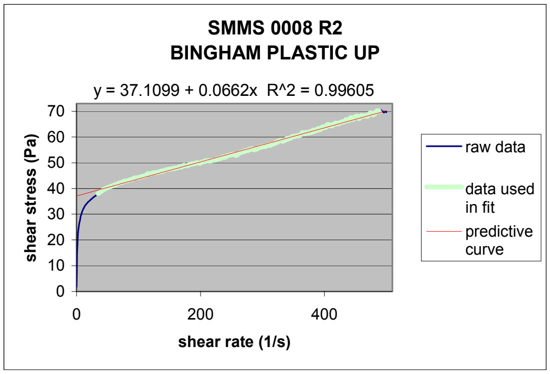


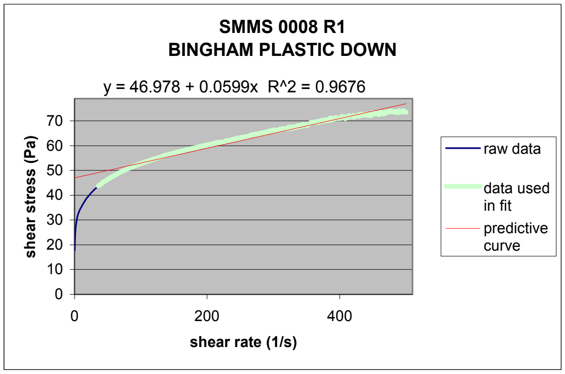


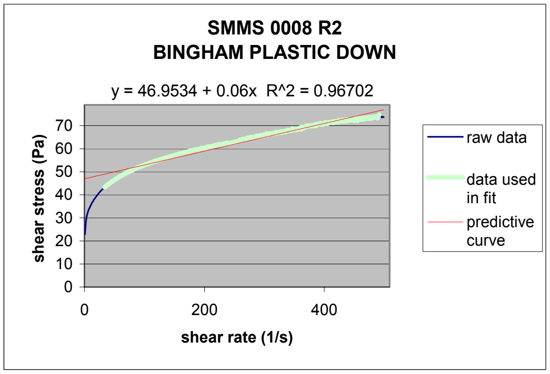


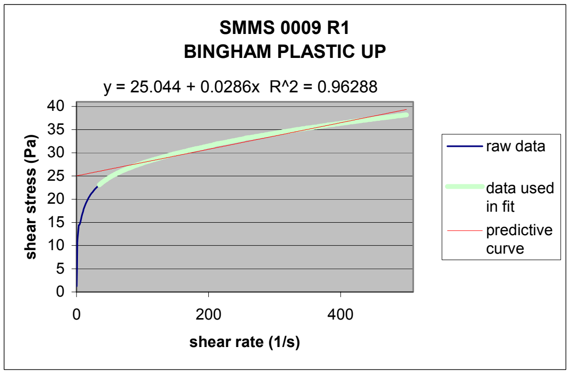


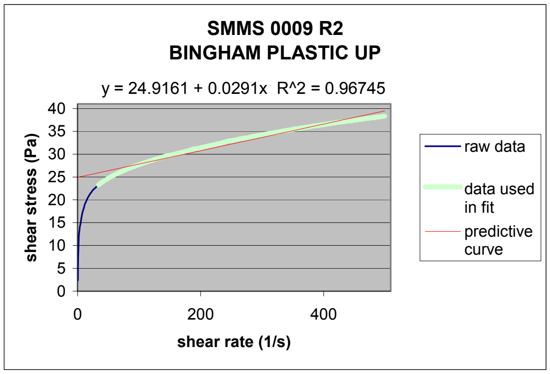

SMMS 0008 R1
BINGHAM PLASTIC UP
y = 37.1309 + 0.0667x R^2 = 0.9964
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

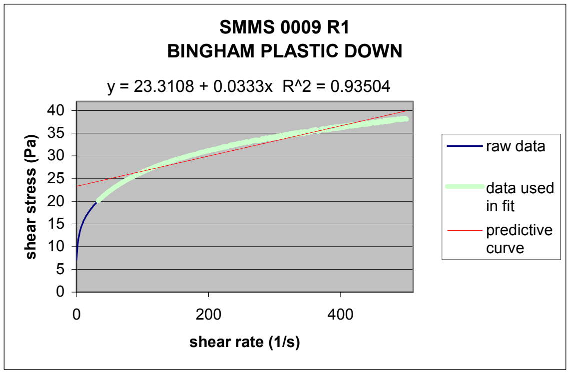

SMMS 0008 R2
BINGHAM PLASTIC UP
y = 37.1099 + 0.0662x R^2 = 0.99605
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

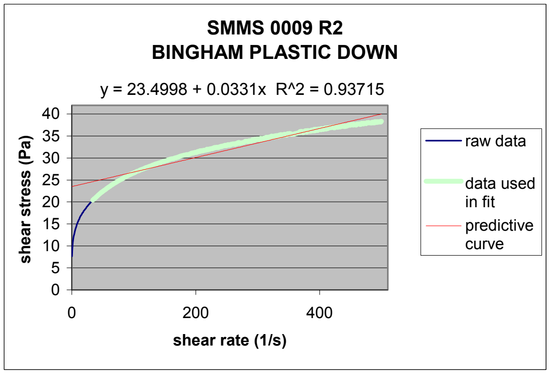

SMMS 0008 R1
BINGHAM PLASTIC DOWN
y = 46.978 + 0.0599x R^2 = 0.9676
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

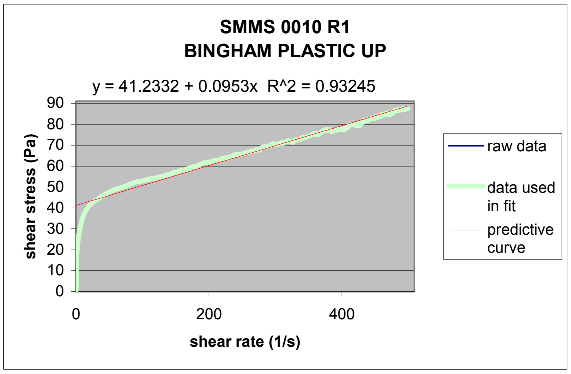

SMMS 0008 R2
BINGHAM PLASTIC DOWN
y = 46.9534 + 0.06x R^2 = 0.96702
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

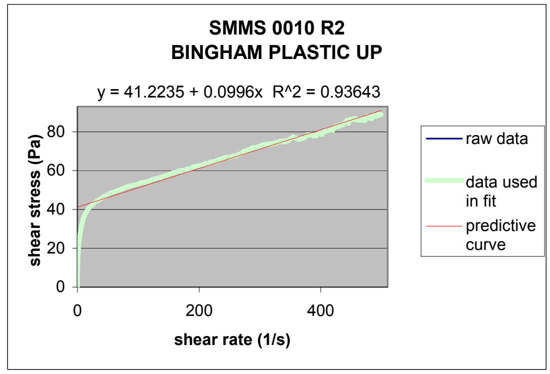

SMMS 0009 R1
BINGHAM PLASTIC UP
y = 25.044 + 0.0286x R^2 = 0.96288
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

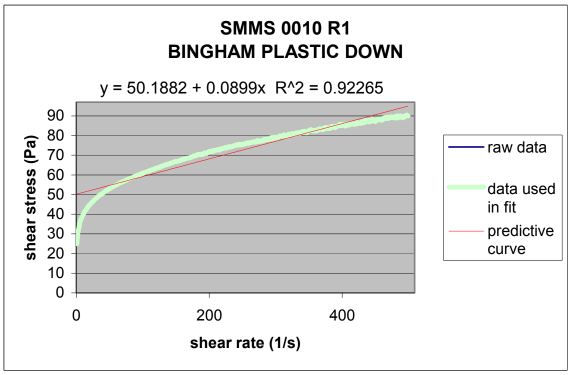

SMMS 0009 R2
BINGHAM PLASTIC UP
y = 24.9161 + 0.0291x R^2 = 0.96745
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

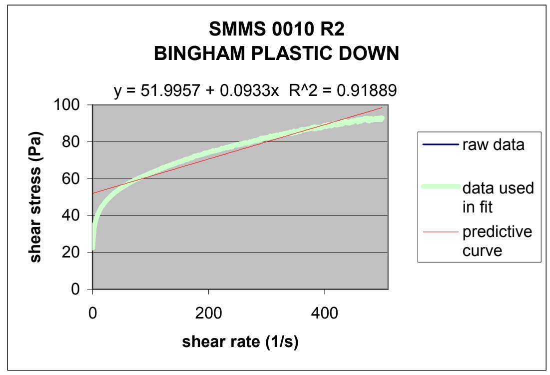

SMMS 0009 R1
BINGHAM PLASTIC DOWN
y = 23.3108 + 0.0333x R^2 = 0.93504
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

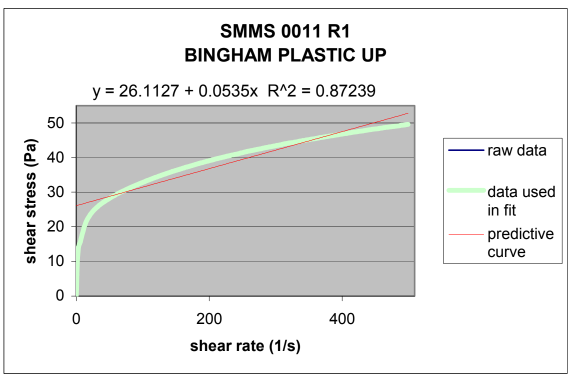

SMMS 0009 R2
BINGHAM PLASTIC DOWN
y = 23.4998 + 0.0331x R^2 = 0.93715
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

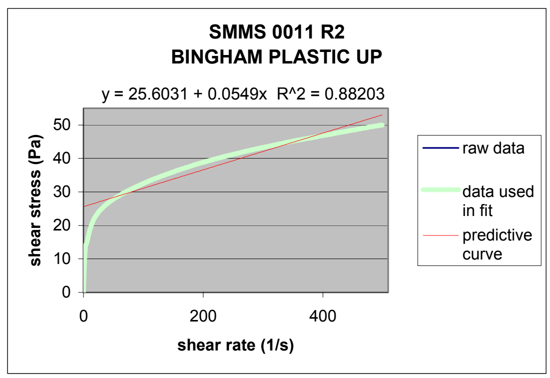

SMMS 0010 R1
BINGHAM PLASTIC UP
y = 41.2332 + 0.0953x R^2 = 0.93245
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

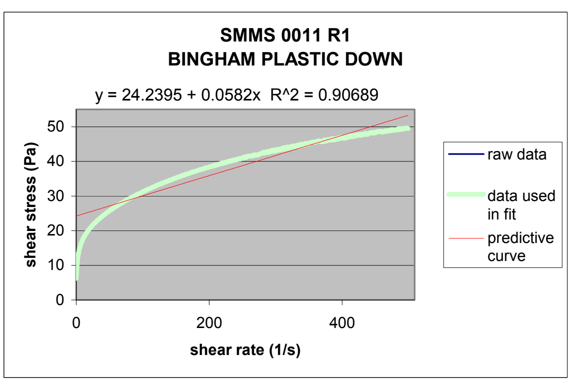

SMMS 0010 R2
BINGHAM PLASTIC UP
y = 41.2235 + 0.0996x R^2 = 0.93643
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

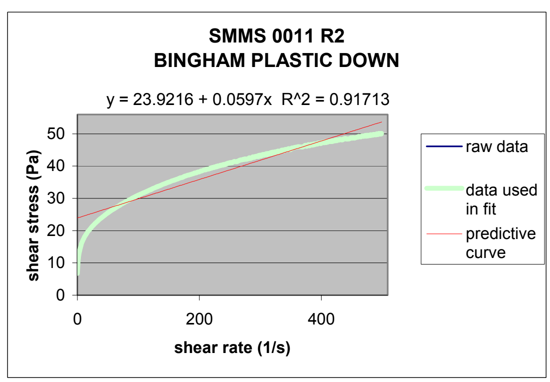

SMMS 0010 R1
BINGHAM PLASTIC DOWN
y = 50.1882 + 0.0899x R^2 = 0.92265
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

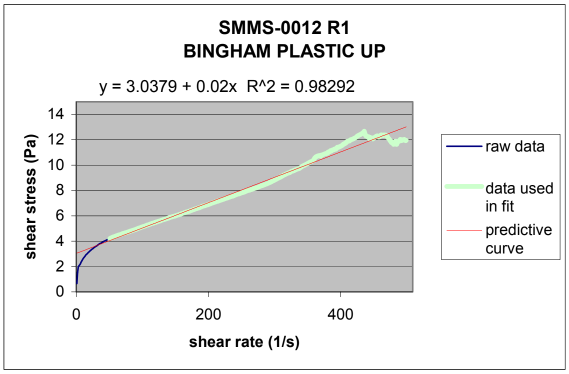

SMMS 0010 R2
BINGHAM PLASTIC DOWN
y = 51.9957 + 0.0933x R^2 = 0.91889
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

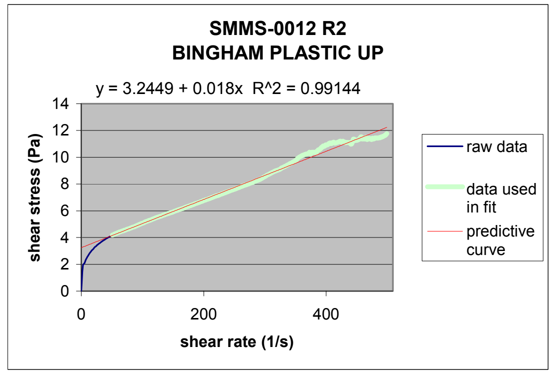

SMMS 0011 R1
BINGHAM PLASTIC UP
y = 26.1127 + 0.0535x R^2 = 0.87239
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

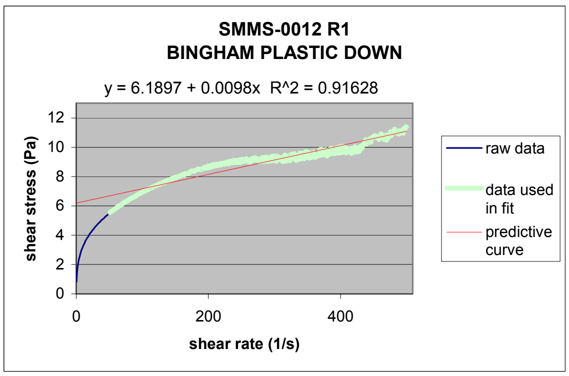

SMMS 0011 R2
BINGHAM PLASTIC UP
y = 25.6031 + 0.0549x R^2 = 0.88203
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

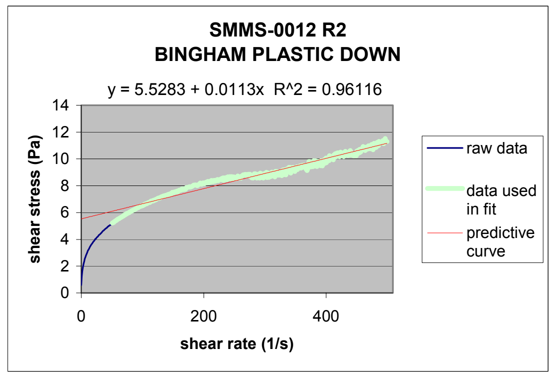

SMMS 0011 R1
BINGHAM PLASTIC DOWN
y = 24.2395 + 0.0582x R^2 = 0.90689
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

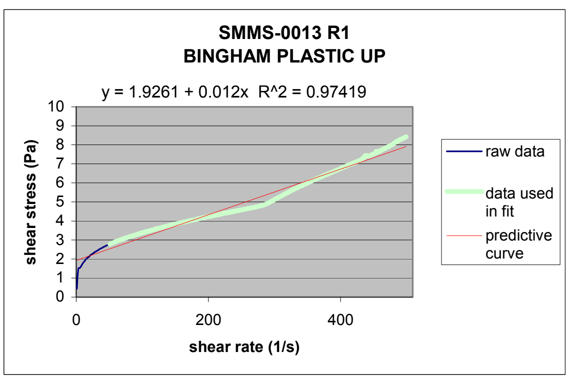

SMMS 0011 R2
BINGHAM PLASTIC DOWN
y = 23.9216 + 0.0597x R^2 = 0.91713
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

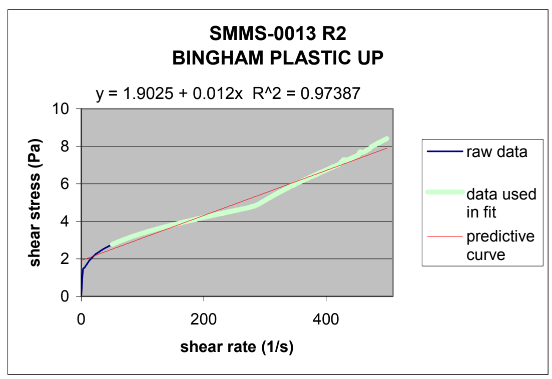

SMMS-0012 R1
BINGHAM PLASTIC UP
y = 3.0379 + 0.02x R^2 = 0.98292
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

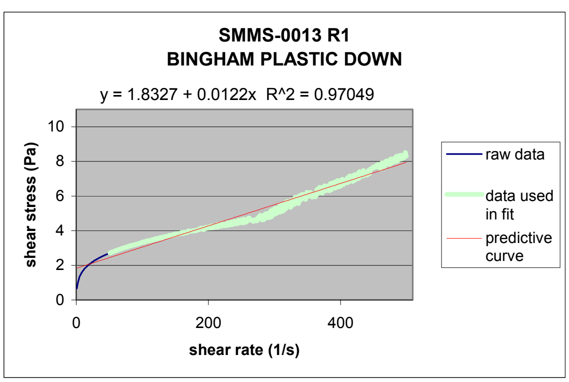

SMMS-0012 R2
BINGHAM PLASTIC UP
y = 3.2449 + 0.018x R^2 = 0.99144
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

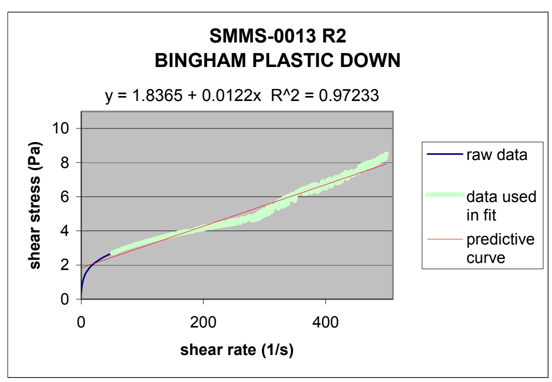

SMMS-0012 R1
BINGHAM PLASTIC DOWN
y = 6.1897 + 0.0098x R^2 = 0.91628
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

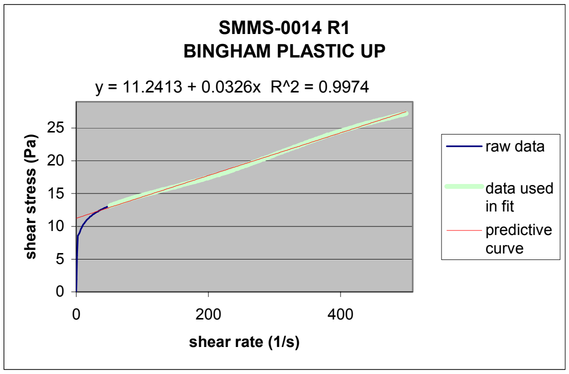

SMMS-0012 R2
BINGHAM PLASTIC DOWN
y = 5.5283 + 0.0113x R^2 = 0.96116
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

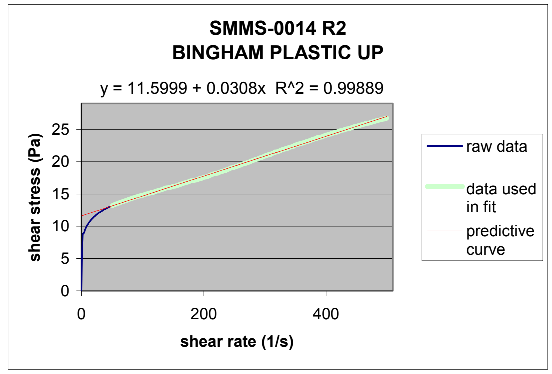

SMMS-0013 R1
BINGHAM PLASTIC UP
y = 1.9261 + 0.012x R^2 = 0.97419
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

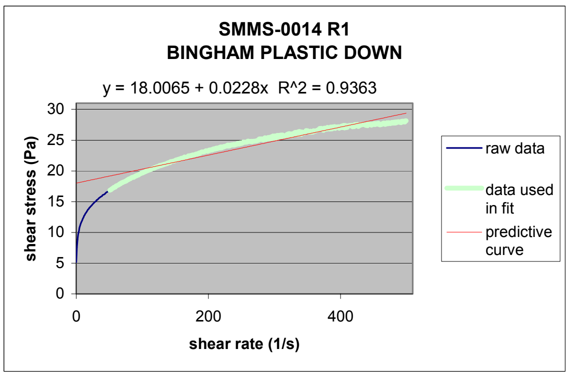

SMMS-0013 R2
BINGHAM PLASTIC UP
y = 1.9025 + 0.012x R^2 = 0.97387
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

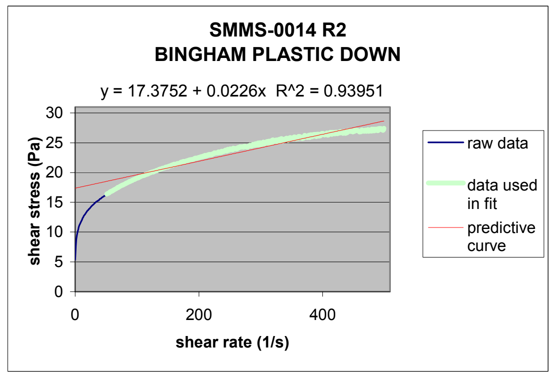

SMMS-0013 R1
BINGHAM PLASTIC DOWN
y = 1.8327 + 0.0122x R^2 = 0.97049
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

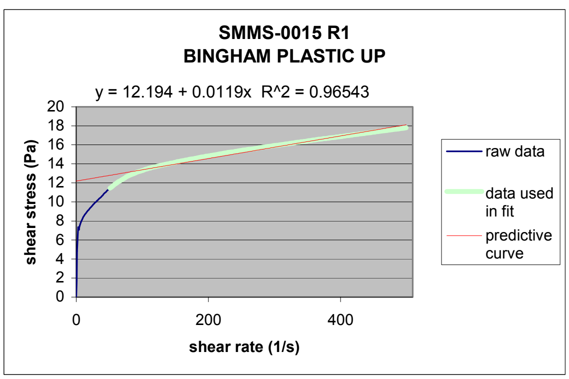

SMMS-0013 R2
BINGHAM PLASTIC DOWN
y = 1.8365 + 0.0122x R^2 = 0.97233
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

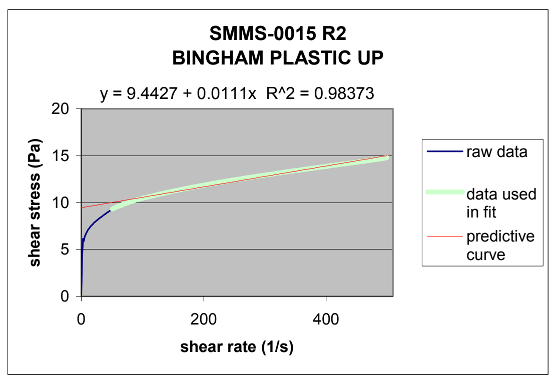

SMMS-0014 R1
BINGHAM PLASTIC UP
y = 11.2413 + 0.0326x R^2 = 0.9974
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

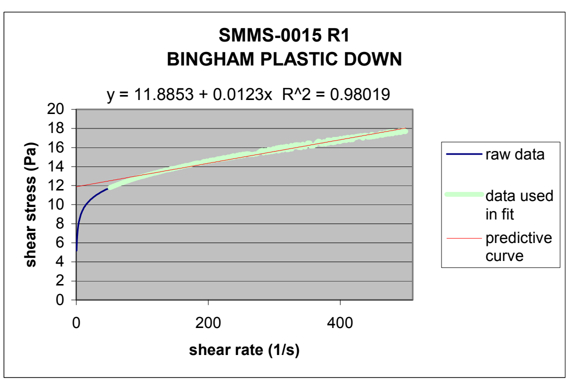

SMMS-0014 R2
BINGHAM PLASTIC UP
y = 11.5999 + 0.0308x R^2 = 0.99889
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

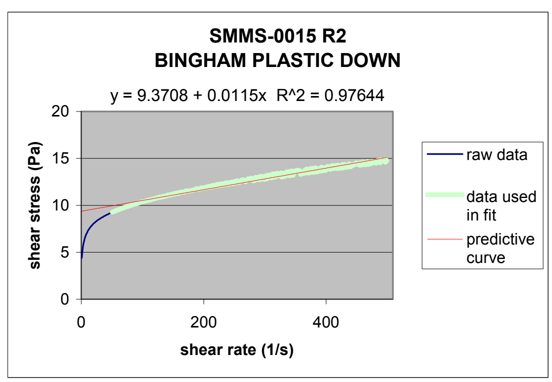

SMMS-0014 R1
BINGHAM PLASTIC DOWN
y = 18.0065 + 0.0228x R^2 = 0.9363
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

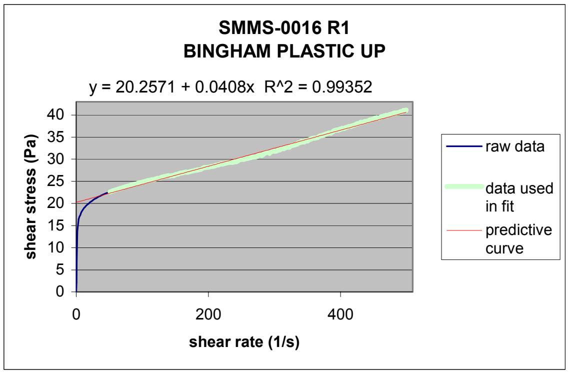

SMMS-0014 R2
BINGHAM PLASTIC DOWN
y = 17.3752 + 0.0226x R^2 = 0.93951
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

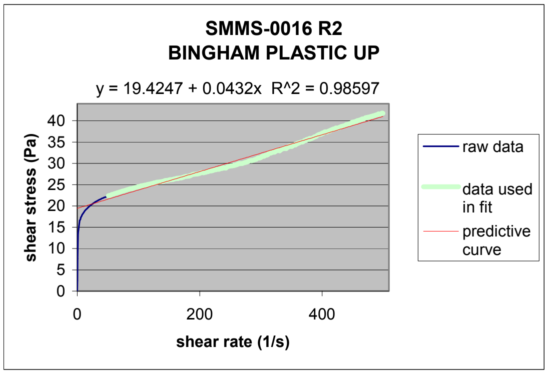

SMMS-0015 R1
BINGHAM PLASTIC UP
y = 12.194 + 0.0119x R^2 = 0.96543
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

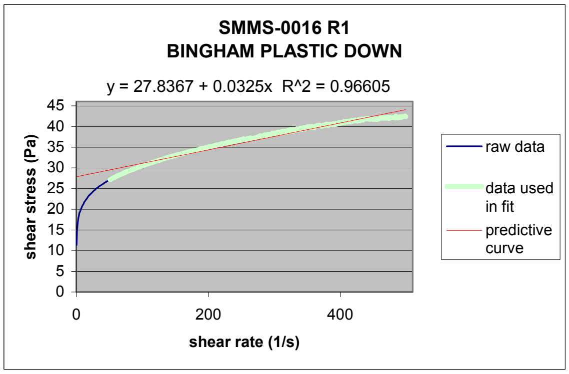

SMMS-0015 R2
BINGHAM PLASTIC UP
y = 9.4427 + 0.0111x R^2 = 0.98373
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

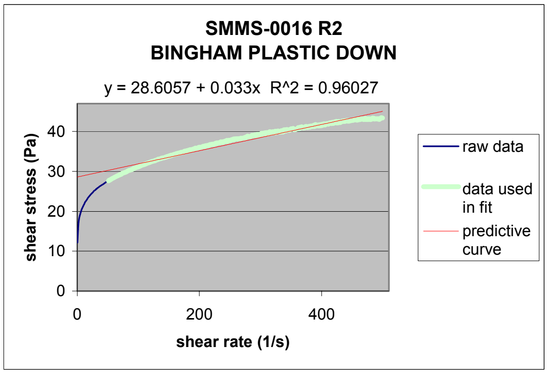

SMMS-0015 R1
BINGHAM PLASTIC DOWN
y = 11.8853 + 0.0123x R^2 = 0.98019
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

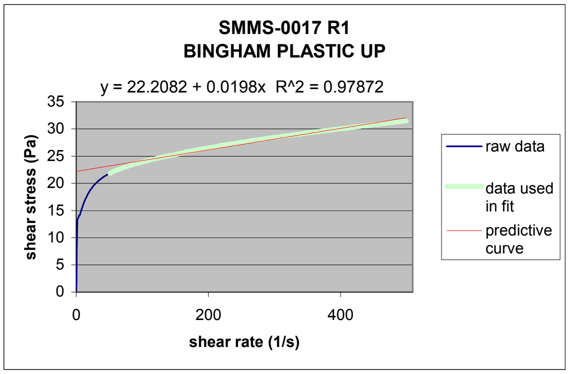

SMMS-0015 R2
BINGHAM PLASTIC DOWN
y = 9.3708 + 0.0115x R^2 = 0.97644
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

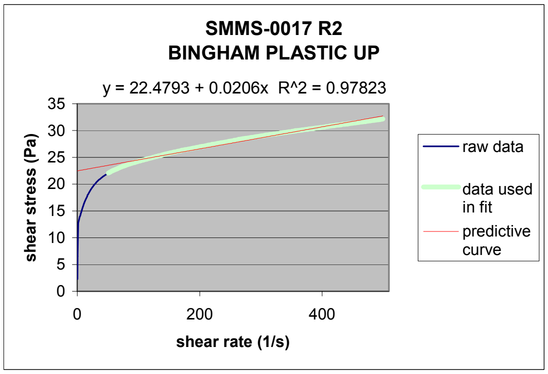

SMMS-0016 R1
BINGHAM PLASTIC UP
y = 20.2571 + 0.0408x R^2 = 0.99352
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

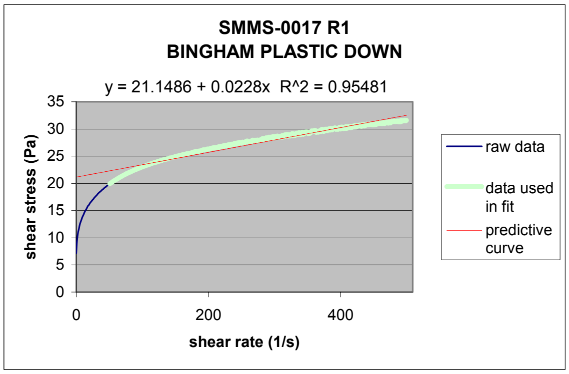

SMMS-0016 R2
BINGHAM PLASTIC UP
y = 19.4247 + 0.0432x R^2 = 0.98597
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

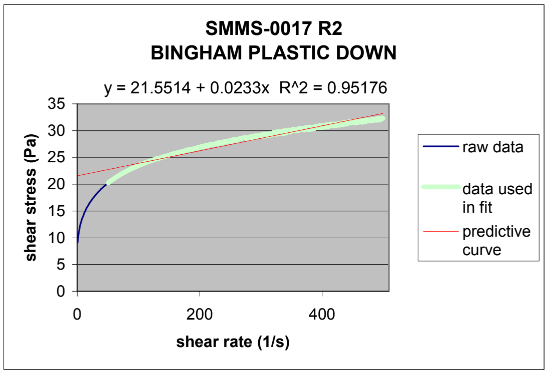

SMMS-0016 R1
BINGHAM PLASTIC DOWN
y = 27.8367 + 0.0325x R^2 = 0.96605
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

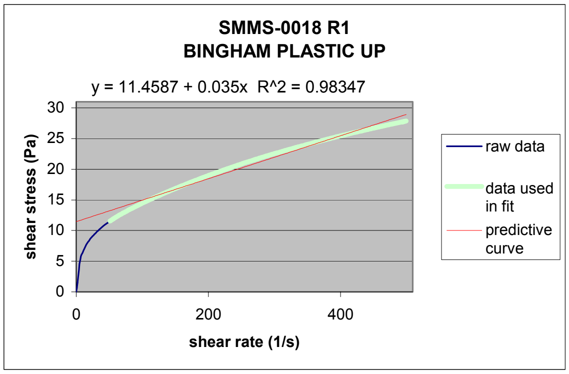

SMMS-0016 R2
BINGHAM PLASTIC DOWN
y = 28.6057 + 0.033x R^2 = 0.96027
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

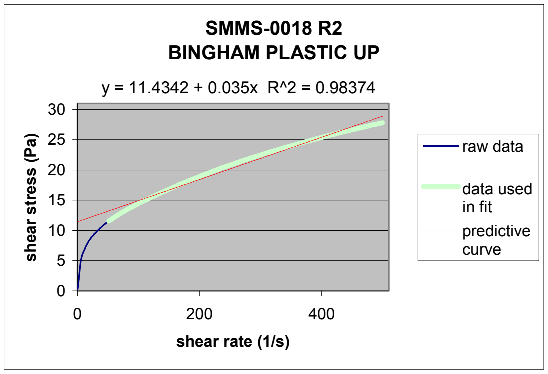

SMMS-0017 R1
BINGHAM PLASTIC UP
y = 22.2082 + 0.0198x R^2 = 0.97872
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

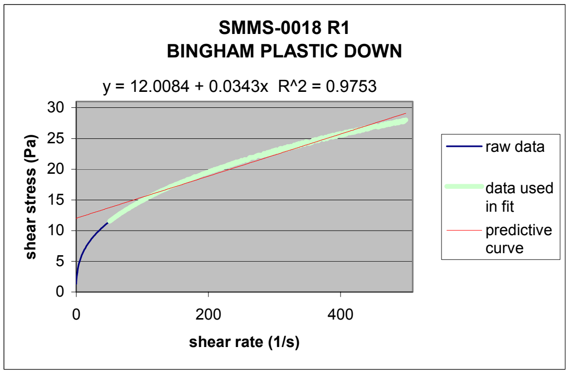

SMMS-0017 R2
BINGHAM PLASTIC UP
y = 22.4793 + 0.0206x R^2 = 0.97823
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

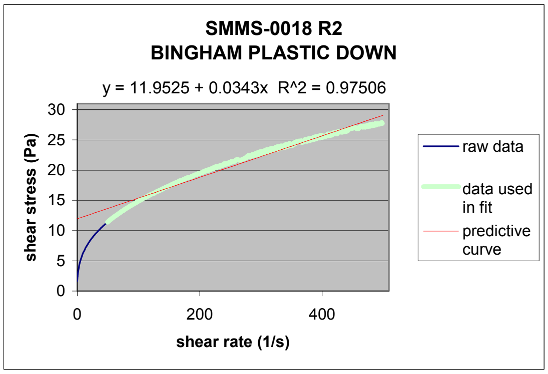

SMMS-0017 R1
BINGHAM PLASTIC DOWN
y = 21.1486 + 0.0228x R^2 = 0.95481
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve


SMMS-0017 R2
BINGHAM PLASTIC DOWN
y = 21.5514 + 0.0233x R^2 = 0.95176
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve


SMMS-0018 R1
BINGHAM PLASTIC UP
y = 11.4587 + 0.035x R^2 = 0.98347
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve


SMMS-0018 R2
BINGHAM PLASTIC UP
y = 11.4342 + 0.035x R^2 = 0.98374
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve


SMMS-0018 R1
BINGHAM PLASTIC DOWN
y = 12.0084 + 0.0343x R^2 = 0.9753
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve


SMMS-0018 R2
BINGHAM PLASTIC DOWN
y = 11.9525 + 0.0343x R^2 = 0.97506
shear stress (Pa)
shear rate (1/s)
raw data
data used in fit
predictive curve

APPENDIX D. EQUIPMENT AND INSTRUMENTATION

Table 1. Equipment List: 1/6th Scaled SRAT/SME/MFT Vessel

Component	Make / Model
Tank	Custom Fabrication per drawing EES-22729-PV-005
Agitator	Lightnin EV1P50M
Impellers	Custom Fabrication per drawing EES-22729-R4-003
Video Camera	Cannon XL1
"Lipstick" Camera	Toshiba IK-CU44A
Video Recorder	Sony MiniDV GV-D1000 NTSC
Bubbler Assembly	Custom Fabrication
Coil Assembly	Custom Fabrication
Fiber Optic Light	Cole Parmer Illuminator 41720
Pump Dip Legs	Custom Fabrication
Supports for bubbler, pump dip legs and sampler	Custom Fabrication
Sampler	Drumstick Coliwasa

Table 2. Instrumentation List: 1/6th Scale SRAT/SME/MFT Vessel

Measured Parameter	Instrument Type	Instrument Model	Instrument M&TE Number	Comments
Agitator Speed	PhotoTachometer	Extech	ITS-DI001	Instrument mounted on tank top and monitoring agitator shaft through set screw opening
Agitator Power Draw	True RMS Power Analyzer	Extech 380803	PA-5555	Agitator powered through instrument
Vessel Temperature	Type K Thermocouple Meter	I^2R Thermowatch TOW-VOVC	TV003K	
	Type K Thermocouple Probe	Omega 1/8" diameter probe, Inconel cladding	ITS-TC001	
Slurry Density via Bubbler	Differential Pressure Meter	Meriam Smart Gauge – 2100 series: 0-200 INWC	ITS-PT001	Bubbler tube mounted above sump and is flush with top of sump with 7 7/8" separation between taps
	Flow Controller	MKS 100 ml/min 1179A12CS1BV	FC10011	Flow will be 25 ml/min
	Flow Controller	MKS 100 ml/min 1179A12CS1BV	FC10010	Flow will be 25 ml/min
	Flow Computer	MKS	N/A	
Vortex Depth	Laser Distance Gauge	Leica Disto Pro4	ITS-LM001	
Time	Stopwatch / Clock	Cole Parmer 100-Hr Triple Display Clock/Timer	N/A	Instrument was ordered with NIST certification

APPENDIX E. Ekato Report

EKATO	AGITATOR TEST RUN FOR ATOMIC WASTE SLURRY	19.11.1982 Fo/Pf Blatt 1 von

PROBLEM:

For evaporation and chemical adjustment a slurry with Bingham behaviour has to be kept in motion in the tank according to Du Pont drawing no. W 752193.

1. Fluid characteristics

Slurry with a solid content of 57,3 %
Slurry density 1540 kg/m³
Slurry pH 7,12
Slurry rheology determined by Haake
Rotovisco 0 RV-3
Yield stress 70 dynes/ cm² 7.0 Pa
consistency 25 mPa s .025 Pa·s

2. Test arrangement

The testing was performed in two different vessel sizes
small vessel diameter 160 mm
volume 5 l
bottom shape: flat

Impellers: one three bladed draft tube propeller dia 50 mm
one flat bladed turbine dia 60 mm
4 blades; height of blades 0,2 x dia;

no baffles are used.
geometrical arrangement see pilot
"Pilot"vessel diameter 400 mm
volume 50 l
bottom shape: flat

Impellers: one three bladed
draft tube propeller dia 110 mm
one 4 bladed flat-blade turbine
dia 110 mm
height of blades 0,27 x dia
off distance bottom of draft tube 33 mm
" of flat blade impeller 2 mm
Distance between impellers 150 mm

EKATO

19.11.1982 Fo/Pf
Blatt 2 von

draft tube dia 125 mm
length draft tube 168 mm

to simulate the process sample pump a solid shaft of dia 25 mm is attached 45 mm from tank wall.

liquid height: 400 mm

The agitators are equipped with Speed variators, torque- and speed measurement devices.

3. Tests

Two series of tests are performed:
- with slurry
- with a transparent liquid having the same flow curve.

3.1 Description of transparent liquid.

The liquid consists of three components.

77,4 % w Polyisobutylen
17,8 % w Benzene
4,8 % Aerosil (Degussa) (fine dispersed SiO_2)

the flow behaviour can be influenced by variation of the composition.
Flow curve see figure 1.

3.2 Results with transparent liquid.

Small vessel:
a speed of $n = 950\ min^{-1}$ is necessary to produce an overall motion in the vessel.

Pilot vessel
a speed of $n = 550\ min^{-1}$ is necessary for good motion.

3.3 Results with SME product.

A confirmation of the speeds mentioned under 3.2 can be made.

EKATO		19.11.1982 Fo/Pf Blatt 3

By means of added particules acting as flow followers the circulation rate is measured.

Based on averaged circulation times the pumping rate was estimated.

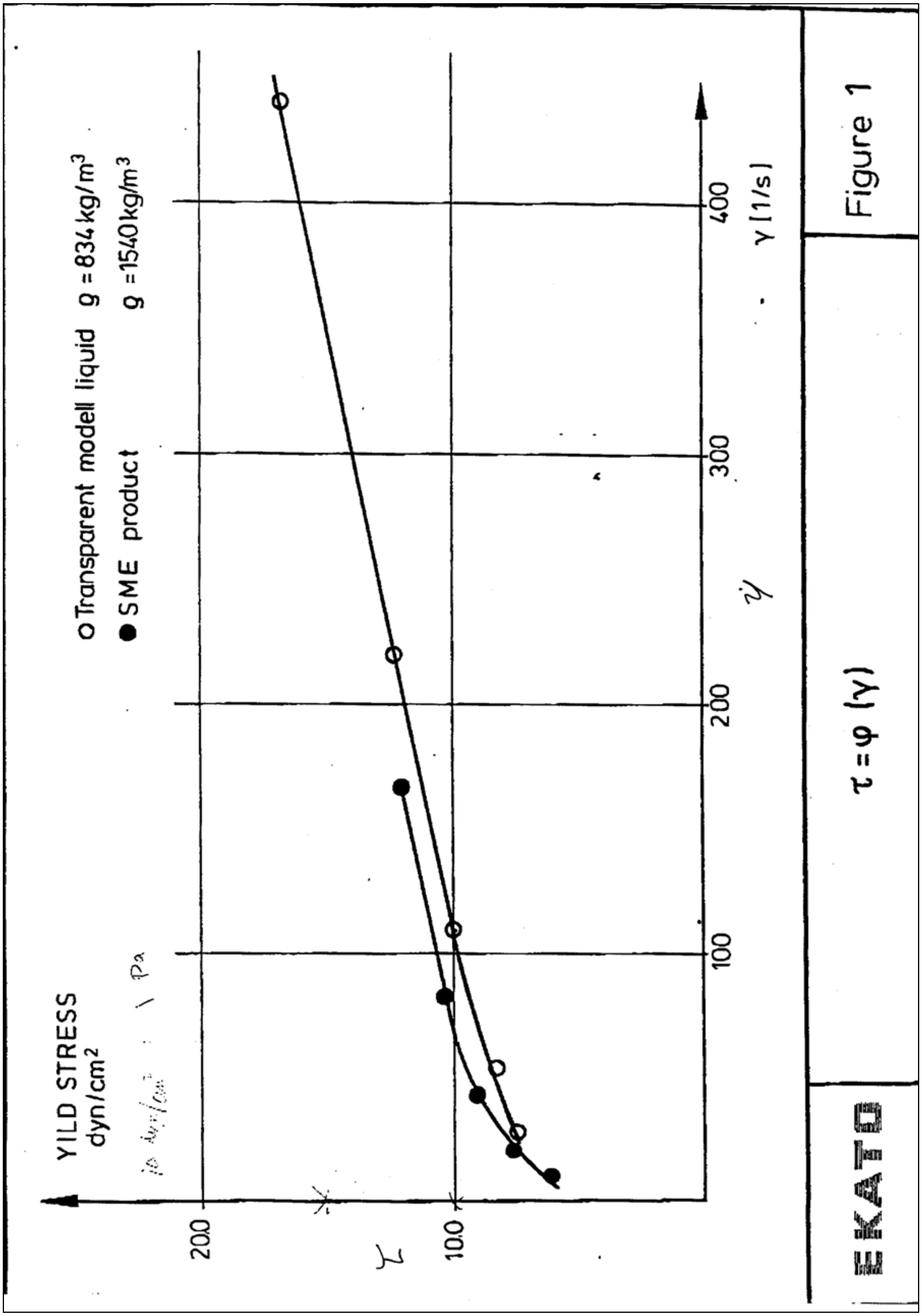
Speed	$\dot{q}$	Q	P/V	Ne
upm	l/s	-	kW/m^3	-
570	13,0	1,02		7,6
600	13,6	1,02	2,0	7,4
650	14,2	0,99		6,8

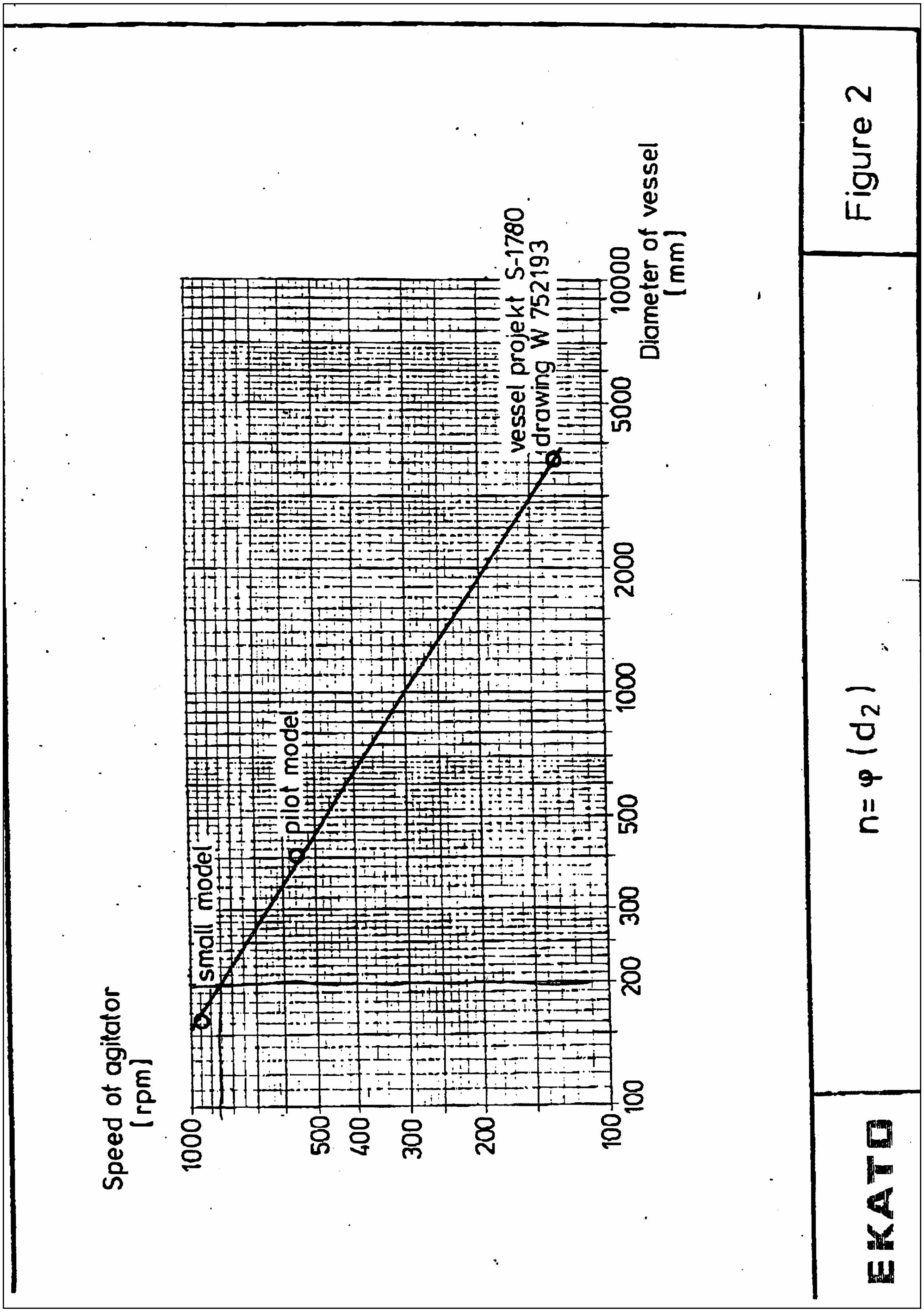
4. Scale up

See figure 2.
For a preliminary determination of the agitator speed in full size scale an extrapolation according to figure 2 has been made.

Result: required speed $n = 130\ min^{-1}$
- with a power number of $Ne = 6$,
- and an impeller diameter of $d_2 = 910$ mm,

The calculated power is $P = 55$ kW
Using a motor with 75 kW the preliminary shaft diameter is 125 mm, based on shaft length of $l = 5000$ mm.


YILD STRESS
dyn/cm²
20.0
10.0
100
200
300
400
γ [1/s]
O Transparent modell liquid ϱ = 834 kg/m³
● SME product ϱ = 1540 kg/m³
τ = φ (γ)
Figure 1
EKATO


Speed of agitator
[rpm]
1000
500
400
300
200
100
100
200
300
500
1000
2000
5000
10000
Diameter of vessel
[mm]
small model
pilot model
vessel projekt S-1780
drawing W 752193
EKATO
n= φ (d2)
Figure 2

APPENDIX F. Run Plan for Frit 418 Settling Tests

**Westinghouse
Savannah River Company**
Aiken, SC 29808

WESTINGHOUSE SAVANNAH RIVER COMPANY
INTEROFFICE MEMORANDUM

SRT-GPD-2004-00075

June 3, 2004

To: S. L. Marra

From: A.R. Marinik

Technical Review: ______________________ ____________
Signature Date

Run Plan for Frit 418 Settling Tests

Task Plan: WSRC-RP-2004-00407

Researcher in Charge:	A. R. Marinik	819-8435	19391
Task Lead:	M. E. Stone	819-8410	17749

The Defense Waste Processing Facility (DWPF) is evaluating the removal of the cooling coils from the Melter Feed Tank (MFT). A Computational Fluid Dynamics (CFD) model has been developed by DWPF Engineering to perform this evaluation. As validation for this model a 1/6th linear scale test will be performed by Savannah River National Laboratory. In order to perform these tests preparatory work must be done to determine the settling rates of Frit 418, both in water, and Xanthan Gum slurry.

To determine the settling rates of Frit 418, three tests will be performed. The first test (Test # 1) will consist of Frit 418 in water. 1.0wt% Frit 418 will be added to 50mL of water and filmed by a time lapse video camera as it settles to the bottom. The second test will consist of Frit 418 in a Xanthan Gum slurry. The Xanthan Gum slurry contains the Kathon as defined by SRT-GPD-2004-00070. 1.0wt% Frit 418 will be added to each of three 50mL samples of Xanthan Gum slurry. The first slurry will have a yield stress of 5 Pa (Test # 2.1), the second will have a yield stress of 10 Pa (Test # 2.2), and the third will have a yield stress of 20 Pa (Test # 2.3). Again, in the 1.0wt% Frit 418/Xanthan Gum tests the frit will be added to the sample and filmed by a time lapse video camera. The third test will consist of 30wt% Frit 418 which has already been added to each of three Xanthan Gum slurries with yield stresses of 5 Pa (Test # 3.1), 10 Pa (Test # 3.2), and 20 Pa (Test # 3.3). The following table summarizes the tests and components thereof.

Test #	Frit 418 (wt%)	Frit 418 (g)	Slurry Yield Stress	Slurry Mass (g)	Sample #
1.0	1.0	0.5	0 Pa	50	Water
2.1	1.0	0.5	5 Pa	50	SMMS-0020
2.2	1.0	0.5	10 Pa	50	SMMS-0022
2.3	1.0	0.5	20 Pa	50	SMMS-0023
3.1	30	N/A[1]	5 Pa	50	SMMS-0019
3.2	30	N/A[1]	10 Pa	50	SMMS-0021
3.3	30	N/A[1]	20 Pa	50	SMMS-0016

[1]The Frit has already been added to this slurry.

In Test # 1 through Test # 2.3 the Xanthan Gum slurry will first be added to the cylinder, and then the Frit 418 will be added on top. In Test #3.1 through Test # 3.3 the Xanthan Gum/Frit 418 slurry will be mixed well before being added to the cylinder. The camera will begin recording before the slurry is added to the container, and the camera will be stopped after complete settling occurs. Complete settling is defined as the point at which all frit has settled upon the bottom of the container. All three tests will be run side by side and filmed simultaneously. Sample placements during the testing/filming are as seen in the following figure.