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Fiscal Year 1993 1/25-Scale Sludge Mobilization Testing

M. R. Powell
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April 1995

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

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

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Summary

Sixteen 1/25-scale sludge mobilization experiments were conducted in fiscal year (FY) 1993. The results of this testing are presented in this document. The ability of a single, centrally-located, scale model mixer pump to resuspend a layer of simulated tank sludge was evaluated for five different simulant types. The resistance of these simulants to the mobilizing action of the mixer pump jets was not found to adequately correlate with simulant vane shear strength. The data indicate that the simulant cohesion, as quantified by tensile strength, may provide a good measure of mobilization resistance.

A single test was done to evaluate whether indexed mixer pump rotation is significantly more effective than the planned continuous oscillation. No significant difference was found in the sludge mobilization caused by these two modes of operation.

Two tests were conducted using a clay-based sludge simulant that contained approximately 5 wt% soluble solids. The distance to which the mixer pump jets were effective for this simulant was approximately 50% greater than on similar simulants that did not contain soluble solids. The implication is that sludge dissolution effects may significantly enhance the performance of mixer pumps in some tanks. The development of a means to correlate the magnitude of this effect with waste properties is a direction for future work.

Two tests were performed with the goal of determining whether the 1/25-scale sludge mobilization data can be scaled linearly to 1/12-scale. The two 1/25-scale tests were conducted using the same simulant recipe as had been used in previous 1/12-scale tests. The difficulty of matching the 1/25-scale simulants with those used previously is thought to have adversely affected the results. Further tests are needed to determine whether the data from sludge mobilization tests can be linearly scaled.

Glossary

a	distance between tank centerline and nozzle discharge (2.2 cm)
D	nozzle diameter, 0.23 in = 0.584 cm for 1/25-scale
DST	double-shell tank
E	erosion rate, $kg/(m^2s)$
ECR	effective cleaning radius, cm
M	erodibility of cohesive soil, $kg/(m^2s)$
M_{sludge}	mass of sludge initially loaded into the tank, kg
M_{super}	mass of supernate initially loaded into the tank, kg
NCRW	neutralized cladding removal waste
PNL	Pacific Northwest Laboratory, Richland, Washington
R_{tank}	tank radius, 45 cm for 1/25-scale
S_t	tensile strength, $kdyne/cm^2$
U_o	nozzle exit velocity, cm/s
V_{super}	volume of supernate in tank, liters
V_{sludge}	volume of sludge in tank, liters
WHC	Westinghouse Hanford Company
ρ_{slurry}	slurry density, kg/liter
τ_c	critical shear stress for erosion, pascals
τ_s	shear strength, $kdyne/cm^2$
τ_w	applied wall shear stress, pascals
τ_y	yield stress, $kdyne/cm^2$

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1.0 Introduction

This report documents FY 1993 technical progress on the sludge mobilization task of the Double-Shell Tank Retrieval Project, which is being conducted by Westinghouse Hanford Company (WHC) and Pacific Northwest Laboratory (PNL).[a] During FY 1993, a series of 1/25-scale sludge mobilization tests were performed to identify the sludge simulant physical properties that can be used to predict the mobilization of tank sludge when exposed to submerged fluid jets.

It is necessary to correlate the mobilization resistance of DST sludge with measurable sludge properties so that successful DST sludge retrieval systems can be designed. It is planned to use mixer pumps in the Hanford DSTs to resuspend the layers of sludge that cover the bottoms of many of the tanks. The number of mixer pumps and their required horsepowers must be accurately estimated based on sludge property measurements to ensure that the sludge will be successfully mobilized. Furthermore, it is desired that over-design of the retrieval systems be avoided to reduce system cost.

Previous sludge mobilization testing has been conducted both in a 1/12-scale tank and in 100-gal plastic drums (bench-scale). These tests demonstrated that the mobilization resistance of selected sludge simulants correlates with measured vane shear strength. However, it was clear from these tests that physical properties in addition to shear strength are probably relevant to sludge mobilization (e.g., sludge cohesiveness). In an effort to identify these additional/alternative properties, a series of 1/25-scale sludge mobilization tests were conducted.

This document describes the results of sixteen 1/25-scale tests conducted during FY 1993. The tests were assigned test numbers of the form "S25-nn-yy" where "nn" is the sequential test number and "yy" is an alphabetic identifier that indicates what type of simulant was used in the test. For example, if "yy" is "K," then kaolin clay was used as the sludge simulant. Similarly, "B" refers to bentonite clay, "KS" refers to kaolin/silica simulant, "KN" refers to kaolin/sodium chloride, and "SS" refers to silica/soda ash. The identifier "KI" is used for test S25-14-KI to signify the use of a kaolin/water simulant with indexed mixer pump oscillation rather than the continuous oscillation used in all other tests.

Following the Introduction, conclusions drawn from the testing and the recommendations for future direction of the sludge mobilization correlation development efforts are presented in Section 2.0. The experimental apparatus and procedures used during the 1/25-scale testing are described in Section 3.0. Section 4.0 presents the data obtained from the 1/25-scale sludge mobilization testing, and Section 5.0 lists the references. Appendix A includes the test plan (DST-TP-93-1) for 1/25-scale sludge mobilization testing and related test procedures. Sludge bank profiles are presented in Appendix B. Appendix C includes photographs of the 1/25-scale apparatus, and Appendix D describes the cohesive erosion model computer program.

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

2.0 Conclusions and Recommendations

The FY 1993 1/25-scale testing of DST sludge simulants has significantly improved our understanding of the mobilization of sludge simulants by fluid jets. Sixteen 1/25-scale tests were conducted using a variety of sludge simulants. The following conclusions were drawn from the testing:

- The mobilization resistance of clay-based sludge simulants is apparently a function of the strength of the interparticle attractive forces in the simulant. Tensile strength and/or sludge yield stress appear to provide a measure of the magnitude of these attractive forces and, thus, of the simulant's mobilization resistance. Further, the simulant shear strength does not necessarily provide a measure of the interparticle attractive forces. Therefore, physical properties other than shear strength must be used to predict mobilization behavior.

- The correlation of effective cleaning radius (ECR) with shear strength developed previously from 1/12-scale test data significantly under-predicts the ECRs observed during 1/25-scale testing of clay simulants. It is possible that the 1/12-scale correlation is unnecessarily conservative, but more data are required to verify this.

- Any improvement in ECR that might be obtained using an indexed pump column rotation instead of continuous 180° oscillation is on the order of or smaller than the 1/25-scale experimental uncertainties. No significant improvement in the ECR was observed when indexed pump rotation was substituted for continuous oscillation. However, the magnitude of the indexed jet effect may still be significant enough to be of interest. Further investigation will be required at larger scale to resolve this.

- A 50% increase in the ECR was observed when a clay-based sludge simulant containing 5 wt% soluble salt (as a solid) was mobilized using water (compared to a simulant without any soluble salt). This implies that "high strength" sludges that contain a significant fraction of soluble salts [e.g., neutralized cladding removal waste (NCRW)] may be more easily mobilized than their strength data would suggest.

- There are some uncertainties surrounding the scaling of the sludge mobilization data collected in scaled tests to full-scale. Comparison of 1/25-scale data with 1/12-scale data does not provide a verification of the current scaling methodology.

The analysis of the 1/25-scale sludge mobilization data has generated several recommendations for the future direction of the sludge mobilization correlation development efforts. The major recommendations are

- The current 1/25-scale data indicate that the simulant tensile strength may be an excellent predictor of the simulant's mobilization resistance. Unfortunately, most of the 1/25-scale tests were carried out using simulants with very similar tensile strengths. Thus, the apparent relationship between ECR and tensile strength is based on just a few data points. More 1/25-scale tests must be conducted in which the tensile strength is specifically varied so that the relationship between ECR and tensile strength can be verified or refuted.

- The suitability of silica/soda ash as a DST sludge simulant must be carefully examined. This simulant was used to develop the 1/12-scale correlation of ECR with simulant shear strength. If there is sufficient technical justification for concluding that DST sludge is more closely simulated by clay-based simulants, then the 1/12-scale ECR correlation may need to be abandoned or modified.

- The development of an improved method for measuring the tensile strength of sludge simulants is essential. Tensile strength is a very promising measure of mobilization resistance. An improved simulant tensiometer is needed not only for simulant characterization, but may someday be needed for hot-cell characterization of core samples.

- A 1/12-scale sludge mobilization test using a clay-based simulant should be conducted before continuing 1/25-scale mobilization testing so that the scaleability of the data can be evaluated. The physical properties of the previously-used (1/12-scale) silica/soda ash sludge simulants are difficult to accurately reproduce. Clay-based simulants exhibit very reproducible physical properties.

- A limited amount of testing should be performed to provide improved confidence in the assumption that jets with equal U_oD's produce identical ECRs and ECR growth rates. In particular, testing should be conducted with variations in nozzle size rather than just varying U_o with a constant nozzle size.

- If testing schedules permit, additional effort should be expended to determine the magnitude of the increase in ECR that results from indexed pump rotation instead of continuous oscillation. This might be easily incorporated into tests being conducted for other reasons (correlation of ECR with tensile strength, for example).

3.0 Experimental

The experimental apparatus and procedures used during the 1/25-scale testing are described in this section. Detailed descriptions of the testing objectives and procedures are given in the *Test Plan for Double-Shell Tank Retrieval Project 1/25-Scale Sludge Mobilization Testing* and related 1/25-scale procedures, which are included in this document as Appendix A.

3.1 Experimental Apparatus

1/25-Scale testing was conducted in a 3-ft diameter, plexiglass tank. Before testing, the bottom of the tank was marked with concentric circles spaced at 2-cm intervals. Eight radial lines (spaced at 45° intervals) were drawn from the tank center to the tank wall and labeled A, B, C,.., and H, respectively. During testing, the location of the sludge/slurry interface was measured at each of these eight locations using the concentric circles to determine the radial distance between the tank center and the interface.

A single, simulated mixer pump was positioned in the center of the tank for each test. One of the existing 1/12-scale mixer pumps was modified for use in the 1/25-scale facility. In the 1/12-scale and full-scale mixer pump designs, the pump suction is located below the nozzles. It was not feasible to operate the 1/25-scale mixer pump in this way and still maintain a scaled distance between the nozzles. The distance between the nozzle tips was judged to be the more important, so the 1/25-scale mixer pump suction is located above the nozzle discharge elevation. Figure 3.1 is a sketch of the 1/25-scale mixer pump and the associated piping. Photographs of the 1/25-scale facility are given in Appendix C.

The slurry enters the suction of the simulated mixer pump and travels up the annular space between a 1-in. and a 2-in. stainless steel tube. The slurry then flows through flexible hose to the intake of the centrifugal pumps. The flow out of the pumps is monitored using a magnetic flow meter and manually controlled via a ball valve. The pressurized slurry flows down the central 1-in. tube of the mixer pump and out the horizontal, diametrically opposed nozzles.

The mixer pump nozzles were located such that their centerline distance above the tank floor was 1/25 of the full-scale distance of 18 in. The nozzles were machined by PNL Crafts Services from tool steel and thermally hardened. Because nozzle design can significantly affect downstream jet velocity, the nozzles were designed such that the nozzle exit velocity profile would be reasonably uniform. The entrance region of each nozzle was angled at 40° (20° half-angle) for a horizontal distance about equal to the nozzle diameter. The target nozzle diameter was 0.24 in. The fabricated nozzles had 0.23-in. diameters. A cross-section sketch of the 1/25-scale nozzles is given in Figure 3.2.

3.2 Experimental Procedure

Each 1/25-scale test was performed in accordance with the 1/25-Scale Sludge Mobilization Testing Procedure (TP93-051-DST-003), which is included in Appendix A. A brief description of the testing procedure is given below.

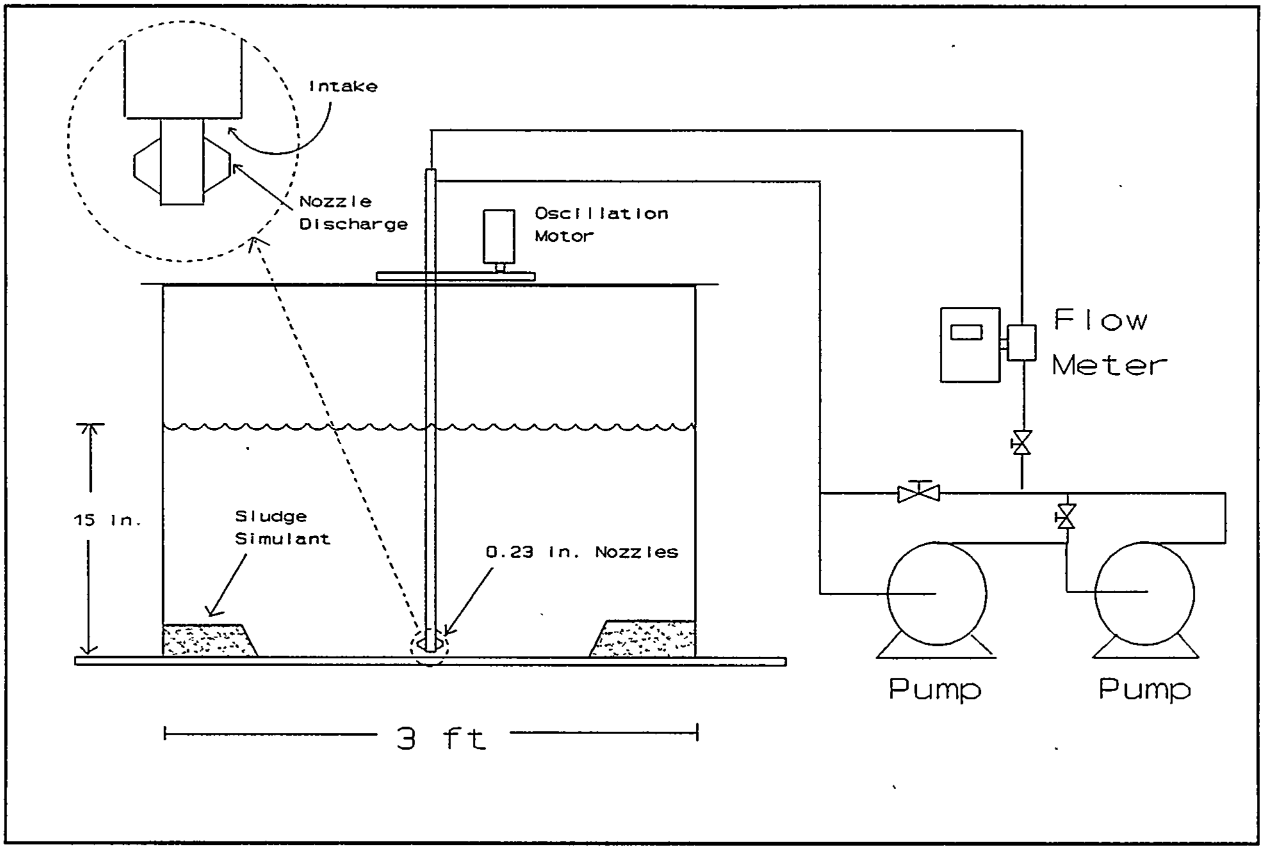

Figure 3.1. Sketch of 1/25-Scale Facility

A known mass corresponding to approximately 50 liters of sludge simulant was placed into the 1/25-scale tank and smoothed to a uniform thickness of about 7.5 cm (3 in.). About 3 liters of simulant was reserved for physical property measurements. The 1/25-scale mixer pump assembly was then positioned in the tank such that the mixer pump centerline coincided with the tank centerline. Two-hundred liters of simulated supernate (in most tests this was water) was then pumped into the tank using a drum pump. The resulting liquid surface was approximately 38 cm (15 in.) above the tank bottom. Care was taken to avoid disturbing the sludge bed while adding the supernate. The 1/25-scale facility centrifugal pumps were then primed using a small auxiliary pump to force tank supernate through the piping. In most tests, provisions were made to prevent this activity from disrupting the sludge.

The mixer pump assembly was continuously oscillated through 180° of rotation at a rate of 4.2 rpm during the test. To begin the test, one of the centrifugal pumps was turned on and the flow control valve adjusted to obtain the desired flow rate. The time at which the pump was activated is assigned the value of 0 minutes. Every minute for the first 10 minutes, the ECR was measured along each of the eight radial lines marked on the tank bottom. The location of the sludge/slurry interface visible from underneath the tank was recorded as the ECR in the datasheets.[a] Following 10 minutes, the

(a) Before analyzing the data, the distance from the tank center to the nozzle exit (approx. 2.2 cm) was subtracted from the ECR data.

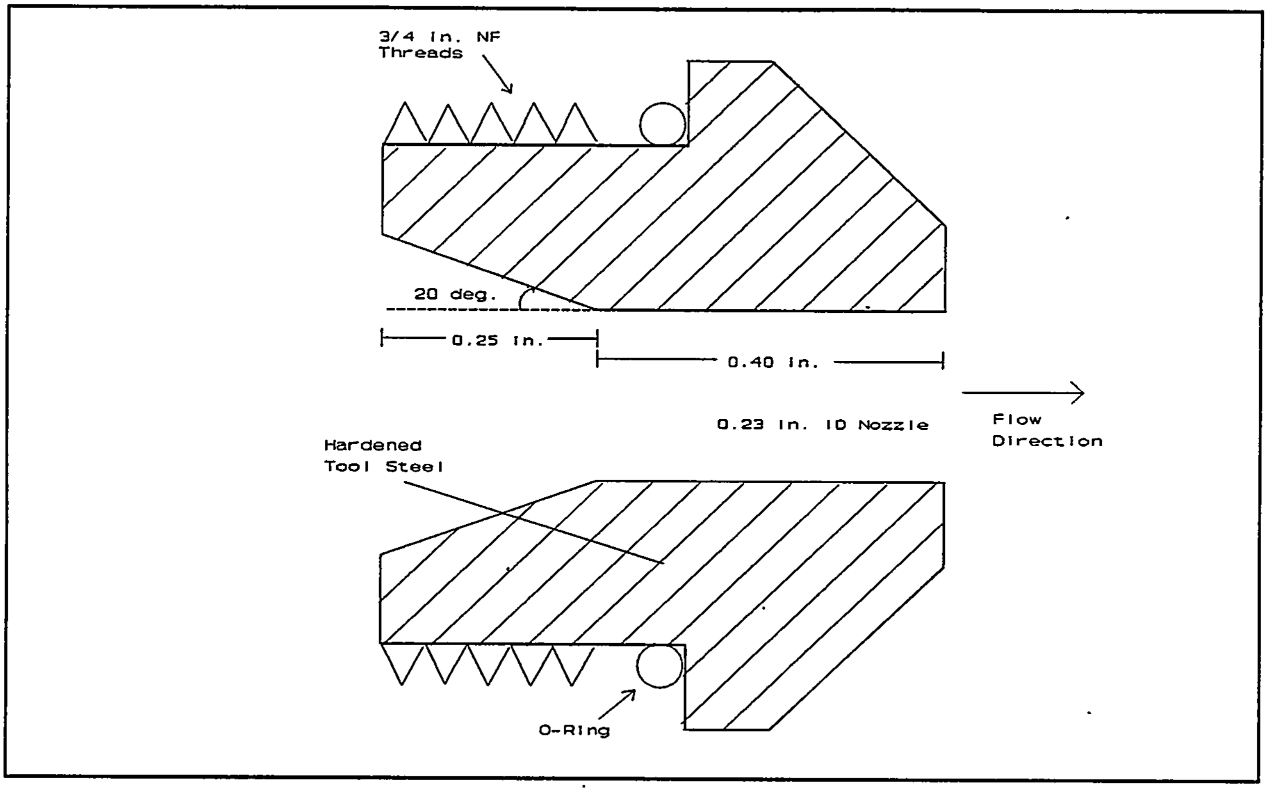

Figure 3.2. 1/25-Scale Nozzle Design

ECR was recorded every 5 minutes until 60 minutes had passed since the pump was started. The ECR was measured every 10 minutes thereafter until either the flow rate was changed or the test ended. Every time the ECR was measured, measurements of the slurry density were also made using either a mechanical oscillation digital density meter, a stainless steel liquid density flask, or both. The slurry temperature was also recorded during most tests (neither the digital density meter nor the platinum resistance temperature device (RTD) thermometer was available for use in test S25-1-K).

Effective cleaning radius, temperature, and slurry density measurement continued until the average of the eight ECRs was observed to be increasing at a rate of less than 1 cm/h for at least one hour. Once this requirement was met, a detailed sketch[(a)] of the ECR profile visible from under the tank was made. The flow rate was then increased and measurements taken as described above until the ECR growth criteria was met. Another sketch of the ECR profile was then prepared. The slurry was pumped out of the tank to expose the sludge bank, which was photographed. The weight of the slurry and the remaining sludge were measured and used to compute the weight percent of the sludge mobilized.

(a) The data from these sketches are presented in Appendix B.

3.3 Measurement and Test Equipment

This section provides a brief description of each of the devices used to obtain the data provided in this report.

3.3.1 ECR Measurements

The ECR recorded during testing was the radial distance between the tank centerline and the sludge/slurry interface. This distance was quantified with the assistance of the concentric circles scribed on the tank bottom using a meterstick before testing. Before these data were analyzed, 2.2 cm was subtracted from each valve to correct for the distance between the tank centerline and the nozzle exit.

3.3.2 Slurry Flow Rate

The flow of slurry through the discharge nozzles was measured using a Schlumberger Industries (Greenwood, SC) Model FM100 pulsed dc magnetic flowmeter. The flowmeter was calibrated using tap water. It was observed during calibration and testing that the flow rate could be maintained within ±0.1 gpm of the desired flow rate. This corresponds to about a ±7 cm^2/s uncertainty in the U_oD values.

3.3.3 Slurry Density

An Anton Paar (Austria) Model DMA35 mechanical oscillation digital density meter was used to monitor slurry density during most tests (it arrived mid-way through test S25-2-K). This device calculates density based on a measurement of the period of oscillation of a small glass tube filled with the sample liquid. The stated accuracy of this device is ±0.001 g/mL. Its calibration was verified by comparing the measured densities of degassed water and 10.0 wt% NaCl solutions at known temperatures with their published densities. The digital density meter was found to read about 0.002 g/mL low.

A Gardco Corp. (Pompano Beach, FL) stainless steel density flask was used periodically as a check on the operation of the digital density meter. The flask is filled to give a precise volume of sample which is then weighed to determine the liquid density. This flask has a stated volume of 83.2±0.5 mL. Using this volume and the same calibration liquids as used for the digital density meter, the density flask gave densities 0.005 g/mL too high. This is within the stated accuracy of the density flask.

3.3.4 Weights

An Arlyn Scales model 310-M 0-1000 lb digital platform scale was used to prepare all simulants and to weigh the amount of sludge and supernate added to and removed from the tank. Accuracy = ±1 %.

A Sartorius (Waukegan, IL) 0 to 2100.00 gram digital platform balance was used to measure the weight of the density flask (filled and empty). This balance is accurate to ±0.02 grams. This balance was used for all tests except S25-1-K. A 0 to 10,000.0-gram digital balance with a ±0.1- gram accuracy was used for this test because the 2100-gram balance had not yet arrived. As a result, the density data for S25-1-K are less accurate.

3.3.5 Slurry Temperature

A Cole-Parmer (Chicago, IL) Digi-Sense Platinum RTD Thermometer (Model 93400-00) was used to monitor the slurry temperature during most tests. In the tests conducted before the RTD thermometer arrived, the temperature readout on the digital density meter was used instead. Both temperature readouts display the temperature with ±0.1°C precision. The accuracy of both devices is better than ±0.5°C.

3.3.6 Sludge Rheology

A Haake (Karlsruhe, West Germany) Rotovisco viscometer with an M5 measurement head was used for all sludge shear strength measurements. Nearly all shear strength measurements were conducted using a fully-submerged, 0.25-in. shear vane ($H_v=D_v$). Where possible, the data obtained using the 0.25-in. vane were verified using a 0.875-in. shear vane. The maximum shear strength that can be measured using the 0.875-in. vane is 24 kdyne/cm^2. The 0.25-in. vane can measure up to 913 kdyne/cm^2.

A Haake (Karlsruhe, West Germany) Rotovisco viscometer with a CV20 measurement head was used for all sludge viscoelasticity measurements.

3.3.7 Sludge Tensile Strength

The tensile strength of each sludge was measured using a device fabricated from the tops of two 200-mL plastic bottles. The device is shown in Figure 3.3. The sludge simulant sample was loaded into the tensiometer, and a tensile force was then applied at a rate of 98±5 kdyne/min (equivalent to a water addition rate of 100±5 mL/min). Following failure of the specimen in a tensile mode, the mass of the water in the 1000-mL plastic bottle (M) and the mass of the upper portion of the tensiometer including the contained sludge (M_t) were determined. These data, along with small allowances for pulley friction (20 grams) and the failure plane diameter (D_t) were used to compute the tensile strength (S_t) according to the equation:

$$S_t = \frac{4(M - M_t - 20\ g)(980\ cm/s^2)}{\pi D_t^2}$$

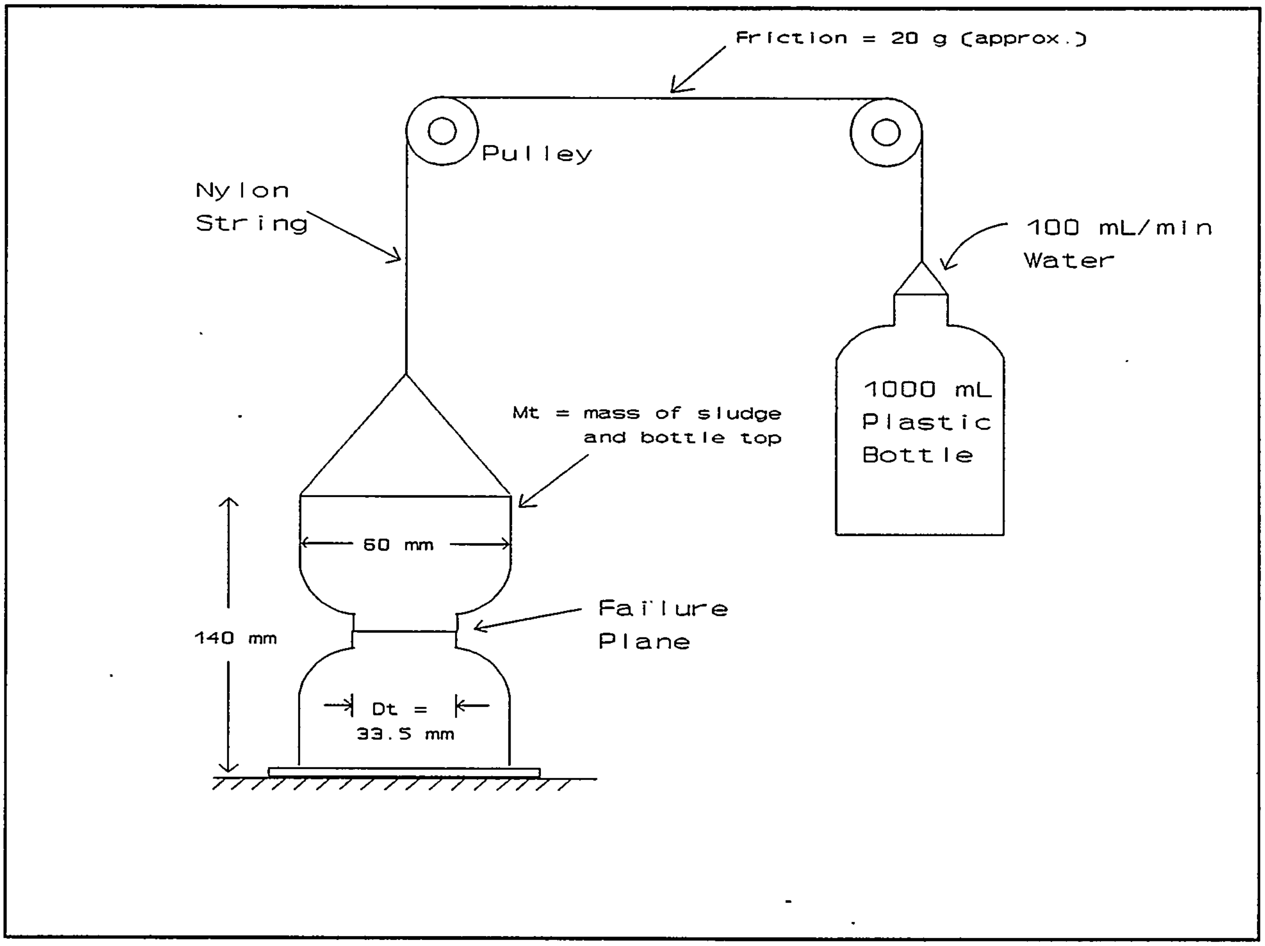

Figure 3.3. Tensile Strength Measurement Device

3.3.8 Sludge Yield Stress

The sludge yield stress was measured on each sludge simulant sample using the Haake viscometer and shear vane described for the shear strength above. The shear vane was inserted into the simulant such that it was fully-submerged. The vane was then rotated at 0.3 rpm for 1.5 minutes. The peak torque observed during this period is used to calculate the shear strength. For 0.5 minutes after the vane rotation was stopped, the torque remaining on the shear vane was monitored. The torque typically decayed to a stable value within 5 to 10 seconds. The torque remaining on the vane 0.5 minutes after the vane stopped was used to calculate the sludge yield stress using the same relationship as used to calculate sludge shear strength.

3.4 Simulants

A variety of sludge simulants were used during the FY 1993 1/25-scale testing. The simulants were selected to provide variations in the key properties thought to govern sludge mobilization. The justification for the selection of each of the simulants is provided in the "1/25-Scale Test Plan" (DST-TP-93-1), which is included in Appendix A.

Clay-based sludge simulants were used for tests S25-1-K through S25-14-KI. All clay-based simulants were prepared in a similar manner. The required mass of each component was weighed out before mixing. If the simulant contained more than one type of dry material (e.g., kaolin/silica simulants), the dry materials were blended before adding the water. The dry materials were then added to the Littleford Mixer followed by the water. The simulants were mixed for 20 to 30 minutes before being placed into covered, 5-gal buckets. Simulants were routinely mixed about 18 hours before being loaded into the 1/25-scale tank. Mobilization testing was started immediately following loading of the sludge.

Tests S25-15-SS and S25-16-SS required that the simulant be prepared differently. The soda ash was first dissolved in the specified quantity of water before the silica was added. The mixing of the silica and soda ash solution for test S25-15-SS was conducted in the 1/25-scale tank. The dry silica was placed in the tank before adding the soda ash solution. The resulting slurry was then mixed to a uniform consistency by hand. The simulant for S25-16-SS was prepared similarly with the exception that the initial mixing of the silica and soda ash was conducted in a drum.

The compositions of the sludge simulants used in the 1/25-scale testing are given in Table 3.1.

In tests S25-1-K through S25-14-KI water was used as the tank supernate. In each test, 200.0 kg of water was added to the tank as supernate. Tests S25-15-SS and S25-16-SS used a 17.1 wt% soda ash solution. In both of these tests, 234 kg (200.0 liters) of this solution was used. To minimize the quantity of hazardous waste generated, the soda ash solution used in test S25-15-SS was reused for test S25-16-SS. This was also routinely done during the FY 1987 pilot-scale tests that tests S25-15-SS and S25-16-SS were designed to simulate.

3.5 Mixer Pump Operation Data

As described in Section 3.2, ECR data were recorded periodically throughout each test and typically the mixer pump was operated first at a low flow rate and then at a higher flow rate. The selection of the initial flow rate for each test was made based on the results of previous tests. It was desired that the ECR reach about 20 to 25 cm from the tank center for the first flow rate. ECRs much less than 20 cm are subject to larger relative measurement uncertainties. If the initial ECR is much greater than 25 cm, then the second flow rate cannot be made much higher than the initial flow rate without the ECR reaching 35 to 40 cm where the effects of the tank wall on the slurry flow patterns will likely affect the ECR growth (tank radius is approximately 45 cm). The second flow rate was selected based on the ECR observed from the first flow rate.

The flow rates selected for each test along with the corresponding nozzle exit velocities and U_oD values are provided in Table 3.2.

Table 3.1. Simulant Compositions

Test Number	Target Composition (wt%)	Measured wt% Solids	Mass of Sludge in Tank (kg)	Volume of Sludge in Tank (L)
S25-1-K	60.0 kaolin 40.0 water	58.3±0.5	73.7	46.0
S25-2-K	65.2 kaolin 34.8 water	63.9±0.5	83.1	49.8
S25-3-K	67.0 kaolin 33.0 water	67.2±0.5	86.5	51.0
S25-4-B	17.0 bentonite 83.0 water	15.1±0.5	58.2	52.5
S25-5-B	25.0 bentonite 75.0 water	22.8±0.5	63.6	54.8
S25-6-B	30.5 bentonite 69.5 water	28.0±0.5	61.1	50.6
S25-7-B	17.5 bentonite 82.5 water	16.6±0.5	55.7	50.0
S25-8-KS	34.8 kaolin 34.8 silica 30.5 water	69.6±0.5	77.8	44.5
S25-9-KS	35.5 kaolin 35.5 silica 29.0 water	70.2±0.5	83.2	47.3
S25-10-KS	36.5 kaolin 36.5 silica 27.0 water	73.3±0.5	89.8	49.3
S25-11-KN	55.8 kaolin 15.5 NaCl 28.7 water	71.5±0.5	89.8	50.6
S25-12-KN	60.0 kaolin 14.3 NaCl 25.7 water	74.2±0.5	93.4	52.2

Table 3.1. (contd)

Test Number	Target Composition (wt%)	Measured wt% Solids	Mass of Sludge in Tank (kg)	Volume of Sludge in Tank (L)
S25-13-K	60.0 kaolin 40.0 water	60.1±0.5	79.1	49.9
S25-14-KI	65.0 kaolin 35.0 water	65.0±0.5	79.6	47.8
S25-15-SS	64.3 silica 5.9 soda ash 29.8 water	70.7±0.5	90.7	50.4
S25-16-SS	64.3 silica 5.9 soda ash 29.8 water	70.0±0.5	90.7	50.4

Test S25-4-B did not result in useable ECR data. When the system piping was back-flushed to prime the centrifugal pumps, supernate was forced underneath the sludge bed. This eliminated the adhesion of the bed to the tank floor. When the simulated mixer pump was activated the bentonite sludge bed was observed to be lifted off the tank floor in the regions where the jets were impacting. As the mixer pump rotated, the sludge bank would rise and fall as the jets passed underneath. This flexing of the sludge quickly caused it to break up into large chunks, which then were pushed around the tank by the jets.

Only one flow rate was used in tests S25-11-KN and S25-12-KN due to the long time required for the ECR growth rates in these tests to fall below the required 1 cm/h.

Test S25-14-KI was unusual in that the mixer pump was not oscillated during much of the test. The flow through the mixer pump was initially started without the jets oscillating. The ECRs produced by the two jets were monitored for 97 minutes before the mixer pump was rotated 90°. The ECRs along the new directions were monitored for 105 minutes. At this point, normal mixer pump oscillation was established and the ECRs were monitored as usual for the next 245 minutes. The mixer pump oscillation was once again stopped, and the ECRs aligned with the nozzles were monitored for the next 90 min before the test was ended.

Table 3.2. Mixer Pump Operation Data

Test Number	Total Flow (±0.1 gpm)	Nozzle Exit Velocity (m/s)	U_oD (±7 cm^2/s)	Time (min)
S25-1-K	4.42	5.21	304	0-232
	7.14	8.41	491	232-492
S25-2-K	8.42	9.92	579	0-340
	9.85	11.61	678	340-580
S25-3-K	8.42	9.92	579	0-284
	9.85	11.61	678	284-644
	8.42	9.91	579	0-30
S25-5-B	3.93	4.63	270	0-65
	7.88	9.28	542	65-295
	9.84	11.61	678	295-340
	11.83	13.93	814	340-570
	11.83	13.93	814	0-252
	16.77	19.75	1153	252-442
S25-7-B	3.93	4.63	270	0-200
	6.89	8.12	474	200-440
S25-8-KS	6.89	8.12	474	0-200
	8.37	9.86	576	200-530
S25-9-KS	4.42	5.21	304	0-275
	8.37	9.86	576	275-606
S25-10-KS	5.90	6.59	406	0-245
	8.87	10.44	610	245-614
S25-11-KN	5.90	6.59	406	0-464
S25-12-KN	5.90	6.59	406	0-490
S25-13-K	4.42	5.21	304	0-270
	8.42	9.92	579	270-480
S25-14-KI	5.90	6.59	406	0-537

Table 3.2. (contd)

Test Number	Total Flow (±0.1 gpm)	Nozzle Exit Velocity (m/s)	U_oD (±7 cm^2/s)	Time (min)
S25-15-SS	6.35	7.48	437	0-240
	12.12	14.28	834	240-680
S25-16-SS	7.96	9.37	547	0-760

4.0 Results and Analyses

This section presents the data obtained from the 1/25-scale sludge mobilization testing. The conclusions drawn from the data are also given in this section.

4.1 Relationship of ECR to Simulant Physical Properties

Each of the 1/25-scale sludge mobilization tests was continued until the ECR growth rate was below 1 cm/h for at least one hour. At the conclusion of each 1/25-scale test, the average ECR was computed from the eight ECR measurements. This value was taken to be the "true" effective cleaning radius for the simulant and jet flow rate being tested.

Had the tests been continued for longer time periods, the average ECRs would likely have continued to increase slowly before reaching a final value. Judging from the observed ECR growth rates, it is expected that the ECRs observed at the end of each test were within about 10% of the ECRs that would have been obtained had the test been run for much longer times (silica/soda ash tests excluded). Future testing should be used to verify this.

Based on previous sludge mobilization testing,[a] for a given simulant the ECR increases linearly with increasing nozzle exit velocity (U_o) and jet nozzle diameter (D). This has been verified experimentally and is supported by an analysis of the equations that describe the downstream velocities of a submerged, turbulent jet.[a] Within the limits of the experimental uncertainties, this linearity between the ECR and U_oD for a given simulant was observed in the 1/25-scale sludge mobilization testing. To make comparisons between the various simulants tested, it is necessary to correct for the differences in jet flow rates used in the different tests [all tests utilized the same 5.84 mm (0.230 in.) ID nozzles].

Because the linearity between ECR and U_oD has been established, the resistance of a given simulant to mobilization can be quantified by the quantity ECR/U_oD. Comparing the value of this quantity between simulants provides a direct comparison of their relative resistances to mobilization. The plots discussed in the remainder of this section are generally ECR/U_oD versus some physical property of the sludge simulants used.

The ECR, U_oD, shear strength (τ_s), yield stress (τ_y), and tensile strength (S_t) data for all the 1/25-scale sludge mobilization tests are given in Table 4.1.

The experimental uncertainties reported with each quantity are the calculated 95% confidence intervals. The confidence intervals are calculated from the standard deviation of a data set of multiple measurements around the mean value of that data set. For the average ECR values, it is assumed that the experimental data collected represent eight replicate measurements of ECR, each subject to some random deviation from the "true" ECR.

(a) Powell, M. R., C. L Fow, G. A. Whyatt, P. A. Scott, and C. M. Ruecker. November 1990. *Proposed Test Strategy for the Evaluation of Double-Shell Tank Sludge Mobilization.* Letter Report prepared by Pacific Northwest Laboratory for Westinghouse Hanford Company.

Table 4.1. Physical Property and ECR Data

Test Number	τ_s (kdyn/cm^2)	τ_y (kdyn/cm^2)	S_t (kdyn/cm^2)	U_oD (cm^2/s)	ECR (cm)
S25-1-K	8.74±.6	2.62±0.3	14.3±.9	304 491	13.8±2.4 22.2±3.1
S25-2-K	18.1±2.5	5.43±0.5	24.2±2.8	579 676	32.5±2.5 35.0±2.3
S25-3-K	40.5±3.4	16.6±1.5	29.3±9.5	579 676	27.1±1.3 32.0±1.6
S25-4-B	5.8±0.7	3.5±0.5	12.1±2.0	579	No Data
S25-5-B	33.1±2.6	24.3±3.0	58.5±4.5	542 814	14.7±2.0 21.3±1.5
S25-6-B	47.6±5.9	33.5±3.2	86.9±26.5	814 1153	22.9±2.0 34.5±6.04
S25-7-B	10.0±1.5	6.8±0.6	24.0±2.6	270 474	17.5±2.8 40.4±5.8[(a)]
S25-8-KS	10.9±0.5	4.7±1.6	20.1±6.4	474 576	29.6±3.3 34.4±3.7
S25-9-KS	16.6±2.2	6.5±1.9	23.0±4.1	304 576	14.2±3.6 32.7±3.7
S25-10-KS	27.2±1.2	10.8±2.5	23.9±4.8	406 610	20.8±3.0 30.5±1.7
S25-11-KN	20.4±1.8	6.2±1.6	42.3±10	406	30.9±1.7
S25-12-KN	48.5±3.1	17.8±1.8	45.8±10	406	28.5±2.8
S25-13-K	10.5±0.5	4.9±0.4	16.7±1.7	304 579	17.4±1.2 31.5±1.4
S25-14-KI	30.7±3.1	11.2±2.0	19.7±3.4	406	24.0±3.1
S25-15-SS	16.7±1.8	0.0	NM	437 836	7.2±0.8 25.1±1.3
S25-16-SS	15.2±2.8	0.0	NM	547	17.2±1.2

(a) Seven of the eight ECR measurements were at the tank wall (tank radius = 45 cm) while one measurement was equal to 23.2 cm. See Figure B.11 in Appendix B.

Note: NM = Not Measured.

The tensile strengths of the silica/soda ash simulants were not measured due to difficulties with the sludge tensiometers. Because the silica/soda ash simulant requires several days to generate its mechanical strength, great care must be taken when loading and storing the silica/soda ash tensile strength samples to avoid sample disruption or drying. Based on S_t measurements made during the FY 1992 laboratory-scale testing, it is expected that the silica/soda ash tensile strengths for test S25-15-SS and S25-16-SS were approximately 12 kdyne/cm^2.

4.1.1 ECR Dependence on Shear Strength (τ_s)

The ECR/U_oD data contained in Table 4.1 are plotted versus the measured sludge simulant shear strength in Figure 4.1. Previous sludge mobilization test data have been plotted in this manner in an effort to extract a correlation of the form

$$ECR = KU_oD\tau_s^n \qquad (4.1)$$

If the ECR depends on τ_s according to this equation, plotting $\log_{10}(ECR/U_oD)$ vs $\log_{10}(\tau_s)$ should result in a straight line with a y-intercept equal to $\log_{10}(K)$ and a slope equal to the exponent "n." The form of this equation results from force balance considerations similar to those used by Churnetski (1982).

The log-log plot of ECR/U_oD vs τ_s (Figure 4.1) does not show any all-encompassing linear trend that would support the ECR equation given above. Such an equation may "fit" the data for any one of the simulants, but it is clear that the data for all the simulants cannot be adequately fit by a single line. Previous sludge mobilization testing data tend to support the linear relationship between log(ECR/U_oD) and log(τ_s), but the 1/25-scale data do not.

The data for the kaolin/water simulants only are plotted in Figure 4.2. Based on this plot it is concluded that the resistance to mobilization of kaolin clay is nearly independent of shear strength. More data points are required to verify this assertion, but it is clear from the existing data that the dependence on shear strength is very weak; at least it is smaller than the magnitude of the experimental uncertainties in the ECR measurements.

It has been speculated that the kaolin clay simulants might be absorbing water from the slurry near the sludge/slurry interface. This would result in a decrease in the shear strength of the sludge near the interface. The weakened sludge would be mobilized by the jet to expose more of the sludge to the slurry. If the kaolin clay simulants all tend to absorb water to roughly the same extent (i.e., equal wt% clay in the absorbing regions), then the effective shear strength of all the kaolin simulants at the sludge/slurry interface would be approximately equal (the shear strength of kaolin/water mixtures is a function primarily of water content). Under these conditions it would be expected that the mobilization resistance of the kaolin/water simulants would be independent of their bulk shear strengths—just as shown in Figure 4.2.

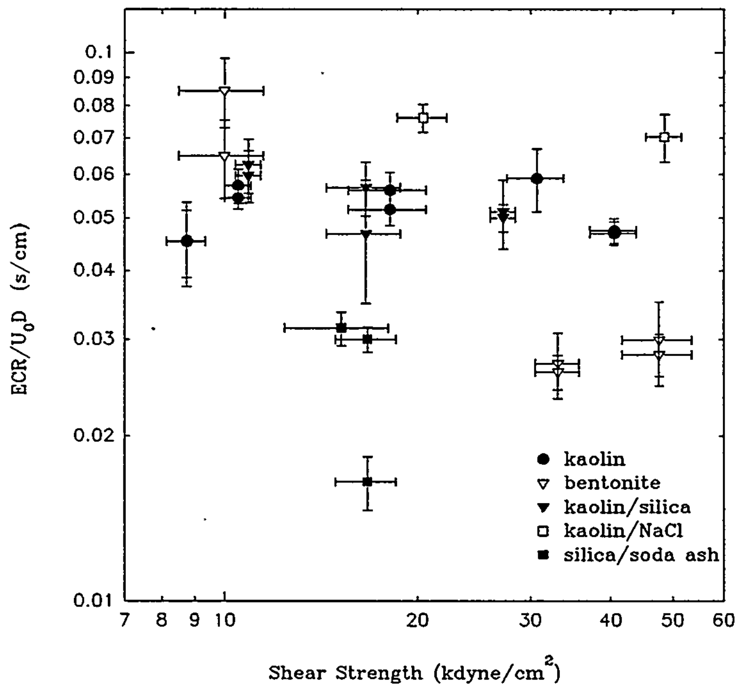

Figure 4.1. 1/25-Scale ECR Data Versus τ_s

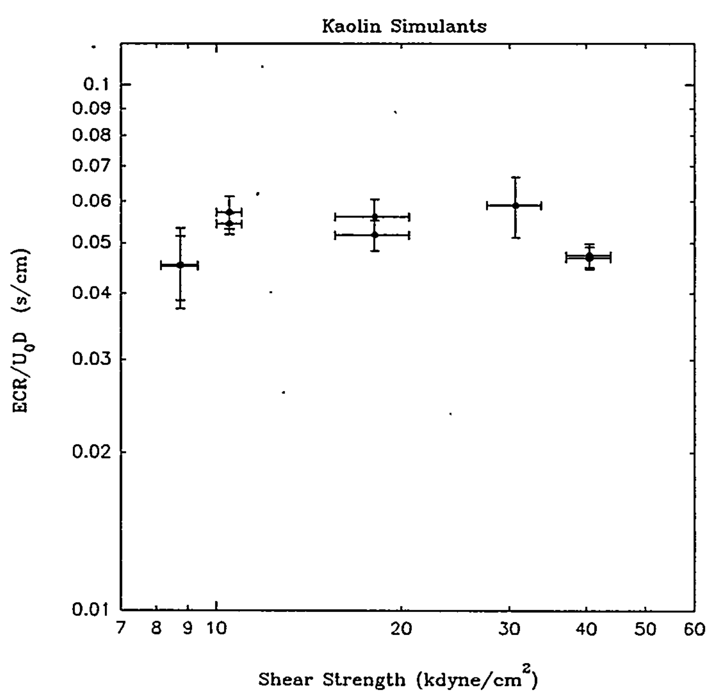

Figure 4.2. Kaolin Simulant ECR vs τ_s

Although this is an attractive explanation for the observed kaolin data, there are reasons to suspect that it is not accurate. First, the permeability of clays is generally very low. To have a significant effect on the rate of ECR growth, the water would need to penetrate into the bulk of the kaolin at a rate on the order of 0.5 cm/h. A test was performed in which kaolin and bentonite (from tests S25-3-K and S25-6-B, respectively) were packed to a 2-cm depth in separate plastic beakers. The samples were weighed, then tap water was added to each beaker to a depth of 2 cm. Both samples were left undisturbed for 3 hours at which time the water was drained and the samples weighed to determine the mass of water that each had absorbed. The kaolin sample gained 0.03 grams of water, and the bentonite sample gained 2.5 grams. These mass gains correspond to water penetration rates of 0.001 cm/h for the kaolin and 0.05 cm/h for bentonite.[a] These rates are clearly too slow to significantly affect ECR growth. Furthermore, if water absorption actually affected the kaolin ECR data, the effect should have been evident in the bentonite data as well. It was not.

As an additional argument, the ECR growth rate data (Figures 4.30 through 4.32 and 4.41) for the kaolin tests demonstrate that the average ECR after only 10 minutes of pump operation is a reasonably constant fraction (80$\pm$5%) of the final ECR. During the first 10 minutes of mixer pump operation, the ECR is growing much too quickly for water permeation into the kaolin to have an effect. If the water permeation was actually obscuring a dependence of ECR on τ_s then it would be expected that a dependence of ECR on τ_s would be evident in the ECR-after-10-minutes data. Because the 10 minute ECR values are consistently 80% of the final values, a plot of the 10 minute ECR values vs τ_s shows the same trends as Figure 4.2. Thus, it is concluded that absorption of water by the kaolin simulants did not significantly affect the ECR measurements.

The ECR/U_0D vs τ_s data for the bentonite clay simulants are given in Figure 4.3. A strong dependence of mobilization resistance on bentonite shear strength is apparent.

Four bentonite simulants were prepared, but only three of the tests resulted in ECR data. The first bentonite test that was attempted resulted in the complete mobilization of the simulant. When the centrifugal pumps were primed by pumping tank liquid backwards through the system piping, the resulting "jet" of fluid issuing vertically downward from the mixer pump intake briefly lifted a large portion of the bentonite by forcing water underneath it. The bentonite, it was observed, tends to stick to itself much more strongly than it adheres to the plexiglass tank. Once water was present between the bentonite layer and the tank floor, there was very little adhesion between the bentonite and the floor. As a result, when the mixer pump was activated the entire sludge bed was observed to lift and flex in response to the jets. This quickly broke the bed into large chunks.

Despite changes in the pump priming procedure to alleviate the problem, two of the three remaining bentonite tests were also affected by the presence of water between the bentonite and the tank floor. When the mixer pump was activated, the jets quickly excavated a region of the sludge roughly 5 to 10 cm from the nozzles and about 3 to 5 cm above the tank floor. The upper 2 to 4 cm of simulant remained intact surrounding the mixer pump column. In effect, the sludge bank was undercut as shown in Figure 4.4. This action of the jet on this sludge bank shape produced a lifting force on the bentonite bed that tended to raise the bentonite a few millimeters off the tank floor.

(a) Strictly speaking, water is not flowing into the bentonite as much as the bentonite is expanding into the water. Bentonite is known as a "swelling" clay because of this property.

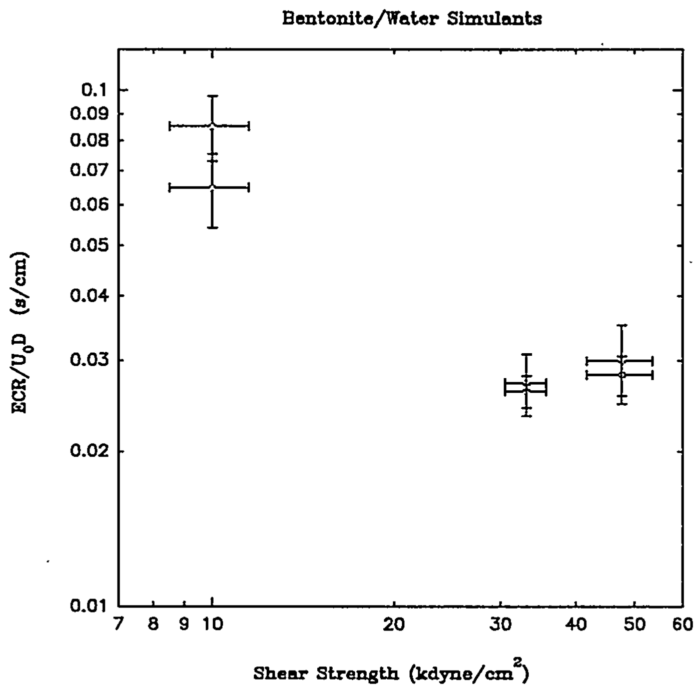

Figure 4.3. Bentonite ECR DAta vs τ_s

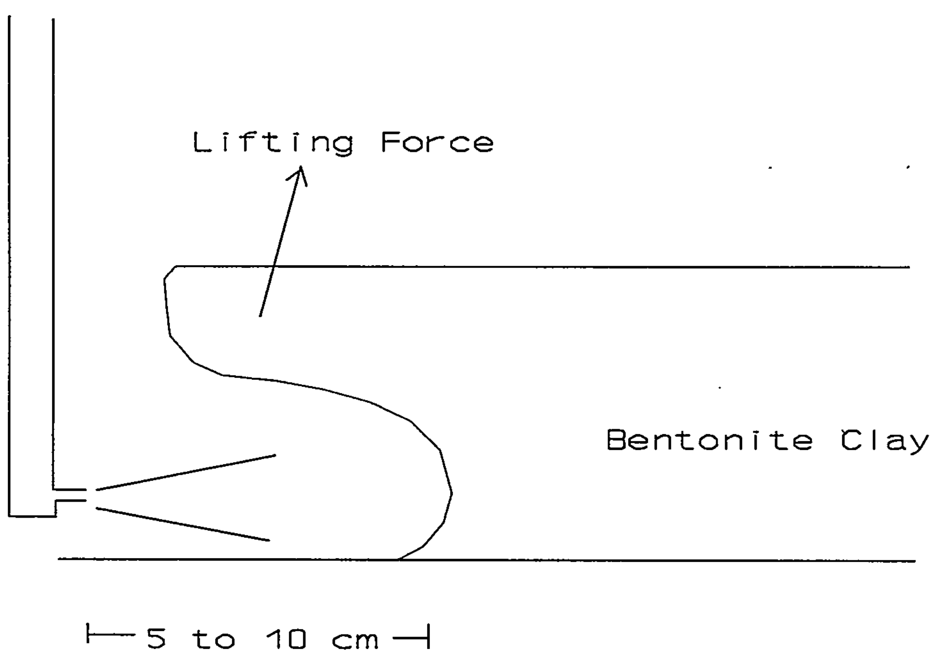

Figure 4.4. Undercut Bentonite Sludge Bank Profile

This effect was noted during tests S25-6-B and S25-7-B. It is suspected that the result of this was to increase the average ECRs. In test S25-6-B, for example, in the first few minutes of the test the bed was observed to be lifted briefly along six of the eight ECR lines marked on the tank bottom. At the end of the test, the average of the ECRs along the six lines that experienced lifting of the bed was 38 cm. The remaining two ECR measurements were 23.8 and 24.3 cm (see Figure B.9 in Appendix B). It is surmised that the lifting of the bentonite sludge bed resulted in larger ECRs than would have been observed had there been no lifting of the bed.

The bentonite bed in test S25-7-B behaved similarly to that in S25-6-B. The ECRs measured along lines where bed lifting had occurred were significantly larger than the ECRs where no lifting was observed. At the end of test S25-7-B, all ECRs were at the tank wall (42.8 cm) except one which was 23.3 cm (see Figure B.11 in Appendix B). It is postulated that these smaller ECRs provide a more accurate measure of the resistance of bentonite clay to mobilization. The enhanced mobilization that results from the bed lifting is not likely to be encountered during the mobilization of the DST sludge due to the much higher density of the sludge (typically 1500 to 1800 kg/m^3). In some of the plots of the bentonite data in later sections of this report both the observed average ECR data (as given in Table 4.1) and the ECRs along the lines where bed lifting did not occur are presented.

Lifting of the bentonite simulant was not observed during test S25-5-B. When the system piping was primed before this test, the flow rate of the priming fluid was restricted to avoid disturbing the sludge simulant. More importantly, though, was the fact that the first mixer pump flow rate was relatively low. The initial flow was set to 4.0 gpm and ECR readings taken for 60 minutes. After 60 minutes, only four of the eight ECRs were greater than 4 cm. The flow rate was then adjusted to 8 gpm and the ECRs monitored for the next 4 hours. It is believed that running the mixer pump at a low flow rate for the first hour permitted the sludge bank to develop a more vertical profile than that shown in Figure 4.4. When the flow was increased to 8 gpm, the sludge bank profile and distance from the jets were sufficient to avoid the lifting force on the sludge bed. If bentonite simulants are tested in the future, it is recommended that the tests be performed in this manner to avoid lifting of the sludge bed. No bed lifting was observed during testing of any of the other simulants.

The dependence of ECR on shear strength for the kaolin/silica simulants is shown in Figure 4.5. A slight increase in the mobilization resistance of this simulant is observed as τ_s is increased, but the magnitude of this dependence is on the order of the magnitude of the uncertainties in the ECR measurements. The kaolin/silica simulants were formulated such that they had equal weight percentages of kaolin clay and Min-U-Sil 30 micron silica flour. The silica was added in an effort to give a simulant for which interparticle attractive forces contributed less to the shear strength than in the kaolin simulants. The mobilization behavior of this simulant is not significantly different from that of the kaolin simulants.

Tests S25-11-KN and S25-12-KN were performed to provide an estimate of the effect of a soluble sludge component on sludge mobilization. Certain DSTs contain sludge that is partially soluble (e.g., NCRW tanks) and the mobilization of these tanks might be carried out using inhibited water as the mobilizing fluid. It is expected that the dissolution of a fraction of the sludge solids from the sludge/slurry interface will increase the ECR. Tests S25-11-KN and S25-12-KN were an attempt to quantify the magnitude of this effect. The ECR/U_oD vs τ_s data for these two tests are given in Figure 4.6.

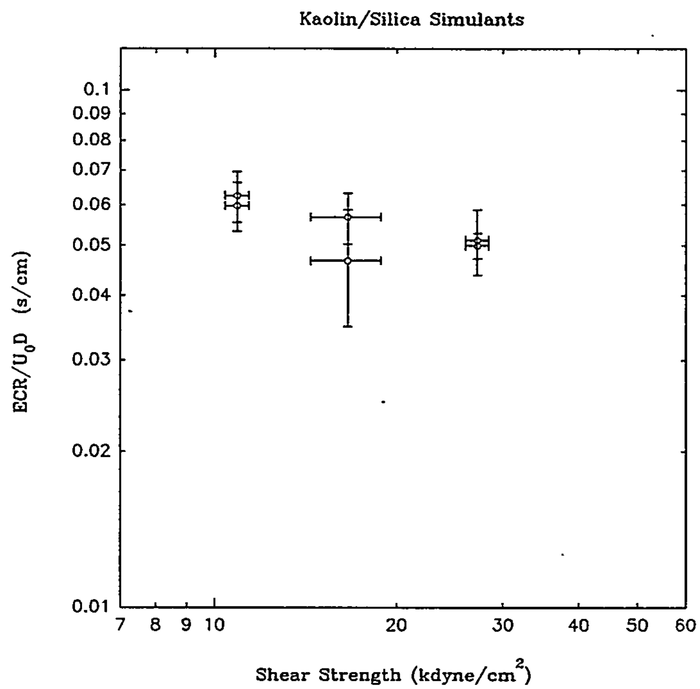

Figure 4.5. Kaolin/Silica ECR Data vs τ_s

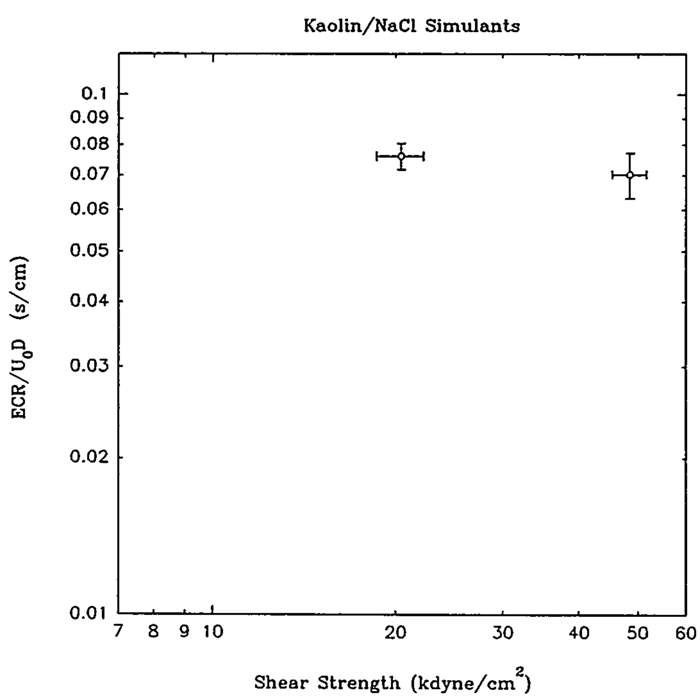

Figure 4.6. Kaolin/NaCl ECR Data vs τ_s

It is apparent from Figures 4.1 and 4.6 that the dissolution of the solid sodium chloride from the kaolin/NaCl simulant resulted in an increased ECR. Compared to the ECRs observed using the kaolin and kaolin/silica simulants, the kaolin/NaCl ECRs are nearly 50% larger. This result provides evidence that a significant increase in ECR can be expected due to the partial dissolution of the sludge. However, it must be stressed that the kaolin/NaCl simulant was not intended to accurately reflect the mobilization behavior of any DST sludge. Testing of chemical sludge simulants will likely be required to provide estimates of the enhanced ECRs expected to result from partial sludge dissolution. The kaolin/NaCl tests were conducted with the goal of establishing whether such an effect could be expected.

Figure 4.7 shows the ECR/U_0D vs τ_s data for the silica/soda ash simulant. The silica/soda ash data are discussed in Section 4.2 of this report.

4.1.2 Comparison of 1/25-Scale Data with 1/12-Scale and Bench-Scale

Previous sludge mobilization testing has been conducted using bentonite, kaolin, and silica/soda ash simulants. Figure 4.8 is a plot of both the 1/25-scale mobilization data and the 1/12-scale data for silica/soda ash simulant. The line through the 1/12-scale data on the plot is the correlation of ECR with U_0D and τ_s developed previously.[a] If the assumption is made that the ECR data scale linearly with the scale of the test facility, then it is apparent that the 1/12-scale correlation of ECR with τ_s predicts ECRs too conservatively for kaolin and bentonite simulants. This is significant because there are reasons to believe that the DST sludge may behave more like the clay simulants than silica/soda ash. For example, most tank sludges have been qualitatively described as "sticky" and have measured particle size distributions that indicate a significant fraction of the particles are smaller than one micron (much like a clay). The silica/soda ash simulant is not really sticky while the clay simulants are, and the silica contains a smaller fraction of submicron particles. It is the submicron particles that have the biggest influence on the cohesiveness of the sludge.

Based on the τ_s = 20.0 kdyne/cm^2 kaolin clay data, for example, the 1/25-scale testing projects that a single, centrally-located mixer pump with a U_0D of 2.18 m^2/s (23.5 ft^2/s) will mobilize 100% of the tank sludge (ECR equals 10.9 m = 35.8 ft).[b] Using the 1/12-scale silica/soda ash correlation, the same mixer pump is predicted to mobilize only 23% of the sludge (ECR = 4.9 m = 16.2 ft).

An alternative explanation of the difference between the 1/12-scale and 1/25-scale data is that the ECR data might not scale linearly as has been assumed. If true, this would imply that linearly scaled ECR data based on small-scale tests tend to over-predict the full-scale ECR. Future tests are needed at 1/25th and 1/12-scale using identical simulants to resolve this issue. The 1/25-scale silica/soda ash data actually compare well with the 1/12-scale (silica/soda ash) data (compare Figure 4.7 with Figure 4.8).

(a) Powell, M. R., C. L Fow, G. A. Whyatt, P. A. Scott, and C. M. Ruecker. November 1990. *Proposed Test Strategy for the Evaluation of Double-Shell Tank Sludge Mobilization.* Letter Report prepared by Pacific Northwest Laboratory for Westinghouse Hanford Company.

(a) This assumes that 100% sludge mobilization is obtained when the predicted ECR equals the distance between the discharge nozzles and the tank wall. The effect of the tank wall on the jet flow patterns near the wall may tend to shelter a heel of sludge from the action of the jet. The significance of these wall effects will be evaluated in future tests.

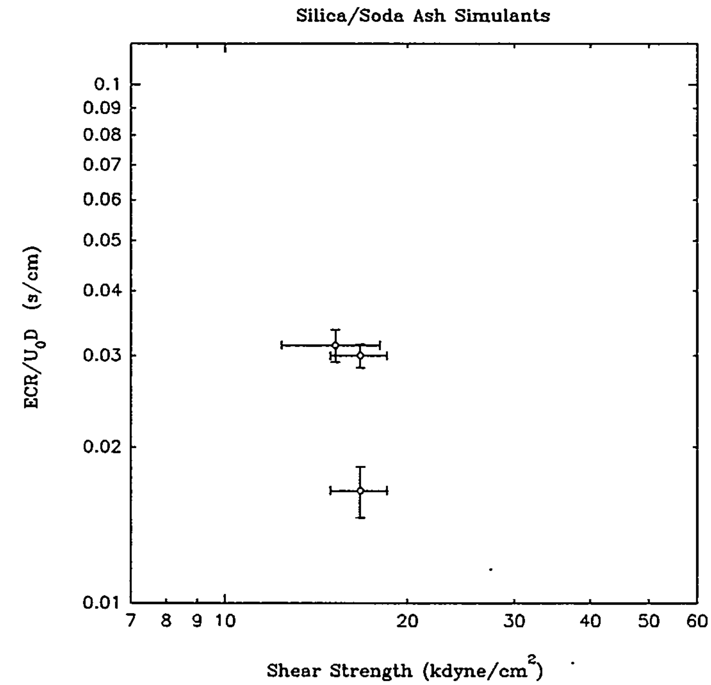

Figure 4.7. Silica/Soda Ash ECR Data vs τ_s

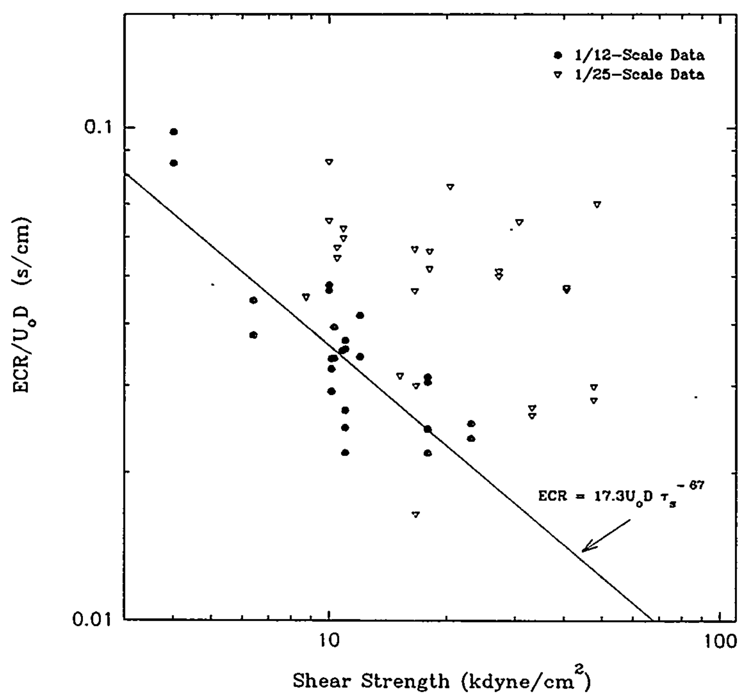

Figure 4.8. Comparison of 1/12-Scale and 1/25-Scale Silica/Soda Ash Data

The 1/25-scale data are compared to the bench-scale sludge mobilization data[a] in Figure 4.9. The bench-scale and 1/25-scale data for the clay simulants compare reasonably well. That is, for a given shear strength, the 1/25-scale ECR/U_oD data for the clays lie within the experimental uncertainty of the bench-scale data.

The silica/soda ash data do not compare well, but this is probably because the bench-scale silica/soda ash simulant had a different composition (higher silica content) and was eroded using tap water rather than soda ash solution as was done in the 1/25-scale tests. It is suspected that the combination of osmotic pressure driving water into the silica/soda ash and the possible dissolution of crystallized salt within the simulant is responsible for the relatively large silica/soda ash ECRs observed during bench-scale testing. An additional effect may have been the increased frictional component of the bench-scale silica/soda ash shear strength, which was due to its higher silica content.

The comparison of the bench-scale and 1/25-scale mobilization data for the kaolin simulants alone is given in Figure 4.10. With the exception of the two bench-scale data points at τ_s = 43.5 kdyne/cm^2, the bench-scale and 1/25-scale data agree within their respective experimental uncertainties.[b] No 1/25-scale tests were performed at the lowest bench-scale shear strength of

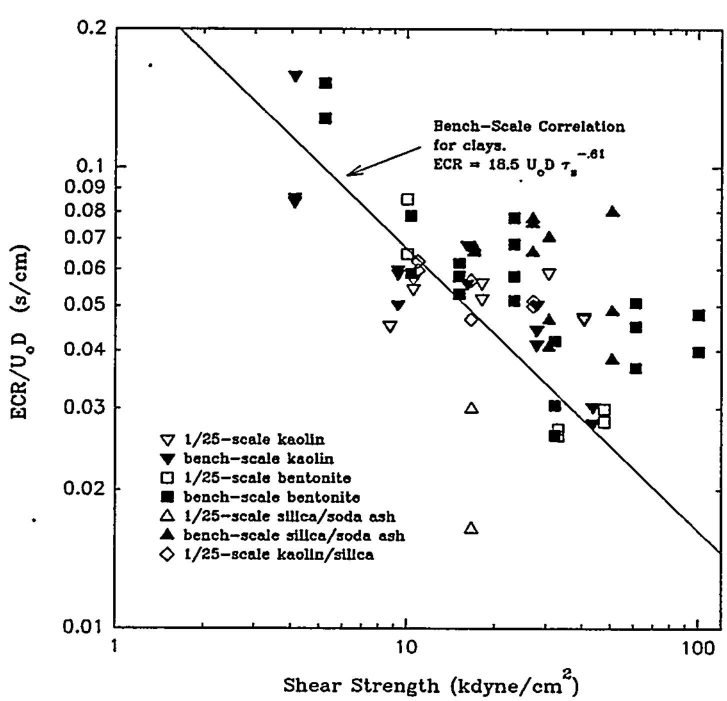

Figure 4.9. Comparison of Bench-Scale and 1/25-Scale Data

(a) Powell, M. R., C. L Fow, G. A. Whyatt, P. A. Scott, and C. M. Ruecker. November 1990. *Proposed Test Strategy for the Evaluation of Double-Shell Tank Sludge Mobilization.* Letter Report prepared by Pacific Northwest Laboratory for Westinghouse Hanford Company.

(b) Refer to Figure 4.1 for the 1/25-scale uncertainties. The magnitudes of the bench-scale uncertainties are expected to be similar.

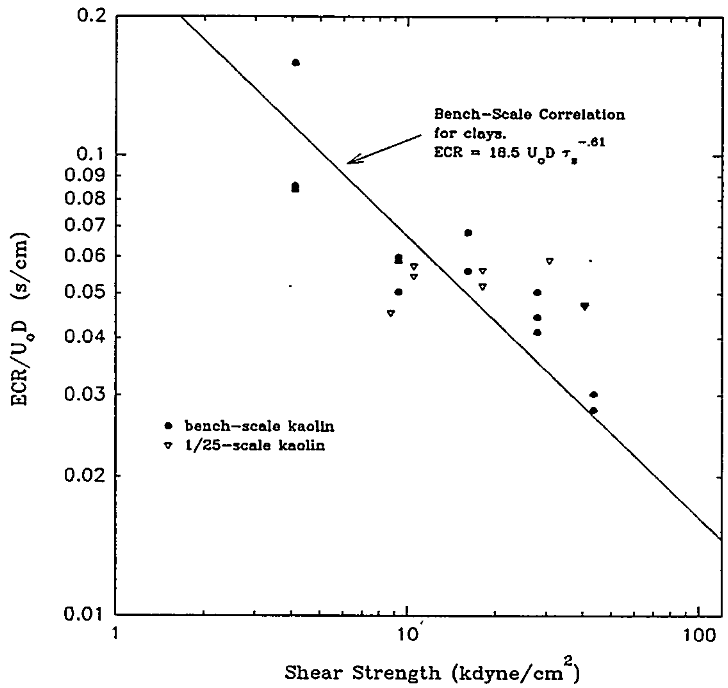

Figure 4.10. Comparison of Bench-Scale and 1/25-Scale Kaolin Data

4 kdyne/cm^2. The kaolin used in test S25-3-K had a τ_s = 40.5 kdyne/cm^2, which is very close to the 43.5 kdyne/cm^2 of the highest strength bench-scale simulant tested. However, the bench-scale kaolin had a much greater resistance to mobilization. A review of this particular bench-scale test (BS-5) does not provide any possible explanation for this observed difference.

The bentonite mobilization data are compared in Figure 4.11. These data all compare favorably. The bench-scale bentonite data at τ_s = 61 and 100 kdyne/cm^2 appear to be more susceptible to mobilization than the trend of the other data would predict. The 100 kdyne/cm^2 data were not included in the bench-scale correlation because experimental observations led to the conclusion that air bubbles trapped in the sludge were decreasing its mobilization resistance. The 61 kdyne/cm^2 point was included in the correlation because the trapped air bubbles did not appear to have affected the mobilization.

4.1.3 ECR Dependence on Sludge Cohesion

The poor correlation between ECR/U_0D and simulant shear strength observed during 1/25-scale testing indicates that measurement of the simulant shear strength alone is not an adequate means of quantifying a simulant's resistance to mobilization. Literature reviews have been conducted in an effort to identify additional or alternative physical property measurements that might provide more reliable predictions of mobilization resistance. Several candidate properties have been identified and are being investigated.

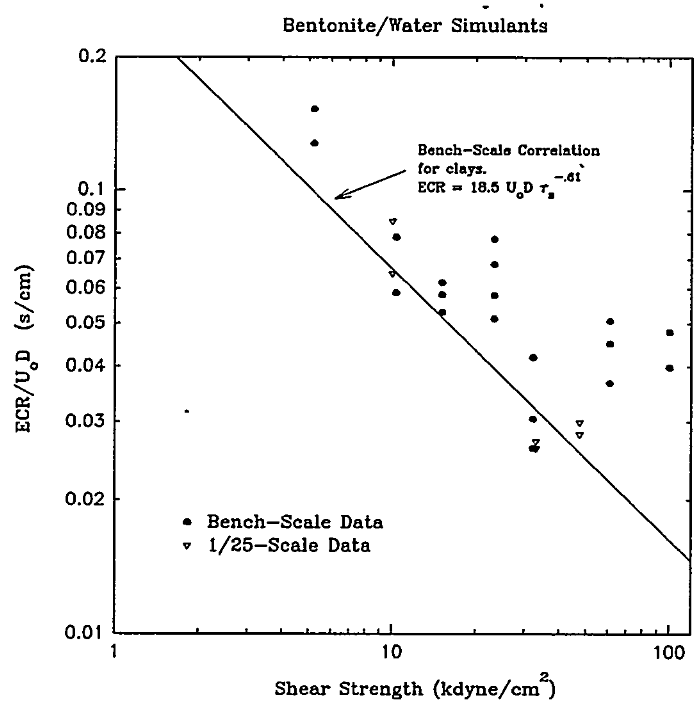

Figure 4.11. Comparison of Bench-Scale and 1/25-Scale Bentonite Data

It is generally agreed in the soil science literature that the erosion resistance of cohesive soils is primarily a function of the strength of the cohesive forces between the soil particles (Mirtskhoulava 1981, for example). In 1937, Hvorslev postulated that the shear strength of a soil can be separated in to a cohesive fraction and a frictional fraction. The cohesive fraction of the shear strength is due to interparticle attractive forces (van der Waals attractions) and the frictional component results from the friction between adjacent soil grains when the soil is deformed. Hvorslev developed a means for quantifying the relative magnitudes of the cohesive and frictional portions of the measured shear strength. This technique requires that a series of shear tests be conducted on the soil under varying consolidation pressures.

Gibson (1953) enhanced Hvorslev's technique and measured the true cohesion and friction on a series of clay samples. Gibson's experiments revealed that the true cohesion for the kaolin clay he tested was about 10% of its measured shear strength. The cohesion of bentonite clay was determined to be 80% of its measured shear strength.

Applying this to the 1/25-scale bentonite, kaolin, and kaolin/silica shear strength data allows the cohesion of each simulant to be estimated. The fractional cohesion of the kaolin/silica simulant is not known but is probably on the order of 50% to 75% of the kaolin cohesive fraction. For the purposes of the plots in this section, it has been assumed that the kaolin and kaolin/silica cohesive fractions are both equal to 10% of the measured shear strength.

Figure 4.12 is a plot of the 1/25-scale kaolin, kaolin/silica, and bentonite ECR/U_0D values vs the simulant cohesion estimated as described above. The effect of using cohesion rather than shear strength is to compress the range of the kaolin and kaolin/silica ECR data to the 1-4 kdyne/cm^2 region of the graph. The bentonite data plotted in Figure 4.12 are based on the average observed ECRs. For reasons discussed in section 4.1.1, these data are not thought to accurately reflect the actual bentonite mobilization resistance. The alternative bentonite ECRs for tests S25-6-B and S25-7-B discussed in section 4.1.1 are used in Figure 4.13. A trend of increasing mobilization resistance (decreasing ECR/U_0D) with increasing simulant cohesion is evident in Figure 4.13. It is recognized that this trend largely depends on the bentonite simulant data.

The data from Figures 4.12 and 4.13 are plotted using linear axes rather than logarithmic axes in Figures 4.14 and 4.15, respectively. The data in Figure 4.15 are reasonably fit using a straight line ($R^2 = 0.85$). The conclusion from this is that the ECR for these simulants may be linearly related to simulant cohesion. It is unlikely that a linear relationship continues to describe the ECR at higher simulant cohesion. If the regression in Figure 4.15 is extrapolated to 60 kdyne/cm^2, an ECR/U_0D of 0.0 is predicted. This would imply that jet mobilization of a $\tau_s = 75$ kdyne/cm^2 bentonite simulant would not be possible regardless of jet flow rate.

4.1.4 ECR Dependence on Sludge Yield Stress

Hvorslev's method for quantifying soil cohesion requires multiple tests under specific conditions, which make it unlikely that this technique would be suitable for hot-cell use. The possibility that the sludge simulant yield stress might provide a measure of cohesion was investigated. The sludge yield stress is quantified by the stress that the simulant can maintain on a shear vane. The 1/25-scale testing yield stress data were produced as an extension of the shear strength testing. The procedure used is described in Section 3.3.

The ECR/U_0D data for the clay-based simulants are plotted vs sludge yield stress in Figures 4.16 through 4.18. The trends in these plots are very similar to those seen in the plots of ECR vs the estimated simulant cohesion. This implies that the sludge yield stress may provide a measure of simulant cohesion for these simulants. This relationship is shown in Figure 4.19. Two linear trends are evident in Figure 4.19. The bentonite data fall along a line with a smaller slope than do the kaolin and kaolin/silica data. It is interesting that if the cohesion is instead estimated as one-half the shear strength of the kaolin and kaolin/silica simulants (instead of one-tenth), then all points fall along the bentonite data line. It is apparent that either the kaolin and kaolin/silica cohesions are not estimated correctly, or the yield stress does not provide a unique measure of cohesion. The latter explanation is judged to be more likely.

4.1.5 ECR Dependence on Tensile Strength (S_t)

It has been suggested in the soil science literature that the cohesion of a soil can be quantified by the soil tensile strength (Searle and Grimshaw 1959). Soil tensile strength, however, is difficult to measure accurately and is not often used in engineering applications, so little development has been done in this area. A crude sludge simulant tensiometer was constructed during FY 1992 for the investigation of tensile strength as a measure of simulant cohesiveness. A description of this device is given in Section 3.3.

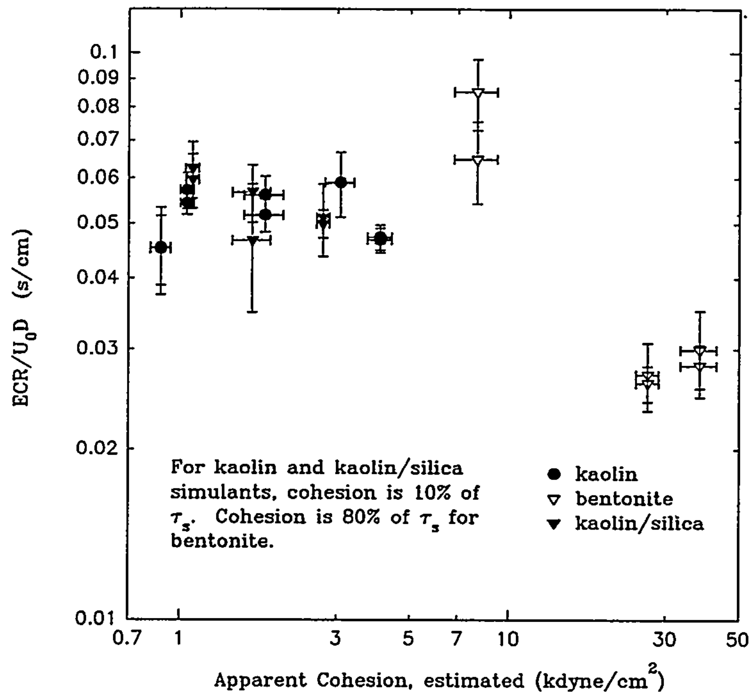

Figure 4.12. ECR vs Simulant Cohesion

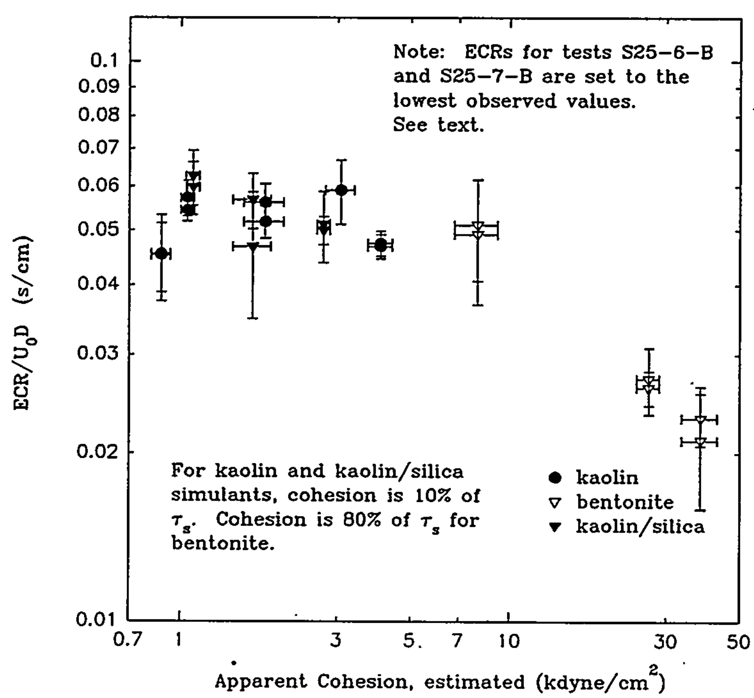

Figure 4.13. ECR vs Cohesion - Adjusted Bentonite Data

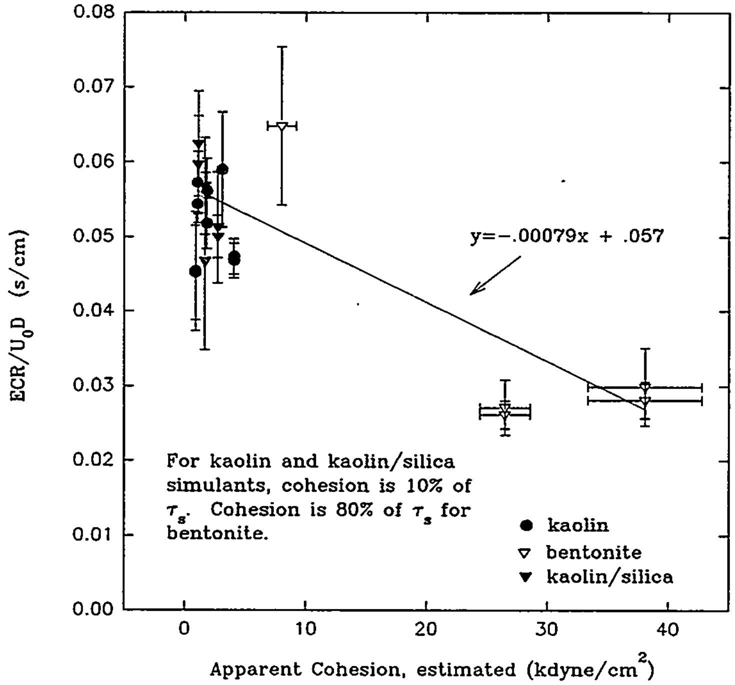

Figure 4.14. ECR vs Cohesion, Linear Plot

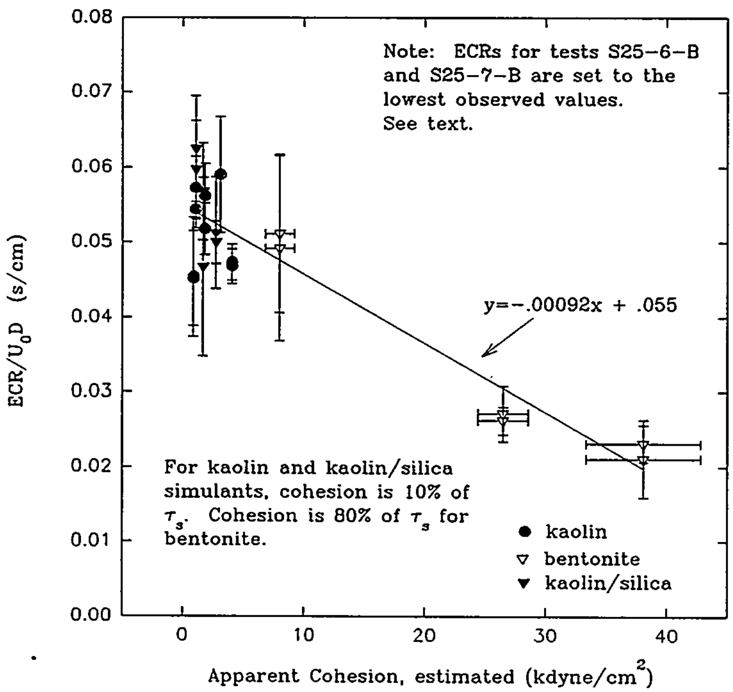

Figure 4.15. ECR vs Cohesion, Linear Plot Using Modified Bentonite Data

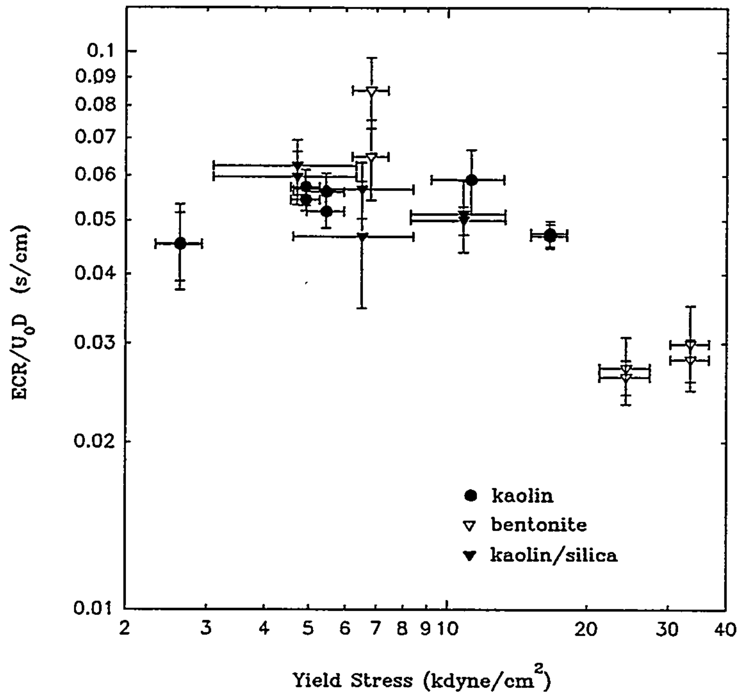

Figure 4.16. ECR vs τ_y

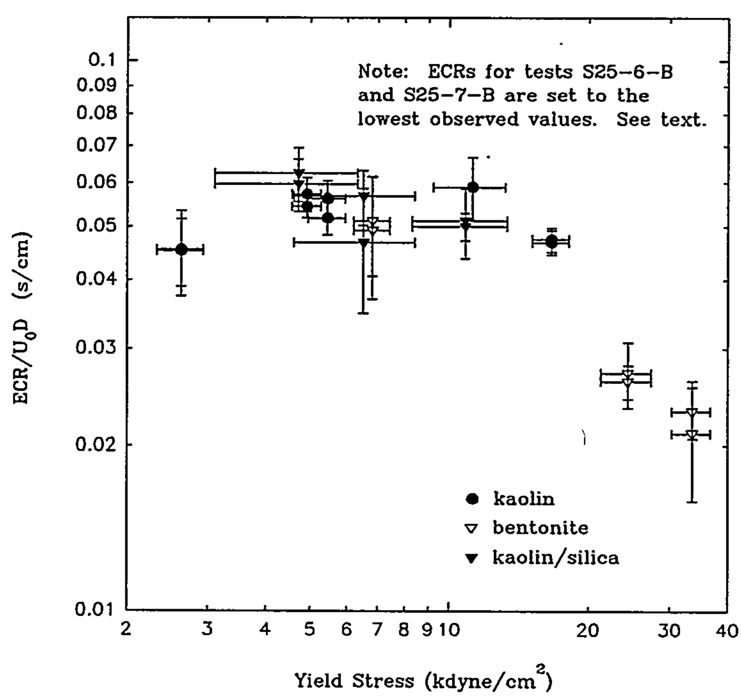

Figure 4.17. ECR vs τ_y - Modified Bentonite Data

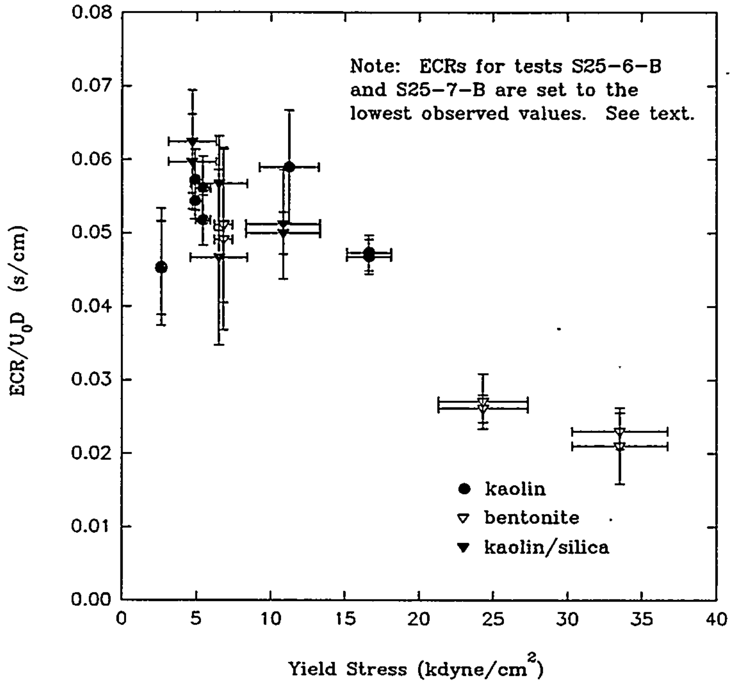

Figure 4.18. ECR vs τ_y - Modified Bentonite Data, Linear Plot

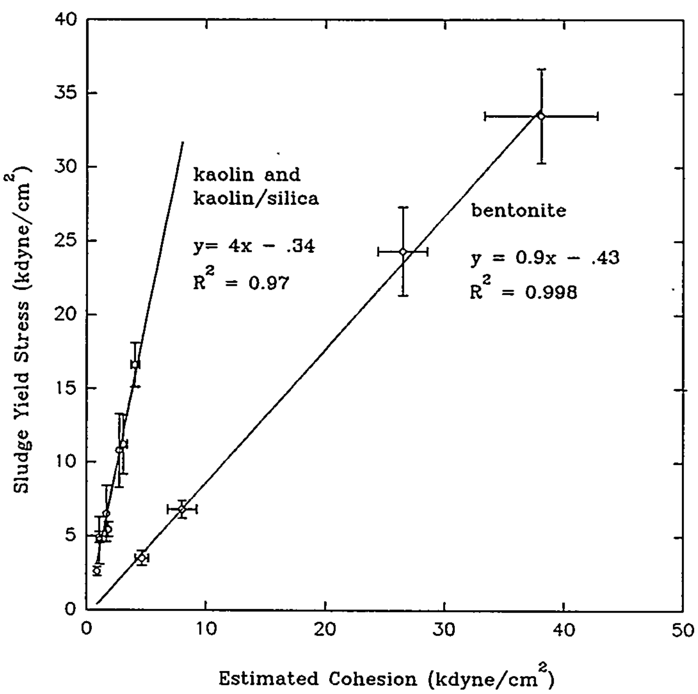

Figure 4.19. τ_y vs Cohesion

The ECR/U_0D data for the clay-based, 1/25-scale sludge simulants are plotted vs the measured simulant tensile strengths in Figure 4.20. Again, the kaolin and kaolin/silica data are all shifted to nearly the same x-axis position. It appears that the sludge tensile strength provides a measure of the sludge's mobilization resistance. It must be cautioned, however, that the relationship shown in Figure 4.20 largely depends on the locations of the two high-strength bentonite samples. More data are required to provide confidence that tensile strength is an adequate predictor of the mobilization of claybased sludge simulants.

The relationship between simulant tensile strength and shear strength is shown in Figure 4.21. The 1/25-scale bentonite tensile strength data are in excellent agreement with the correlation observed during FY 1992 laboratory-scale testing.[a] The $\tau_s > 30$ kdyne/cm^2 kaolin data points (S25-3-K and S25-14-KI), however, are significantly lower than what would be predicted by the lab-scale correlation for kaolin clays. The tensile strength of each simulant was measured four times. The tensile strengths for S25-3-K ranged from 23.0 to 34.5 kdyne/cm^2 and S25-14-KI ranged between 17.8 and 22.3 kdyne/cm^2. More tensile strength measurements of high shear strength kaolin simulants would be required to determine whether the S25-3-K and S25-14-KI measurements were low (perhaps due to an error in the measurement technique) or if the FY 1992 laboratory-scale correlation is inaccurate.

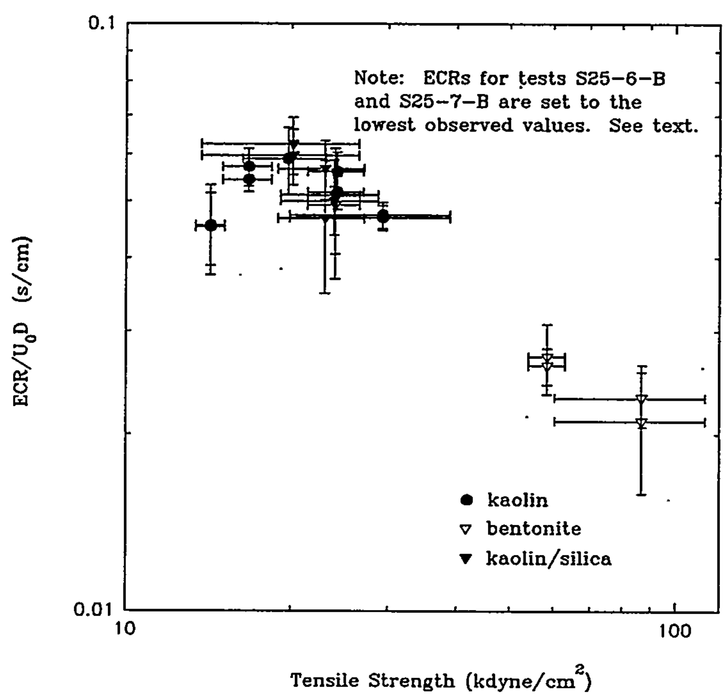

Figure 4.20. ECR vs Tensile Strength

(a) Powell, M. R. June 1993. *FY 1992 Laboratory-Scale Sludge Mobilization Simulant Testing.* Letter Report prepared by Pacific Northwest Laboratory for Westinghouse Hanford Company.

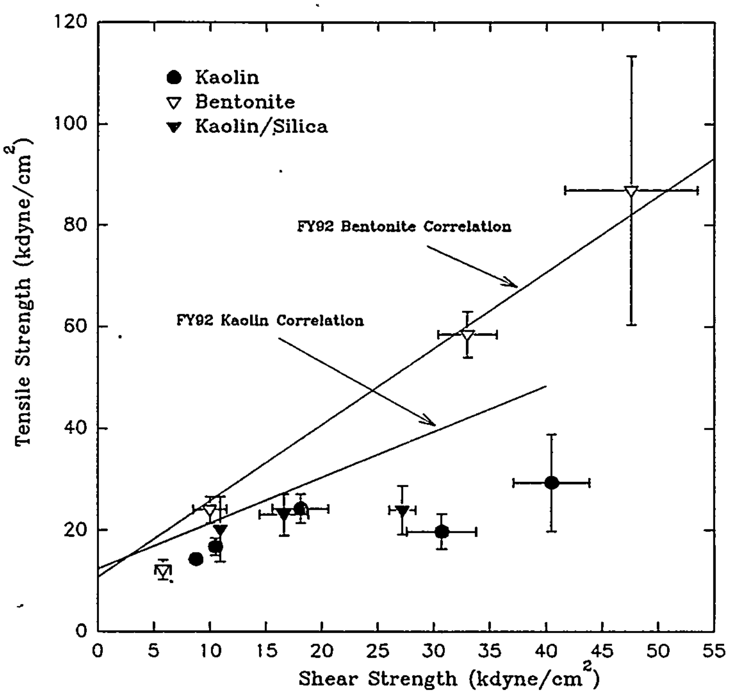

Figure 4.21. Tensile Strength vs Shear Strength

Kaolin/silica simulants were not tested during the FY 1992 lab-scale testing program, so no comparison between the 1/25-scale data and previous tensile strength data can be made. It is worth noting that the kaolin/silica tensile strengths are about equal to the kaolin tensile strengths. It is inferred from this that both simulants owe a roughly equal fraction of their measured shear strengths to cohesion.

4.1.6 Correlation of ECR with Other Simulant Properties

Attempts were made to correlate the ECR/U_0D data with the energy of rupture and the viscoelastic properties of the simulants. The energy of rupture was estimated by integrating the shear strength stress vs strain curve up to the point of failure (the same point where shear strength measurement is taken). It was found that the energy of rupture correlated linearly with the measured shear strength for the simulants tested. Because of this, a plot of ECR/U_0D vs rupture energy looks nearly identical to the ECR/U_0D vs τ_s plot of Figure 4.1.

An attempt was made to characterize the viscoelasticity of the waste simulants. However, these efforts were hindered by the fact that the Haake software required to make these measurements is still being developed by Haake. An "unofficial" version of the software was obtained for testing purposes and used to make the viscoelastic measurements on the simulants, but it is difficult to use (no software manuals are available yet). The data obtained do not correlate with the observed mobilization behavior. The application of these measurements is still being investigated, because it is not known whether the lack of correlation is real or if it is due to a measurement or data interpretation error. Fiscal year 1994 work will include an examination of viscoelastic properties of sludge simulants and their correlation with mobilization resistance.

4.2 Scaleup of 1/25-Scale Data

A methodology has been established for the scaling of sludge mobilization data between scaled experiments and full-scale.[a] Based on the theoretical equations for turbulent jet velocity decay, it is theorized that by conducting a geometrically-scaled sludge mobilization test using a scaled nozzle diameter and equal nozzle exit velocities the ECR data from the scaled test can be dimensionally-scaled up to make full-scale mobilization predictions. The 1/25-scale mobilization tests were conducted according to this scaling methodology.

Two 1/25-scale tests were conducted with the specific goal of determining whether the current scaling methodology is supported by the experimental data. Tests S25-15-SS and S25-16-SS were conducted using nearly the same sludge simulants as were used in 1/12-scale tests NCAW-17 and NCAW-18, respectively. The 1/25-scale U_0D values were scaled linearly with tank size [i.e., 1/25-scale U_0D = (1/12-scale U_0D)x(12/25)]. The 1/25-scale mixer pump oscillation rate was 25/12 times that used during the 1/12-scale tests. According to the sludge mobilization scaling methodology, the tests should give equal ECR/U_0D data.

A comparison of the S25-15-SS and NCAW-17 test data is given in Figure 4.22. The 1/12-scale ECR data and their respective error bars have been multiplied by the fraction 12/25 so that they may be directly compared to the 1/25-scale data. Further, the NCAW-17 test used 3 U_0D's instead of the 2 used in S25-15-SS. The intermediate U_0D ECR data have been omitted from the plot (hence the horizontal line in the NCAW-17 data between 140 and 240 minutes). No scaling of time has been applied to the data.

The 1/25-scale ECR data for the first U_0D lag the 1/12-scale data considerably. This is attributed to the presence of a 2 to 4 cm "foot" of sludge at the base of the 1/25-scale sludge bank. The vertical portion of the sludge bank was approximately 2 to 4 cm farther from the jet nozzles than was the sludge/slurry interface visible from under the tank. The "foot" of sludge was less than 1-cm thick. Even if the sludge bank profile was similar in NCAW-17, it is unlikely that the recorded 1/12-scale ECRs included the sludge bank foot. The 1/12-scale ECRs were measured by pulling a stick radially outward from the mixer pump until the sludge bank was encountered. Because the observed foot was so thin, it is probable that this method of measuring the ECR would tend to ignore the presence of the foot; the resistance to the stick offered by the thin sludge layer is probably not significant.

If 2 to 4 cm are added to all the 1/25-scale ECR data for the first U_0D, they fall within the error bars of the NCAW-17 ECR data.

(a) Powell, M. R., C. L Fow, G. A. Whyatt, P. A. Scott, and C. M. Ruecker. November 1990. *Proposed Test Strategy for the Evaluation of Double-Shell Tank Sludge Mobilization*. Letter Report prepared by Pacific Northwest Laboratory for Westinghouse Hanford Company.

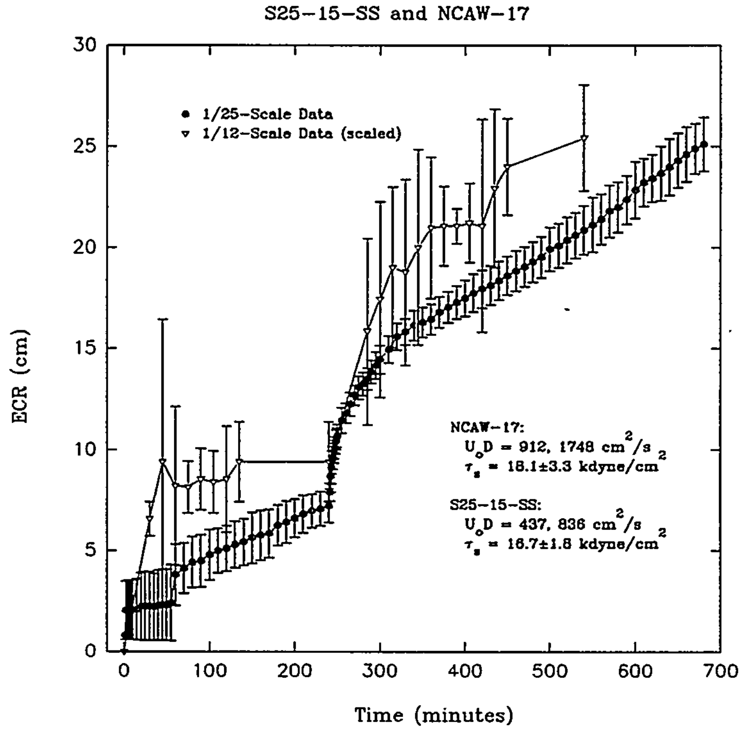

Figure 4.22. Comparison of 1/25- and 1/12-Scale ECR Data

The 1/25-scale ECR data for the second U_0D are systematically lower than the 1/12-scale data. The sludge bank foot observed during the first U_0D was removed when the flow was increased, so the difference cannot be attributed to the foot. A difference between the tests not yet mentioned was the difference in nozzle exit velocities. If geometrically-scaled nozzle diameters are used, then equal U_0's are required to maintain a scaled U_0D. When test NCAW-17 was conducted, however, the 0.208-in. nozzles used were based on an assumed full-scale nozzle size of 2.5 in. The full-scale nozzle diameter estimate has since been revised to 6 in. The nozzles used in the 1/25-scale tests were 0.230 in., which corresponds to a 5.75-in. full-scale nozzle.[a] As a result, the U_0's used in test S25-15-SS were 7.5 and 14.3 m/s. By comparison, the NCAW-17 nozzle exit velocities were 17.3 and 33.1 m/s, respectively. The 1/12-scale U_0's were 2.3 times those used in the 1/25-scale tests. It is possible that this difference resulted in the observed difference between the 1/25-scale and 1/12-scale data shown in Figure 4.22. This hypothesis is examined in the paragraphs that follow.

(a) It was intended that the 1/25-scale nozzles be machined to a 0.24-in. diameter so that the corresponding full-scale size would be 6 in. The as-built nozzles had a measured diameter of 0.23 in. This was judged to be acceptable.

The maximum jet velocity (U_{max}) decay equation for turbulent jets (Rajaratnam 1976) is typically written as

$$U_{max} = \frac{KU_oD}{x} \qquad (4.2)$$

where x is the downstream distance from the nozzle and K is a proportionality constant. Based on this equation, jets with equal U_oD's will have equal maximum velocities (U_{max}) at equal downstream distances (x). Experimental data support this assertion. This equation is the basis for the scaling methodology assumption that jets with equal U_oD's will produce equal ECRs. The sludge mobilization data collected thus far have tended to support this.

Very few sludge mobilization tests have been conducted using different nozzle diameters and the same U_oD's. 1/12-scale test NCAW-18 is the only test performed to date where different diameter nozzles were used with their flow rates adjusted to give equal U_oD's. Two mixer pumps with different nozzle diameters (.208 in. and .313 in.) were used to test the effect of varying the nozzle diameter while maintaining a constant U_oD. The ECR data collected during NCAW-18 are shown in Figure 4.23. Although the ECRs from both mixer pumps reached nearly the same value by the end of the test, the ECRs produced by pump #2 are systematically lower than those of pump #1. Pump #2 had the larger nozzle diameter and, hence, the smaller nozzle exit velocity. The error bars on the points on Figure 4.23 have been removed for clarity. The average uncertainty in the ECRs is about

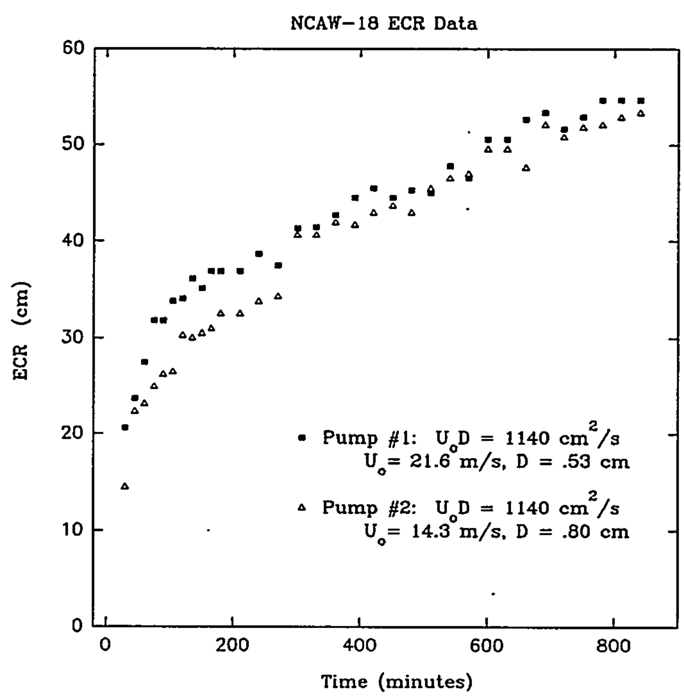

Figure 4.23. NCAW-18 ECR vs Time Data

±6 cm. This is approximately the difference between the data from both pumps, so it cannot be concluded that the difference between the pump #1 and pump #2 data is statistically significant.

Based on the data presented in Figures 4.22 and 4.23, it is *suggested* that for equal U_0D's, a jet with a lower U_o (and correspondingly higher D) may result in a slower ECR growth rate than a jet with a higher U_o (and lower D). This is very speculative at this point, but it should not be assumed *a priori* that ECR growth rate is a function only of U_0D and does not depend specifically on either U_o or D. Experimental data are needed to determine the validity of the current assumption that ECR is proportional to U_0D.

The ECR data for tests S25-16-SS and NCAW-18 (pump #2) are compared in Figure 4.24. The 1/25-scale ECR data are significantly lower than the scaled 1/12-scale data. The primary reason for this difference is thought to be the difference in simulant shear strength. The S25-16-SS simulant was allowed to cure for the same length of time that the S25-15-SS simulant required to reach 10.0 kdyne/cm^2. However, the S25-16-SS simulant gained strength more quickly, so the simulant shear strength at the beginning of the test was considerably higher (τ_s = 15.2 kdyne/cm^2) than the target strength of 10.0 kdyne/cm^2. To correct for this error, the 1/12-scale NCAW-18 ECR data were adjusted for the shear strength difference using the 1/12-scale correlation of ECR with shear strength developed using silica/soda ash simulant. This involved multiplying all the NCAW-18 ECR data by $(10.5/15.2)^{0.67} = 0.78$. The adjusted ECR data are plotted along with the S25-16-SS data in Figure 4.25.

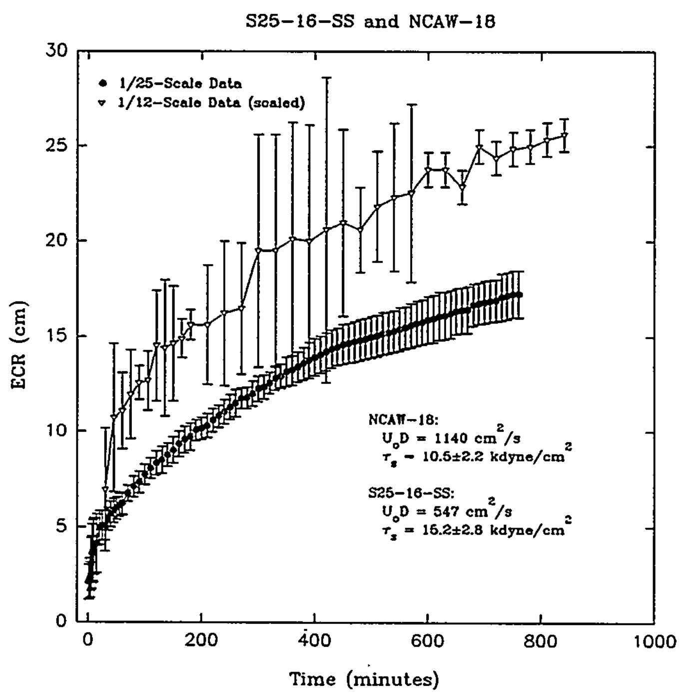

Figure 4.24. Comparison of NCAW-18 and S25-16-SS Data

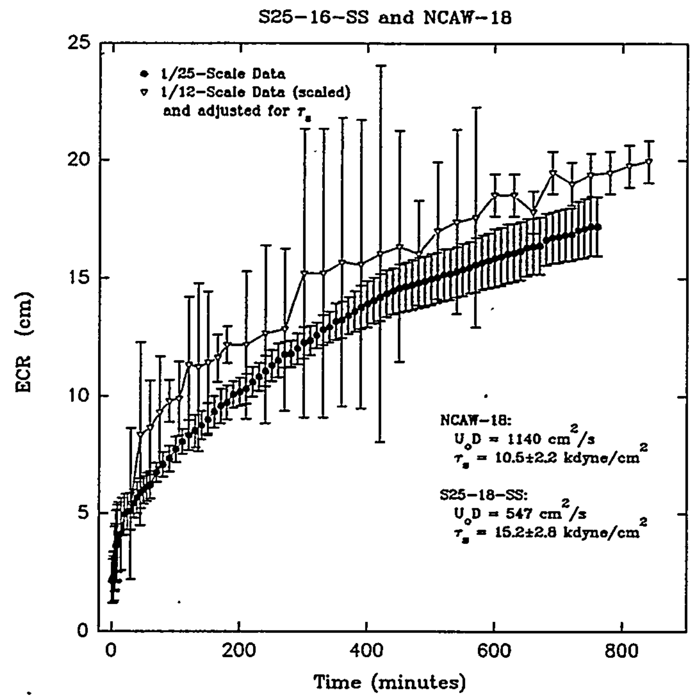

Figure 4.25. Comparison of Adjusted NCAW-18 and S25-16-SS Data

The agreement between the 1/25-scale and 1/12-scale data is much better using the adjusted data. At approximately 420 minutes, the decision was made during test S25-16-SS to hold the tank temperature constant for the remainder of the test. Lab-scale testing has shown that the silica/soda ash simulant shear strength decreases with increasing temperature. The tank temperature was stabilized after 420 minutes to evaluate whether the increasing tank temperature was responsible for the fact that the ECR was growing nearly linearly. It is seen in the curve that a slight decrease in the rate of ECR growth occurred once the tank temperature was stabilized. If this had not been done, it is likely that the agreement between the 1/25- and 1/12-scale data would have been improved for the time >420 minutes data. However, the tank temperature would have continued to climb to a level considerably higher than that typically encountered during 1/12-scale testing. Slurry temperature was not routinely monitored during 1/12-scale testing, but the measurements that were taken indicate the slurry typically reached 35 ± 5°C during the tests. After 420 minutes, the tank temperature in S25-16-SS was held at 38 ± 1.5°C.

According to the currently assumed sludge mobilization scaling methodology, the ECR growth rate observed at 1/25-scale should have been roughly twice that of the 1/12-scale data. That is, the length of time required to reach a given ECR is inversely proportional to the geometric scale factor. One hour of operation at 1/25-scale should correspond to 25 hours of full-scale operation. The comparison of the 1/12- and 1/25-scale data in Figures 4.24 and 4.25, however, indicates that no time scaling is required. It is not clear how to interpret this possibility in terms of the mechanics of sludge mobilization. The cohesive erosion model computer program described in Appendix D predicts that time does scale with the geometric scale factor. 1/12-scale testing using a clay-based simulant should be conducted to further investigate the time scaling effects.

4.3 Effect of Indexed Jets on ECR

It has been suggested that the effectiveness of the mixer pump jets may be somewhat diminished due to the fact that the mixer pump is rotating. As the mixer pump rotates, the leading edge of the jets encounter stagnant tank fluid that must be accelerated by the jet. A stationary jet, by contrast, does not have to entrain this additional fluid (a fully-developed flow pattern exists). It is suspected that the maximum downstream jet velocity of the rotating jets will decrease as a result of the additional fluid entrainment. Test S25-14-KI was conducted in an effort to examine the magnitude of this effect.

The indexed jet test was conducted as described in Section 3.5. The data collected are presented in Figures 4.26 through 4.29.

The mixer pump jets were initially aligned with the ECRa and ECRe measurement lines. Growth in these two directions was rapid. After 45 minutes at this nozzle position, no further ECR growth was observed for the next 45 minutes. The ECRs reached were 18.8 cm and 24.8 cm. This gives an average ECR/U_0D equal to 0.054. This is not significantly higher than what was observed from the oscillating jet ECR/U_0D's for kaolin clay (range of 0.045 to 0.057 with average = 0.051).

After the first 90 minutes, the mixer pump was re-oriented such that the nozzles were directed along ECRc and ECRg. The ECRs obtained were 25.1 cm and 17.3 cm. The average ECR/U_0D is then 0.052. Again, this is not significantly higher than the average for the oscillating pump kaolin clay data.

Following the ECR measurements along c and g, the mixer pump was oscillated at its normal rate of 4.2 rpm for the next 245 minutes after which time the average ECR was 23.8 cm (ECR/U_0D = 0.059). The jets were oriented along the ECRa and ECRe lines as they were at the beginning of the test and the oscillation stopped. The ECRs were monitored for the next 90 minutes and a 1 cm ECR growth was observed along both ECR lines. It is unclear whether this ECR growth is significant when compared to that expected from the extrapolation of the ECR growth rate before stopping the nozzle oscillations.

The conclusion to be drawn from test S25-14-K1 is that jet indexing may increase the downstream velocity of the fluid jets enough to result in a small increase in ECR. This testing has established that the magnitude of the effect is certainly smaller than about a 20% increase in ECR. However, even if only a 10% improvement in ECR can be shown to result, jet indexing might be recommended for mixer pump operation. A 10% ECR increase can make the difference between 85% of the waste mobilized and 100%.

To better establish the magnitude of the jet indexing effect, more tests at 1/25-scale would be required using both oscillating and indexed jets so that a statistical comparison could be performed. Alternatively, tests at a larger scale (e.g., 1/12- or 1/4-scale) would be relatively less sensitive to the 5-10 cm variations seen in ECR along different radial lines in the tank. Just a few larger-scale tests might be able to establish the magnitude of the jet indexing effect.

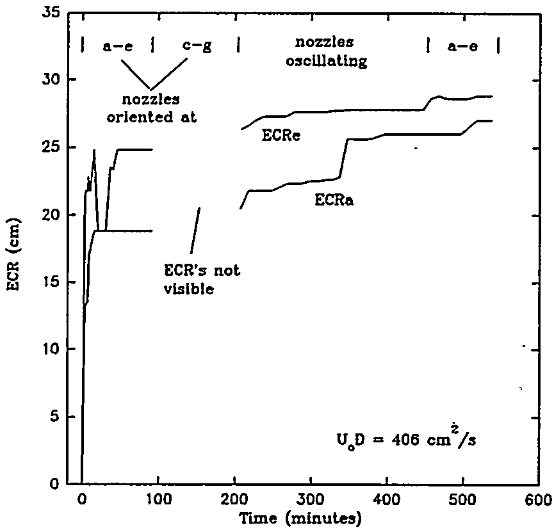

Figure 4.26. ECR Growth Along A and E (Test S25-14-KI)

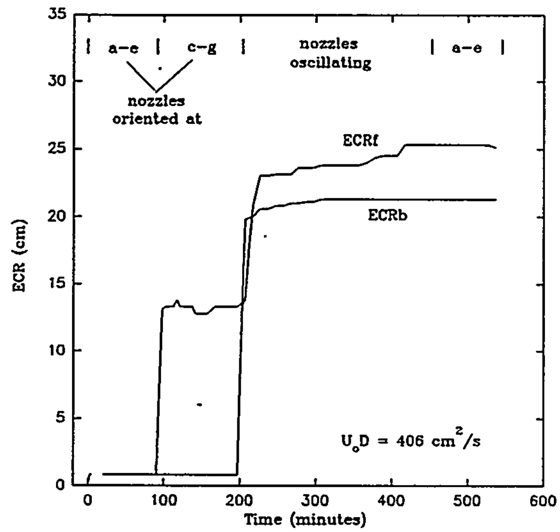

Figure 4.27. ECR Growth Along B and F (Test S25-14-KI)

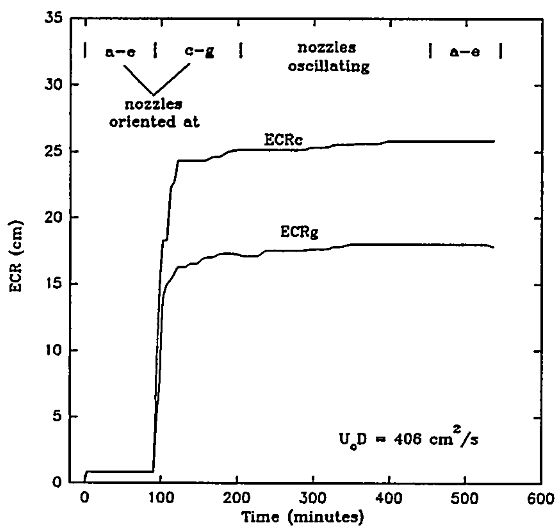

Figure 4.28. ECR Growth Along C and G (Test S25-14-KI)

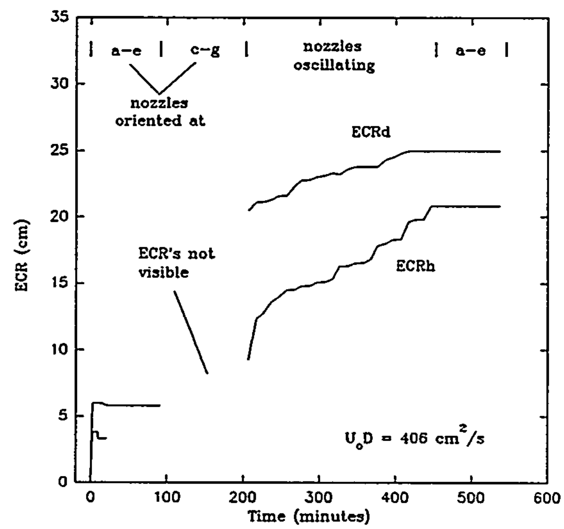

Figure 4.29. ECR Growth Along D and H (Test S25-14-KI)

4.4 ECR Versus Time Profiles and Cohesive Erosion Model Fits

Using the computer code described in Appendix D, the ECR vs time profiles from the 1/25-scale tests were used to estimate the erodibility (M) and the critical shear stress (τ_c) of each simulant tested.[(a)] The ECR vs time data for each test and the ECR vs time profile generated by the computer code are presented in Figures 4.30 through 4.43. The erosion rate is calculated from the applied stress on the sludge surface (τ_w) and the sludge-dependent parameters M and τ_c according to the equation:

$$E(kg/m^2s) = M \left[\frac{\tau_w}{\tau_c} - 1 \right] \quad (4.3)$$

Generally, good fits of the ECR vs time data for each test are obtained using the proper combination of M and τ_c. The τ_c values obtained by fitting the 1/25-scale kaolin simulant mobilization data are roughly half the τ_c values measured for kaolin clay using a waterjet directed normally to the flattened simulant surface[(b)]. The τ_c's measured using the waterjet method ranged from about 15 to 25 pascals for kaolin. This is compared to the range of 1/25-scale τ_c's of 6 to 10 pascals. It is not known why the 1/25-scale τ_c's are lower than those measured during the FY 1992 lab-scale testing. The critical shear stress distributions are calculated based on different correlations and the computer model uses questionable assumptions about the shear stress distribution near the sludge bank (see Appendix D). This may be the source of the difference.

The lab-scale critical shear stress measurements for the erosion of bentonite clay samples ranged from 12 to 25 pascals. The 1/25-scale bentonite τ_c's ranged from 3 to 15.5 pascals - again, roughly half the values observed during lab-scale testing. The kaolin and bentonite simulant materials used in the 1/25-scale testing were identical to those used in the lab-scale tests. The temperature of the eroding flüid, however, was typically about 10°C warmer during the 1/25-scale tests. Kaolin and bentonite shear strengths have been found to be largely independent of temperature over this range, but it is not known whether this is also true of tensile strength.

It must be stressed that the M and τ_c data presented in Figures 4.30 through 4.43 were generated using computer code that makes several questionable assumptions about the shear stress distributions produced by the jet on the sludge bank. The M and τ_c data presented in this document should be interpreted with due caution.

(a) The data for test S25-14-KI were not fit using the cohesive erosion model because the computer code was not designed to incorporate indexed jet movement.

(b) Powell, M. R., C. L Fow, G. A. Whyatt, P. A. Scott, and C. M. Ruecker. November 1990. *Proposed Test Strategy for the Evaluation of Double-Shell Tank Sludge Mobilization.* Letter Report prepared by Pacific Northwest Laboratory for Westinghouse Hanford Company.

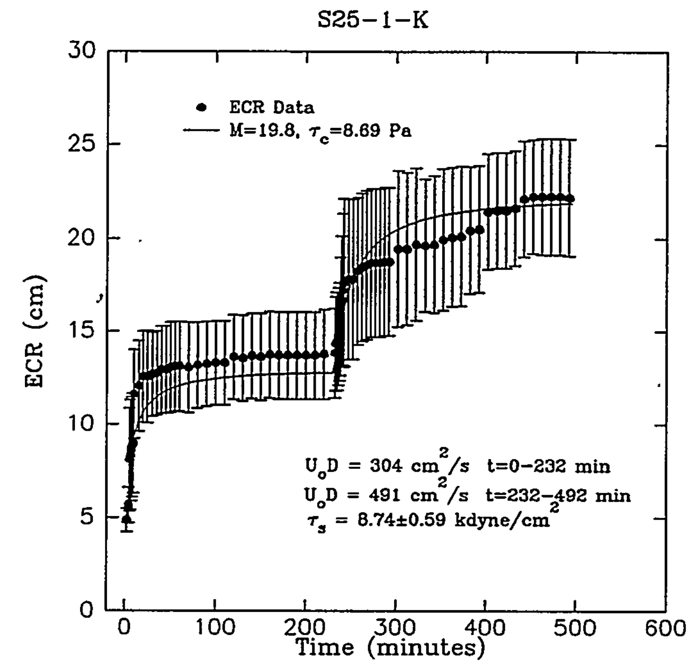

Figure 4.30. ECR vs Time and Cohesive Erosion Model Fit of S25-1-K

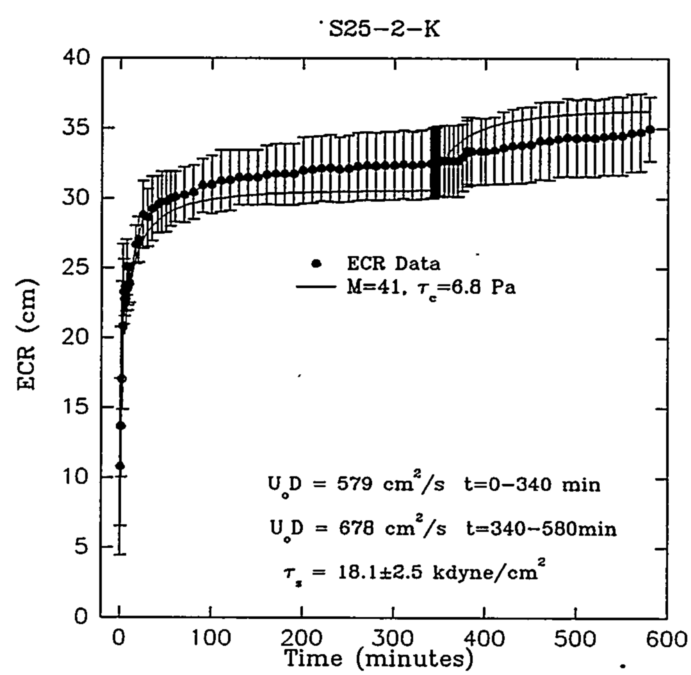

Figure 4.31. ECR vs Time and Cohesive Erosion Model Fit for S25-2-K

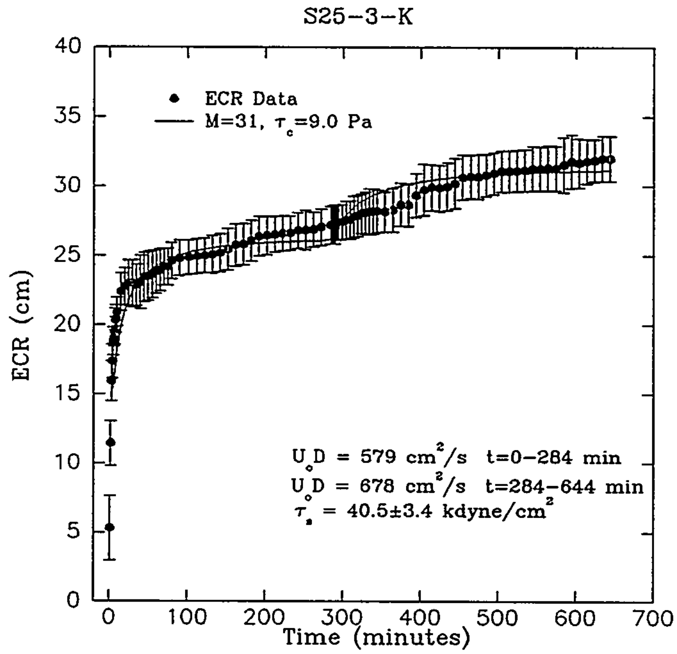

Figure 4.32. ECR vs Time and Cohesive Erosion Model Fit for S25-3-K

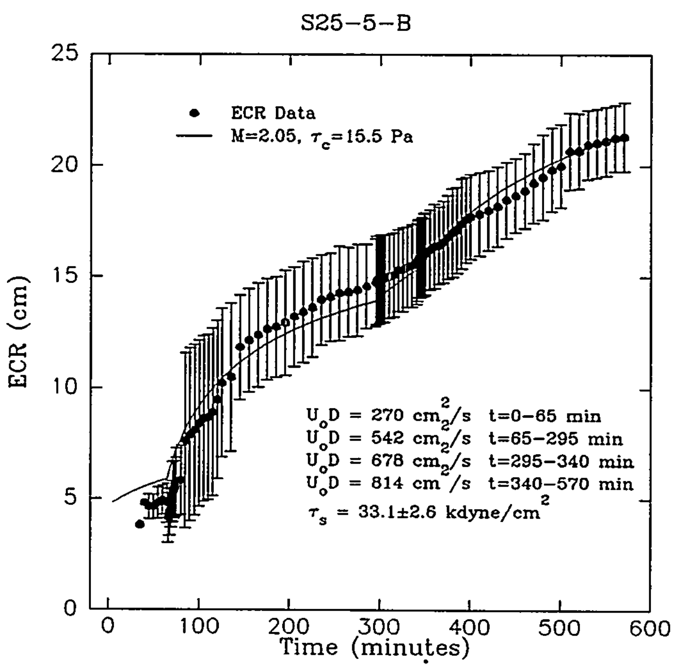

Figure 4.33. ECR vs Time and Cohesive Erosion Model Fit for S25-5-B

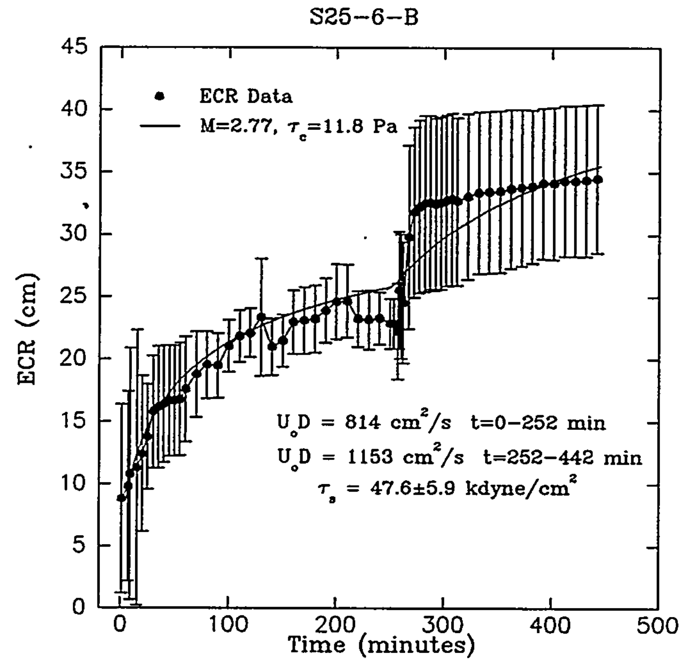

Figure 4.34. ECR vs Time and Cohesive Erosion Model Fit for S25-6-B

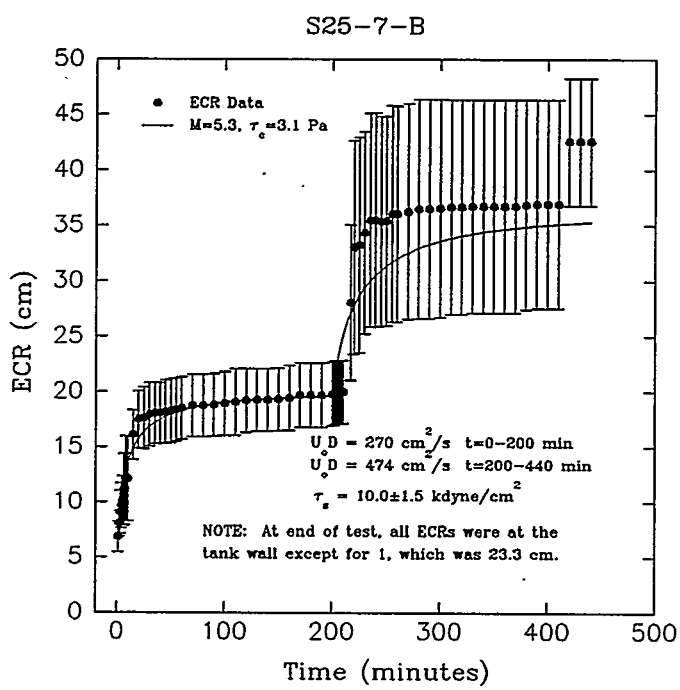

Figure 4.35. ECR vs Time and Cohesive Erosion Model Fit for S25-7-B

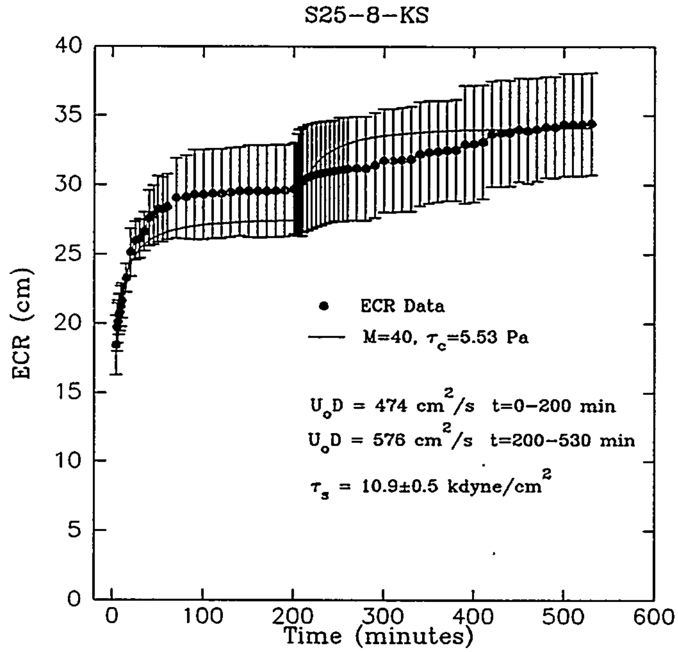

Figure 4.36. ECR vs Time and Cohesive Erosion Model Fit for S25-8-KS

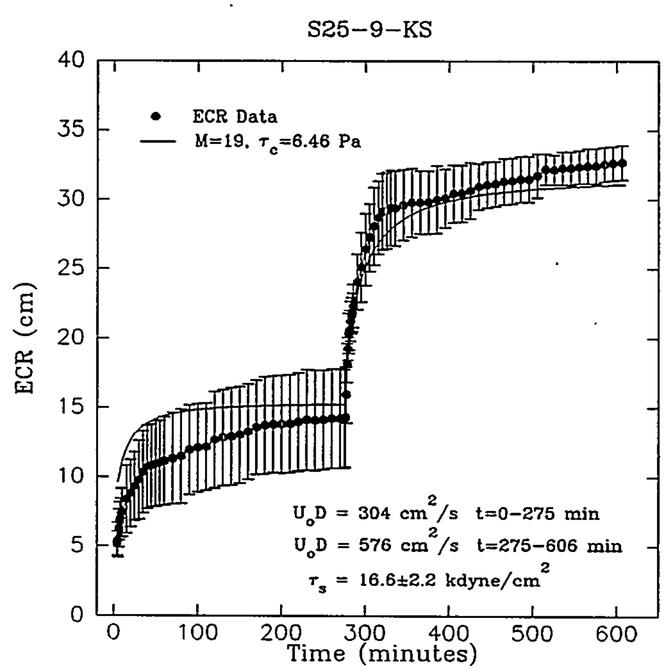

Figure 4.37. ECR vs Time and Cohesive Erosion Model Fit for S25-9-KS

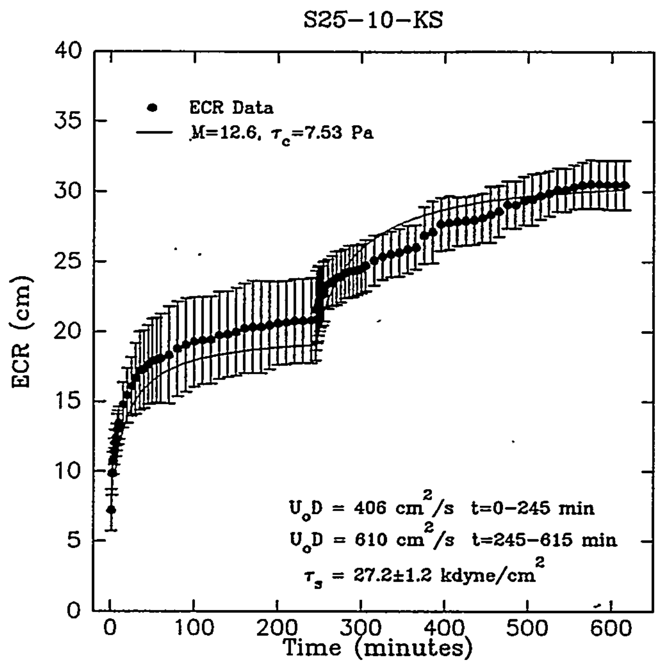

Figure 4.38. ECR vs Time and Cohesive Erosion Model Fit for S25-10-KS

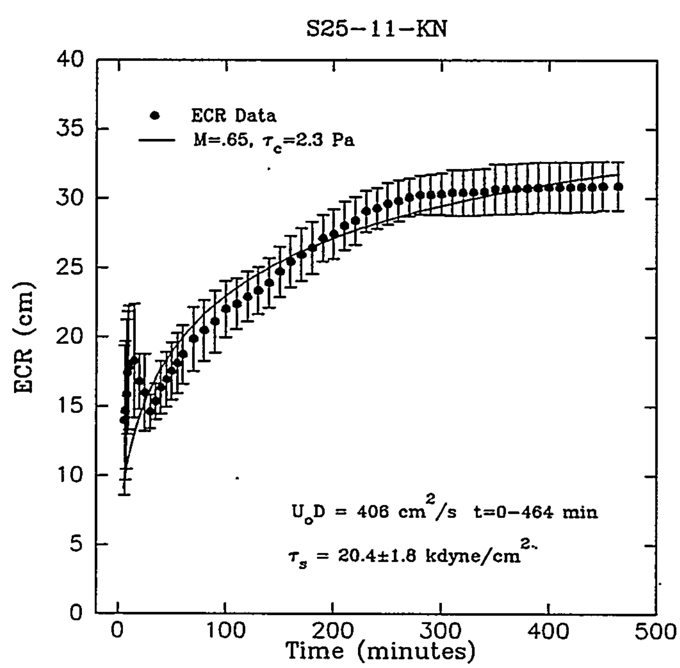

Figure 4.39. ECR vs Time and Cohesive Erosion Model Fit for S25-11-KN

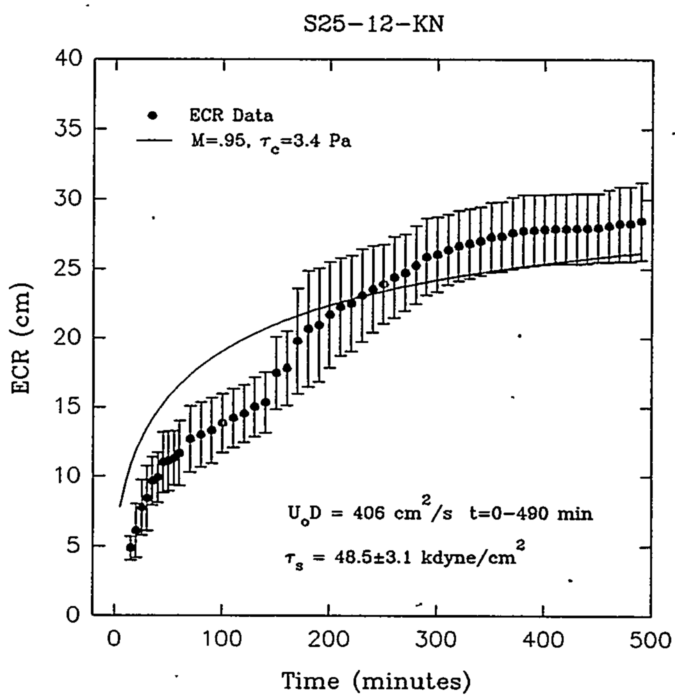

Figure 4.40. ECR vs Time and Cohesive Erosion Model Fit for S25-12-KN

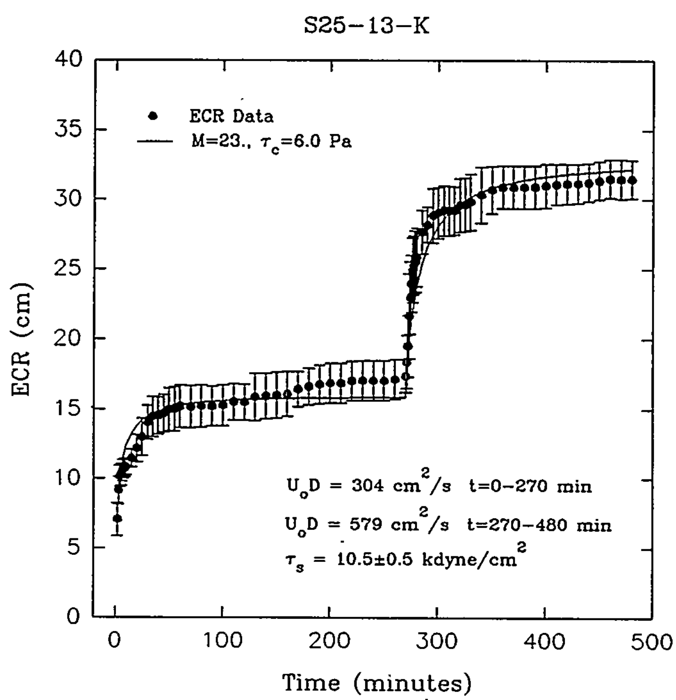

Figure 4.41. ECR vs Time and Cohesive Erosion Model Fit for S25-13-K

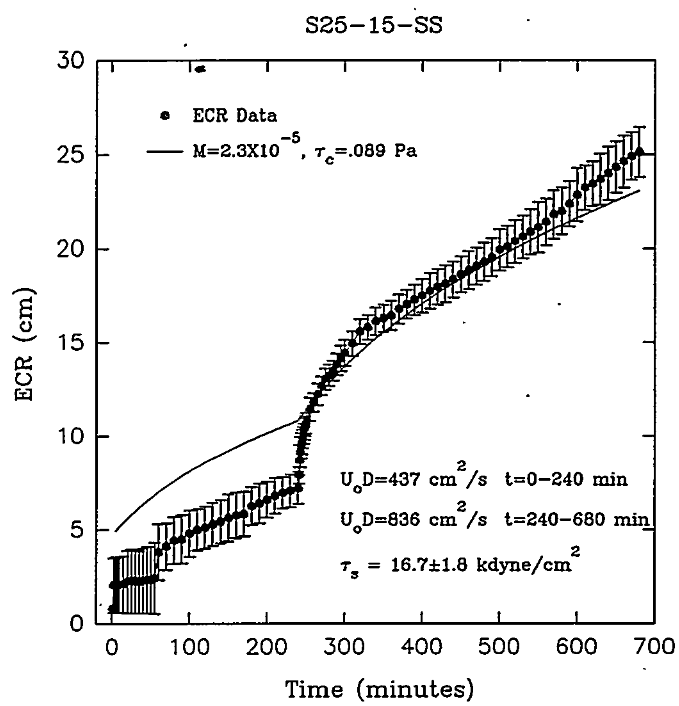

Figure 4.42. ECR vs Time and Cohesive Erosion Model Fit for S25-15-SS

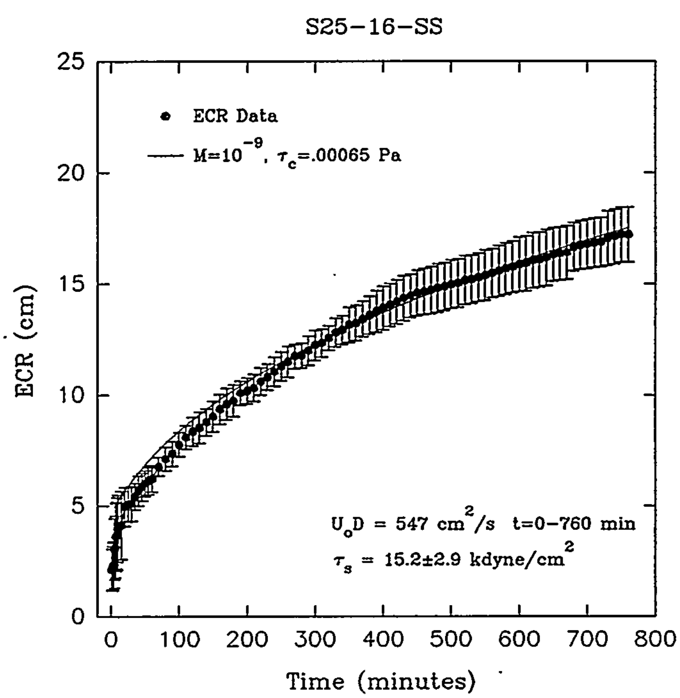

Figure 4.43. ECR vs Time and Cohesive Erosion Model Fit for S25-16-SS

4.5 Slurry Density and Temperature Data

During each 1/25-scale sludge mobilization test, the slurry density and temperature were recorded each time ECR measurements were recorded.[a] The slurry density was monitored as an alternative measure of the ECR. If it is assumed that the sludge bank profile is vertical and that all the mobilized sludge is well mixed in the tank slurry (i.e., it does not settle out), then a straight-forward relationship between slurry density and ECR can be formulated. Given these assumptions, the ECR (in meters) can be computed from the slurry density using the equation:

$$ECR = R_{tank} \sqrt{\frac{V_{super}\rho_{slurry} - M_{super}}{M_{sludge} - V_{sludge}\rho_{slurry}}} - a \qquad (4.4)$$

where ECR = estimate of distance from nozzle tip to sludge bank (assumed vertical bank)
V_{super} = initial supernate volume, liters
V_{sludge} = initial sludge volume, liters
ρ_{slurry} = measured slurry density, kg/liter
M_{super} = initial supernate mass, kg
M_{sludge} = initial sludge mass, kg
R_{tank} = tank radius, meters
a = distance between mixer pump centerline and nozzle discharge, meters

This equation was used to compute the ECR based on the measured slurry density. These data are compared to the observed ECR data in Figures 4.44 through 4.72 along with plots of the measured slurry density and temperature values.

The ECR calculated from the slurry density tends to lag the measured ECR during the early portions of the test and, if the ECR grows large enough, the calculated ECR exceeds the measured ECR. Early in the test, the sludge is being mobilized from the central portion of the tank. If the action of the jets near the tank walls is not too strong, some of the mobilized simulant tends to settle on top of the existing sludge bank. While this is happening, the slurry density tends to be lower than what would be calculated based on the ECR. Once the ECR reaches far enough outward that the fluid jets resuspend the settled solids (this typically occurred between an average ECR of 25 and 30 cm), the measured slurry density increases to what is predicted based on the average ECR. If the sludge bank profile is sloped rather than vertical, then the slurry density becomes even greater than that predicted by the ECR measurement.

This particle settling effect was most noticeable during the tests of simulants with larger average particle sizes. The silica/soda ash and kaolin/silica simulants had the largest particle sizes, followed by the kaolin and kaolin/NaCl simulants. The bentonite simulants had the smallest mean particle size.

(a) Slurry temperature data were not recorded during test S25-1-K due to the late arrival of the temperature measurement equipment.

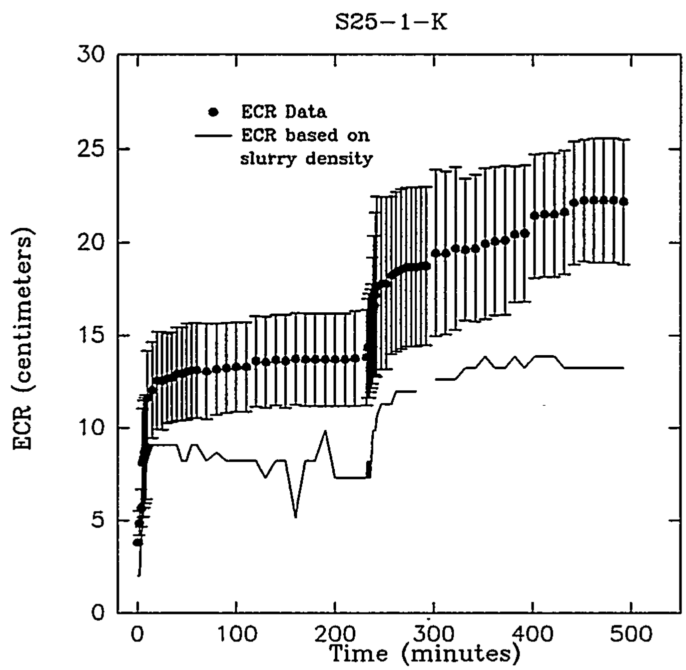

Figure 4.44. ECR vs Time for S25-1-K

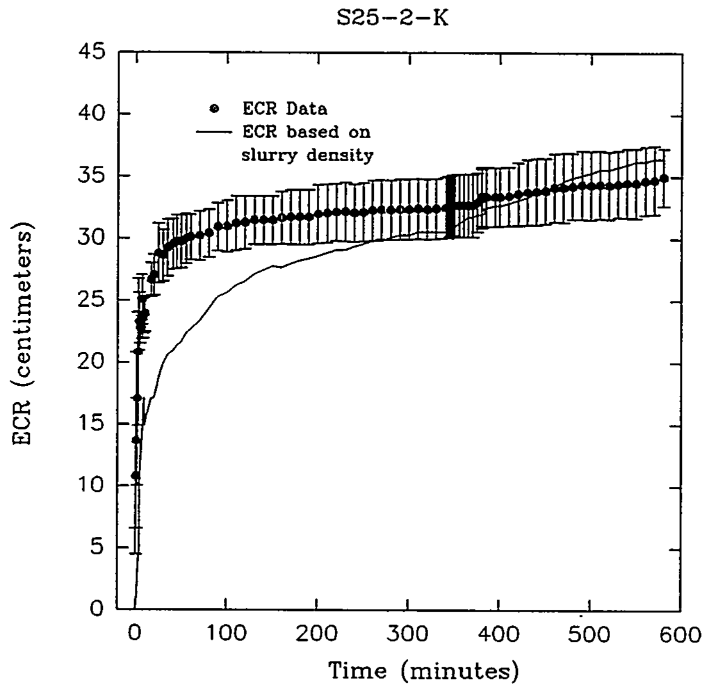

Figure 4.45. ECR vs Time for S25-2-K

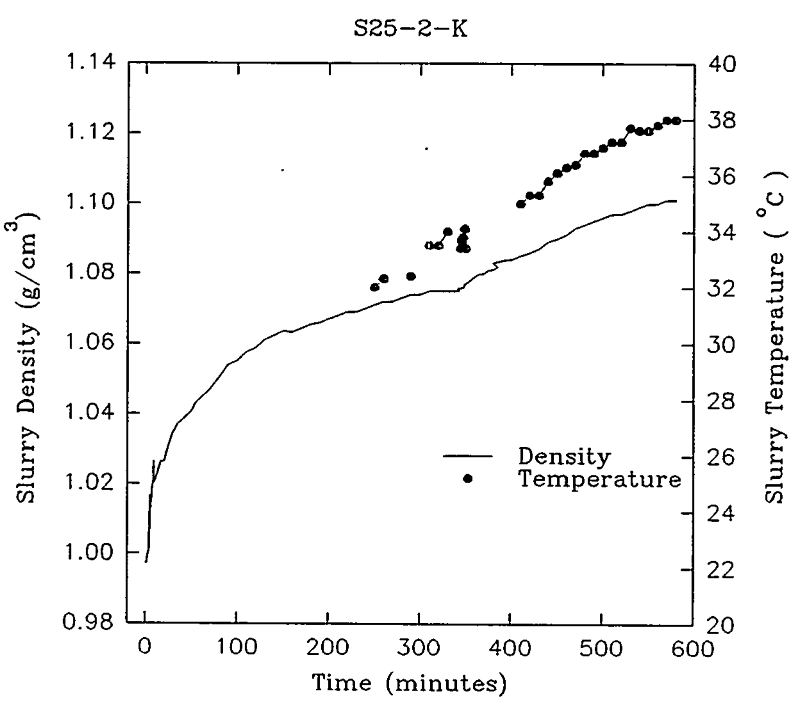

Figure 4.46. Density and Temperature (S25-2-K)

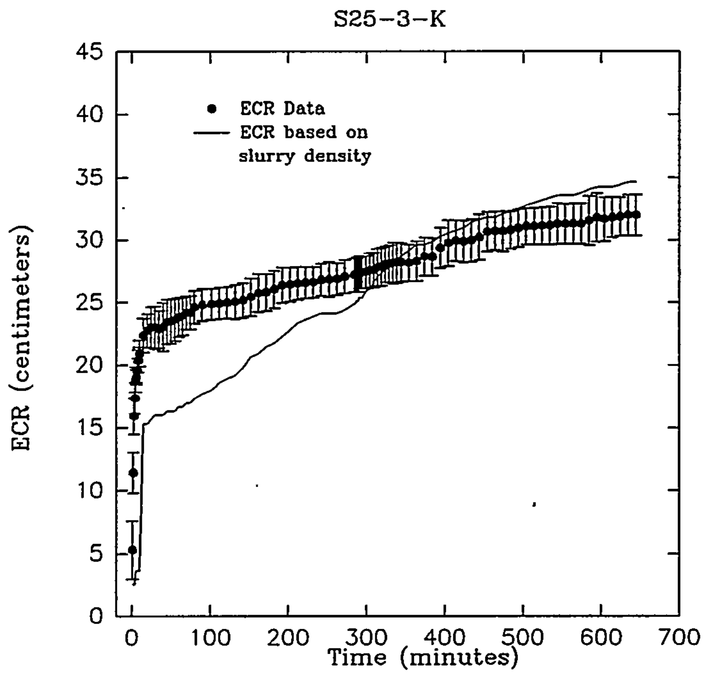

Figure 4.47. ECR vs Time S25-3-K

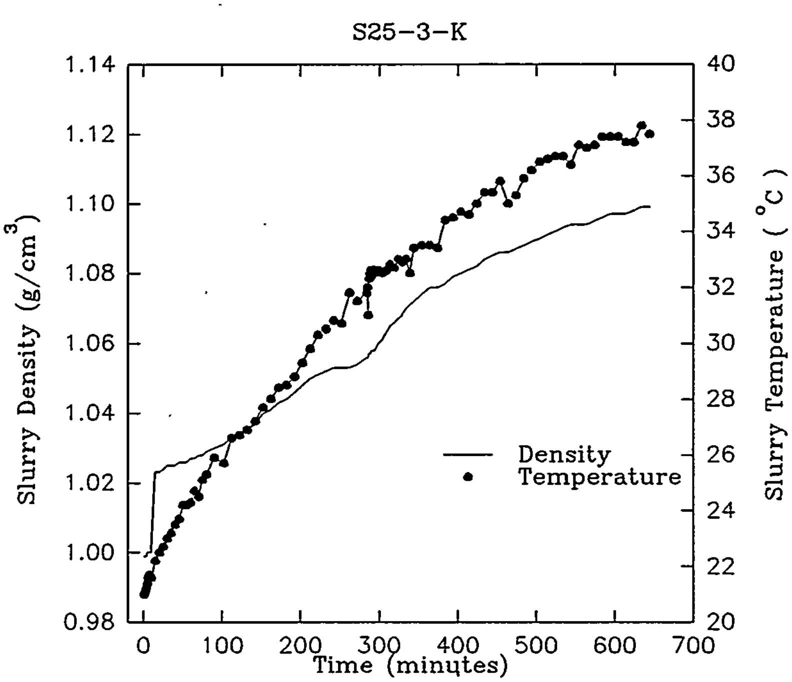

Figure 4.48. Density and Temperature (S25-3-K)

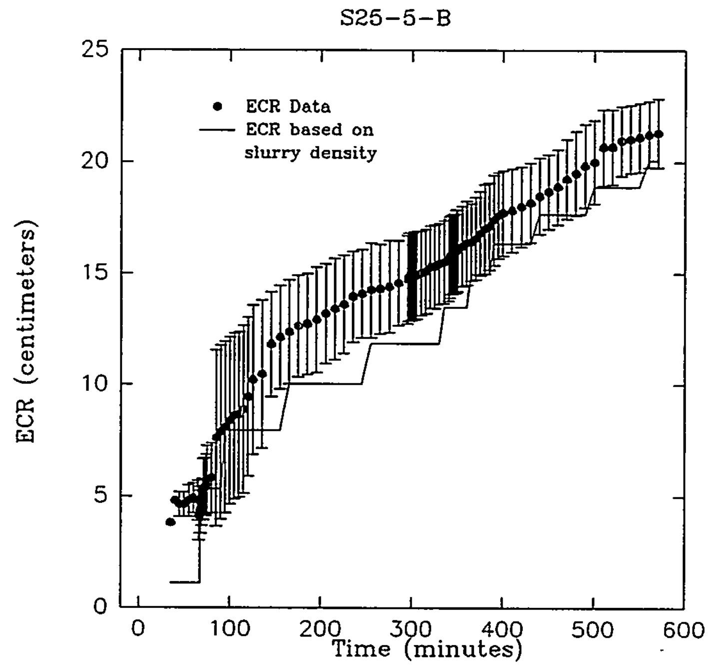

Figure 4.49. ECR vs Time for S25-5-B

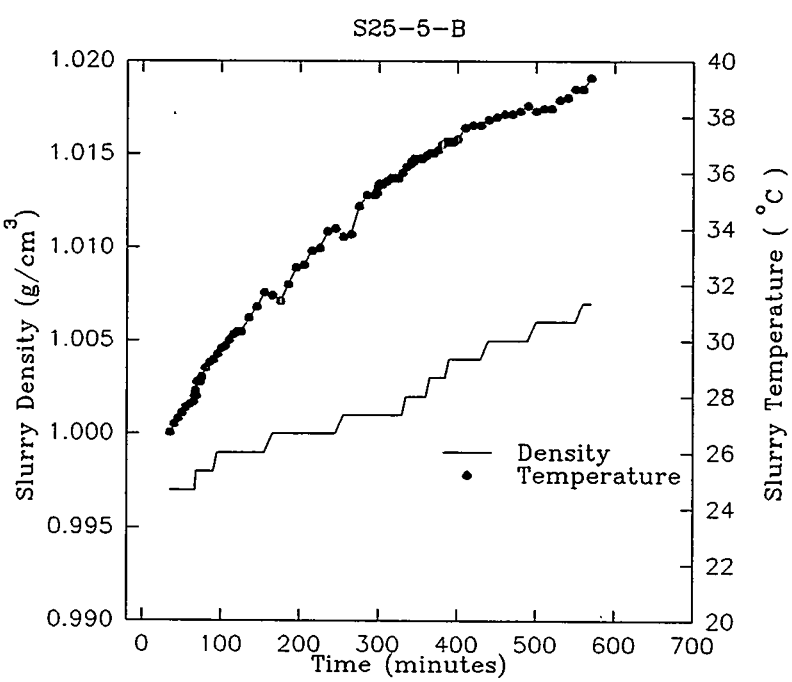

Figure 4.50. Density and Temperature (S25-5-B)

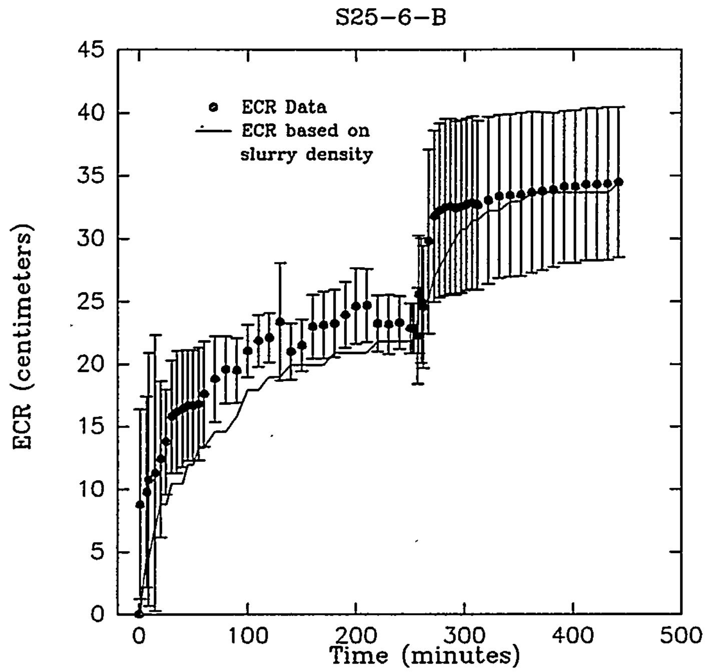

Figure 4.51. ECR vs Time for S25-6-B

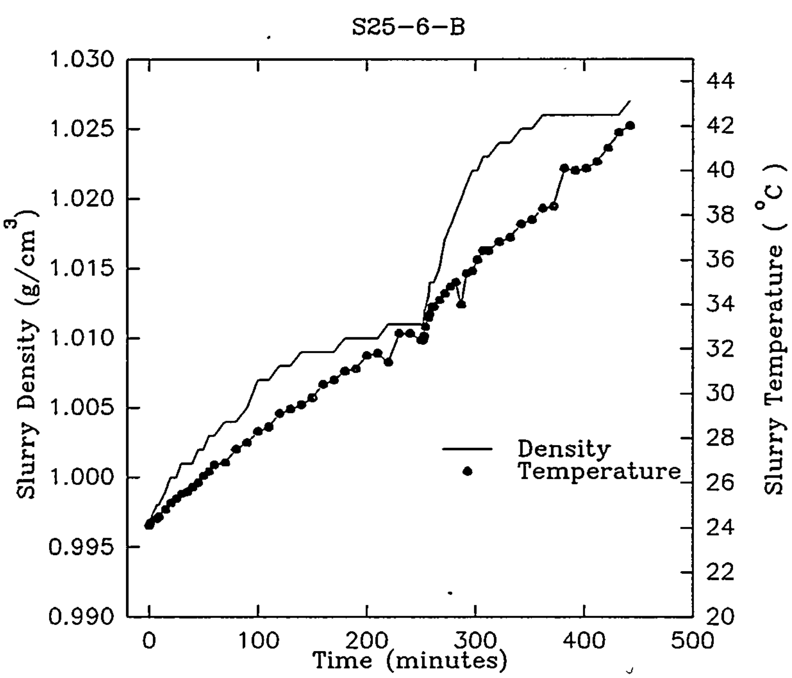

Figure 4.52. Density and Temperature (S25-6-B)

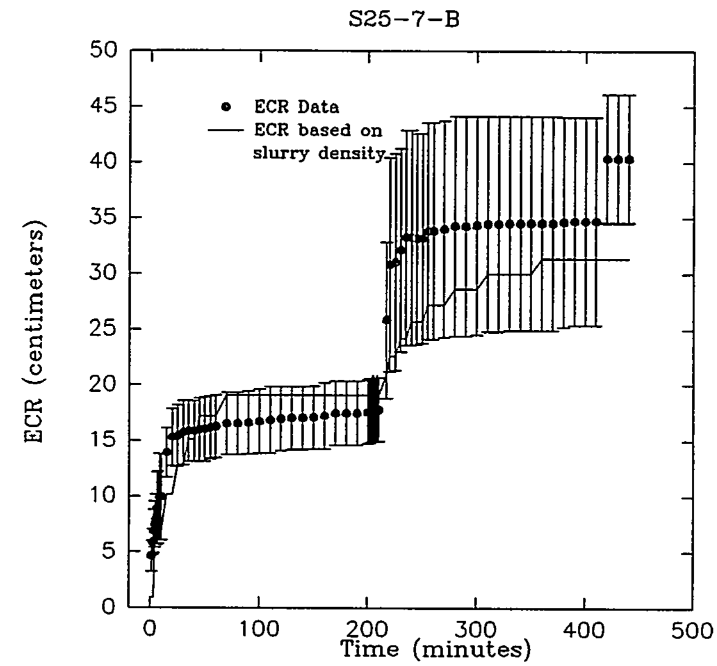

Figure 4.53. ECR vs Time for S25-7-B

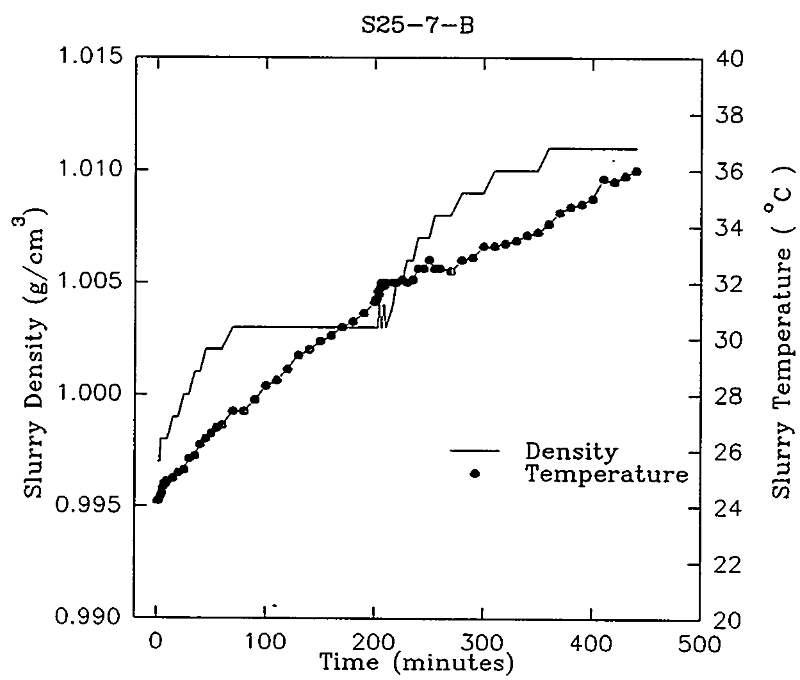

Figure 4.54. Density and Temperature (S25-7-B)

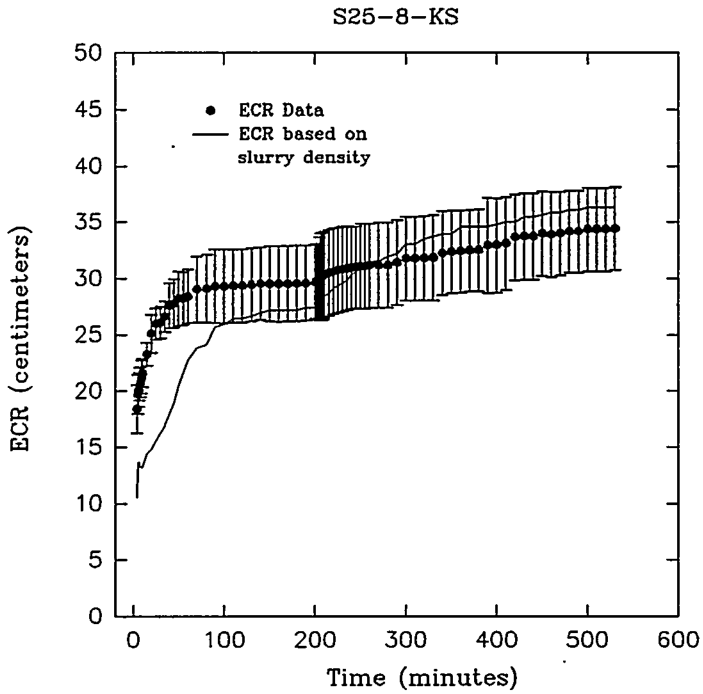

Figure 4.55. ECR vs Time for S25-8-KS

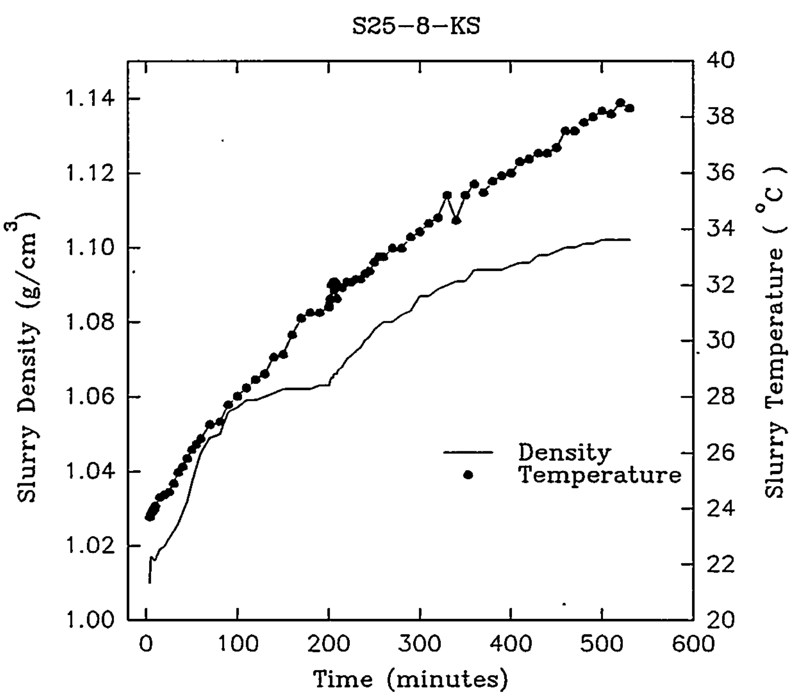

Figure 4.56. Density and Temperature (S25-8-KS)

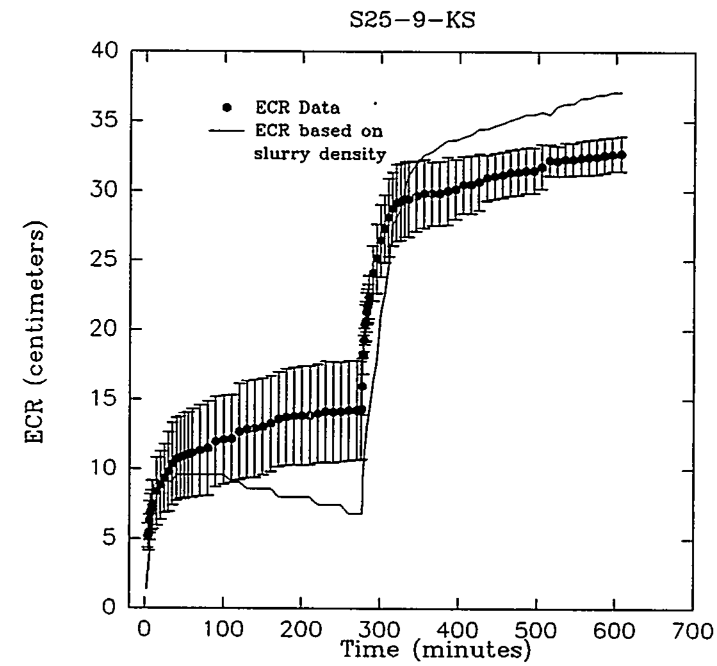

Figure 4.57. ECR vs Time for S25-9-KS

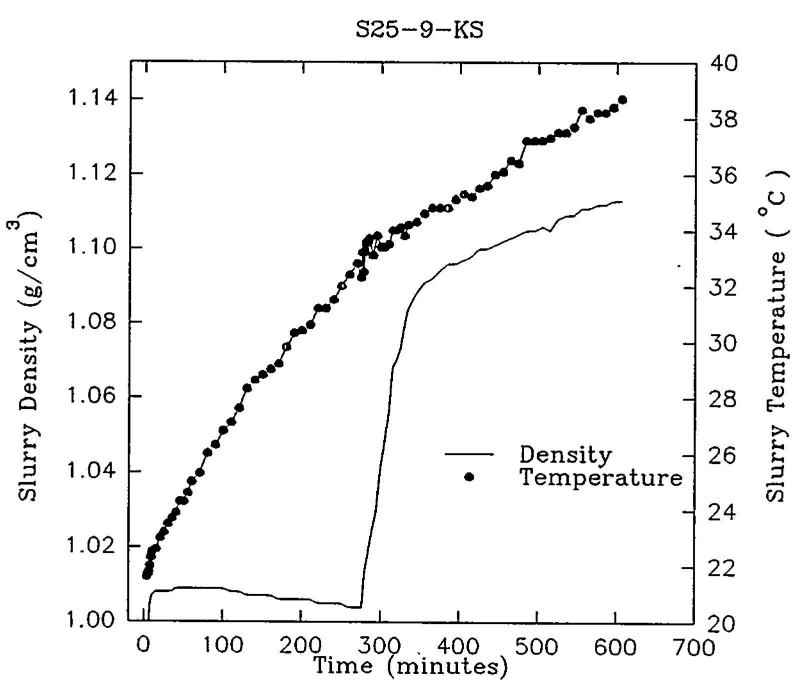

Figure 4.58. Density and Temperature (S25-9-KS)

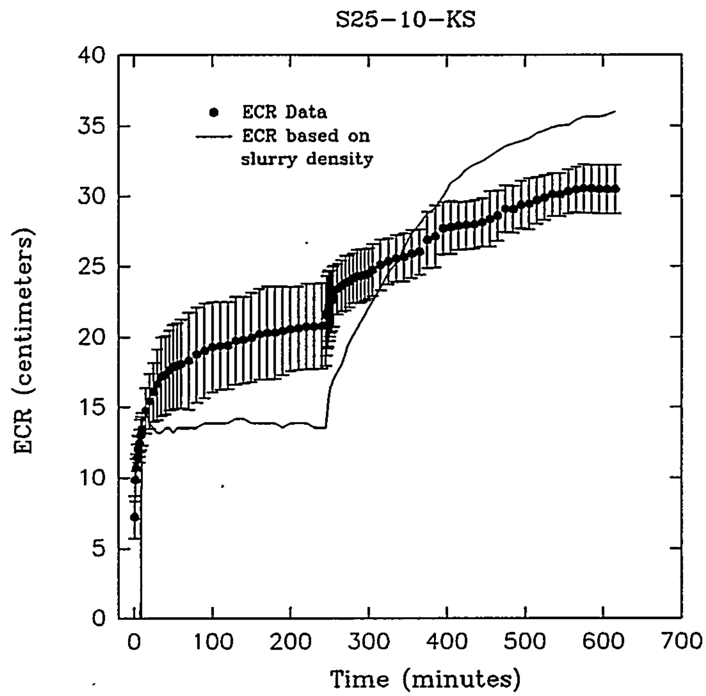

Figure 4.59. ECR vs Time for S25-10-KS

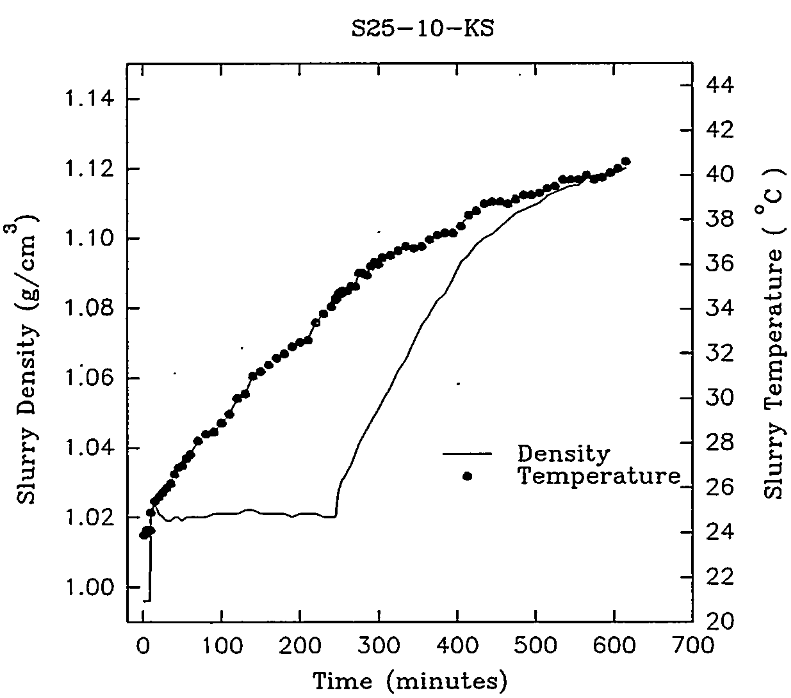

Figure 4.60. Density and Temperature (S25-10-KS)

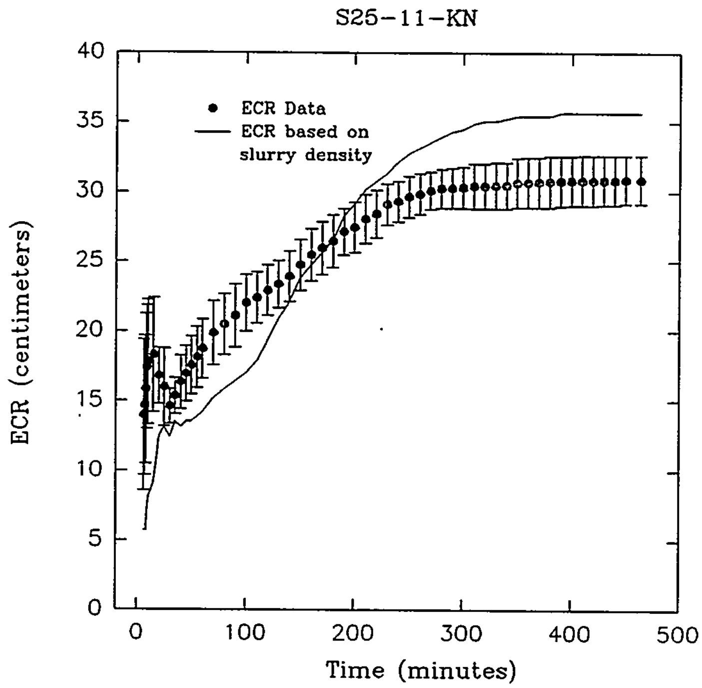

Figure 4.61. ECR vs Time for S25-11-KN

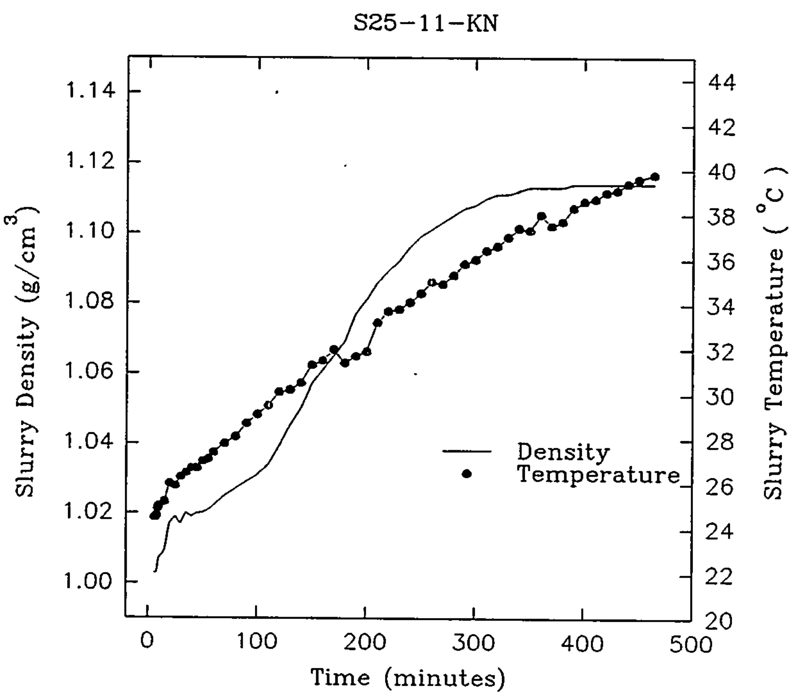

Figure 4.62. Density and Temperature (S25-11-KN)

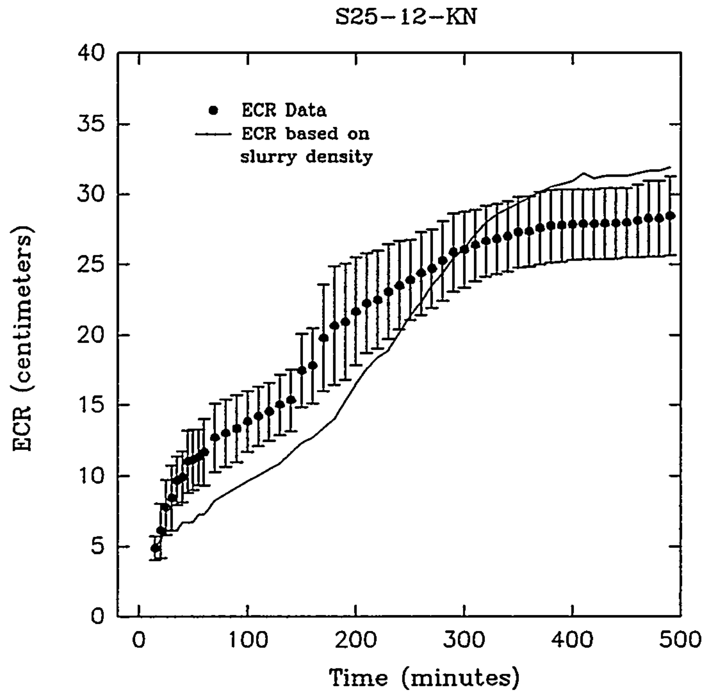

Figure 4.63. ECR vs Time for S25-12-KN

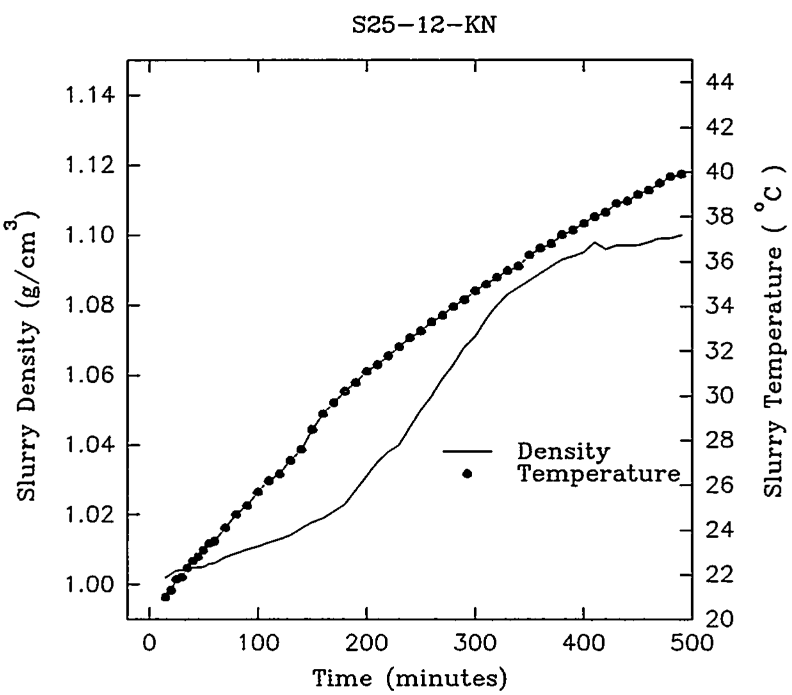

Figure 4.64. Density and Temperature (S25-12-KN)

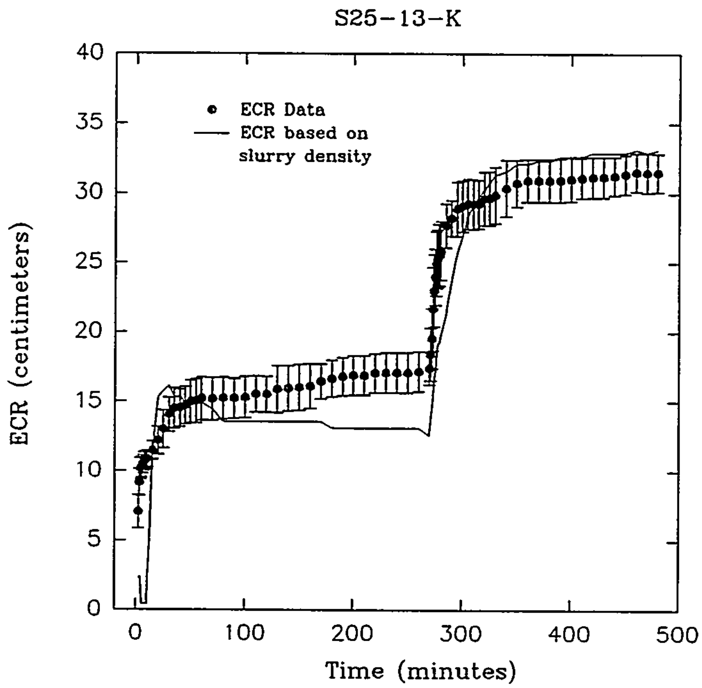

Figure 4.65. ECR vs Time for S25-13-K

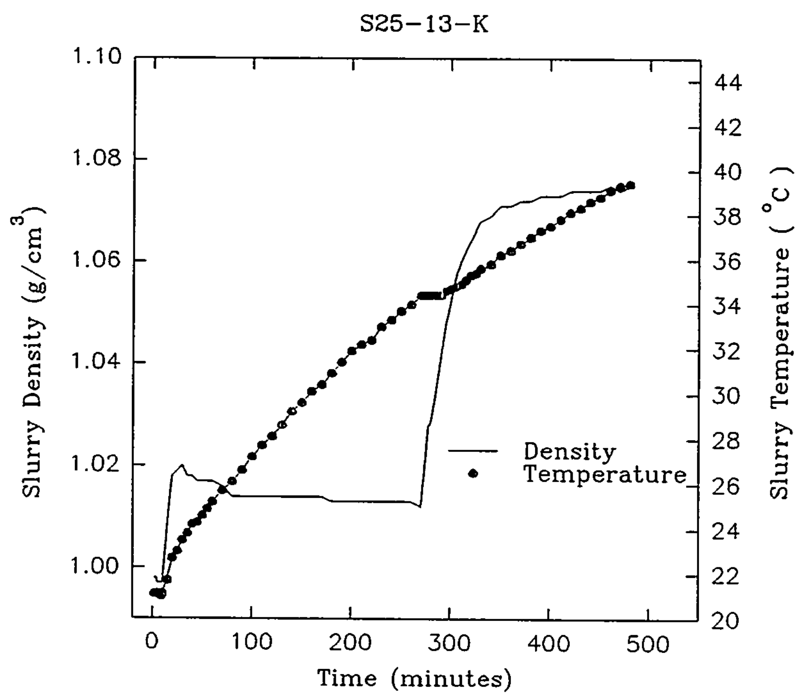

Figure 4.66. Density and Temperature (S25-13-K)

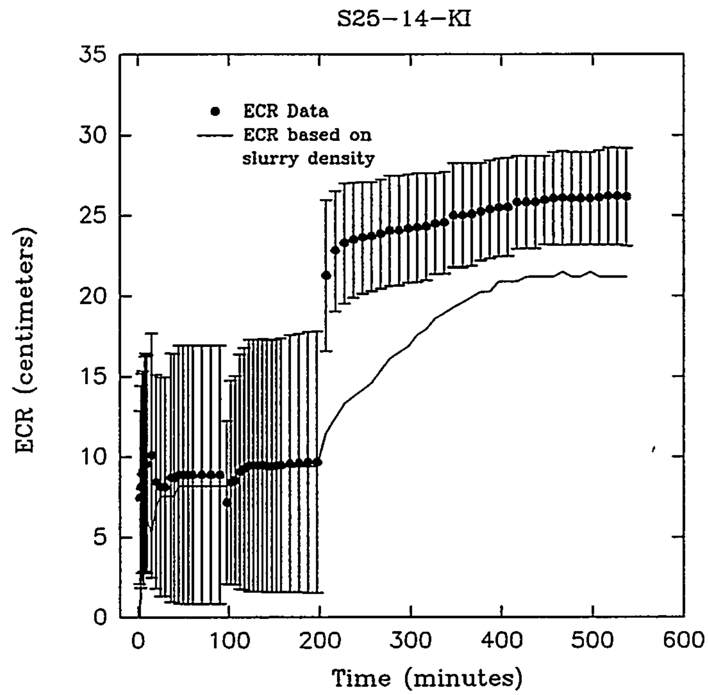

Figure 4.67. ECR vs Time for S25-14-KI

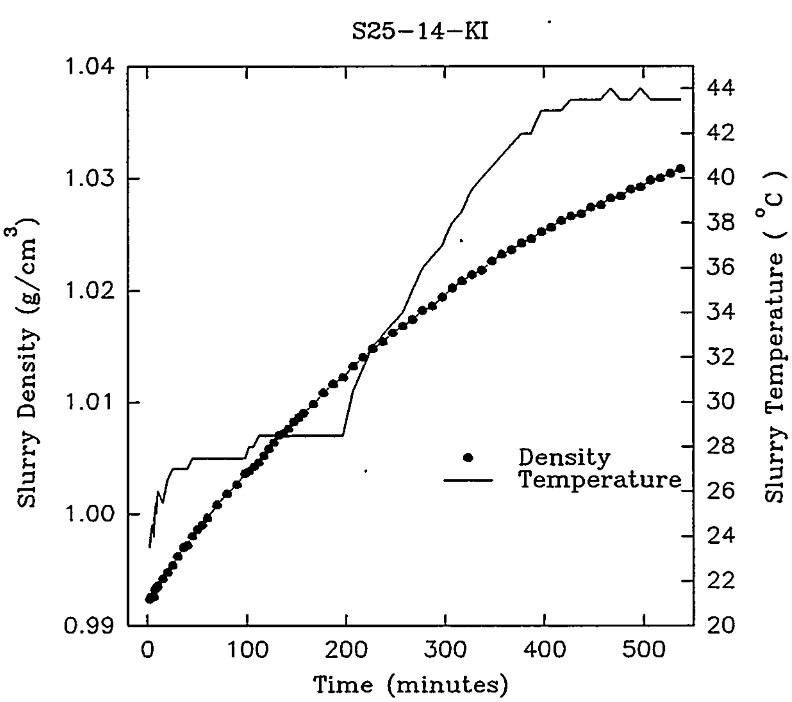

Figure 4.68. Density and Temperature (S25-14-KI)

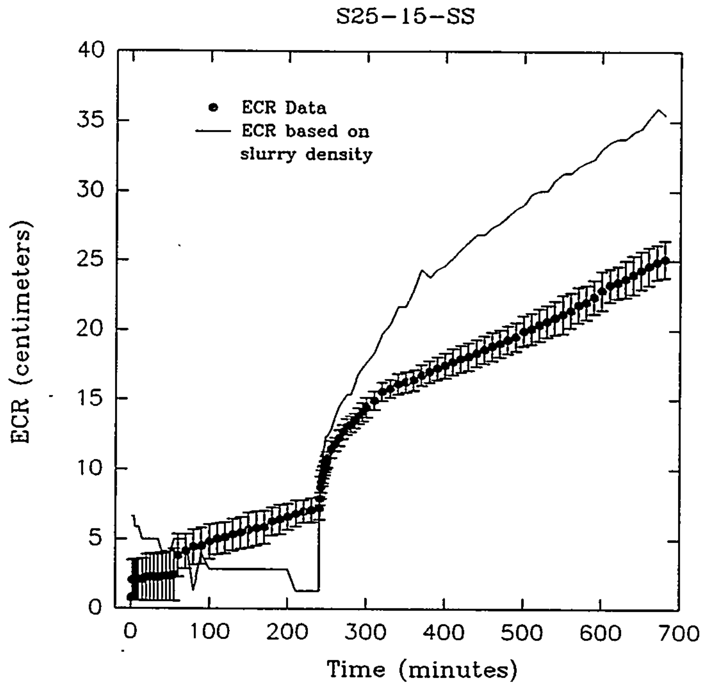

Figure 4.69. ECR vs Time for S25-15-SS

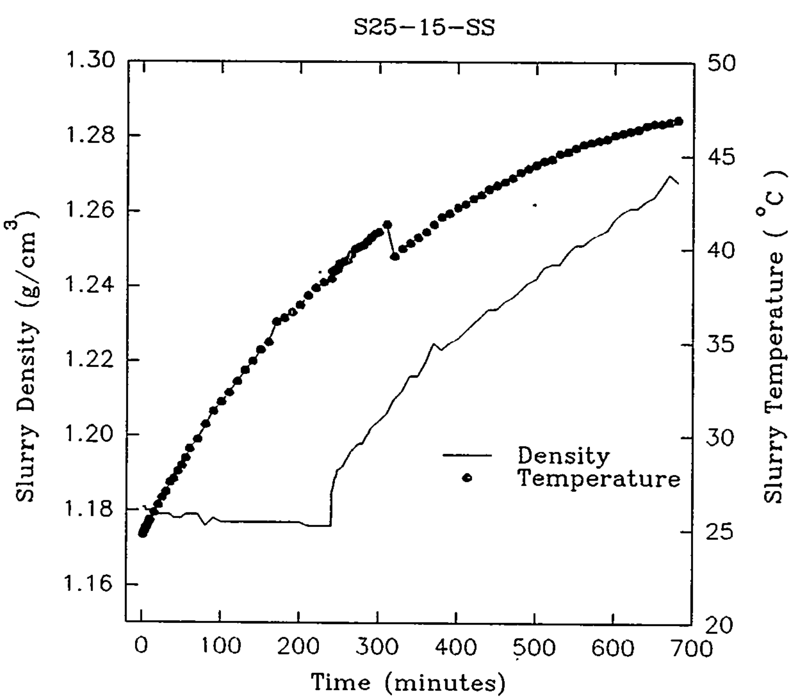

Figure 4.70. Density and Temperature (S25-15-SS)

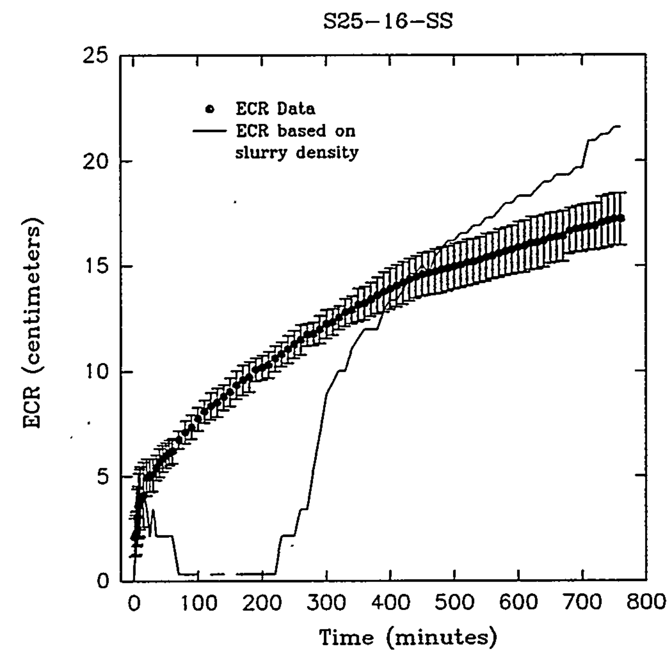

Figure 4.71. ECR vs Time for S25-16-SS (At 700 minutes, 13.6 kg of ice were added to the tank to lower the temperature. This affected the density as well.)

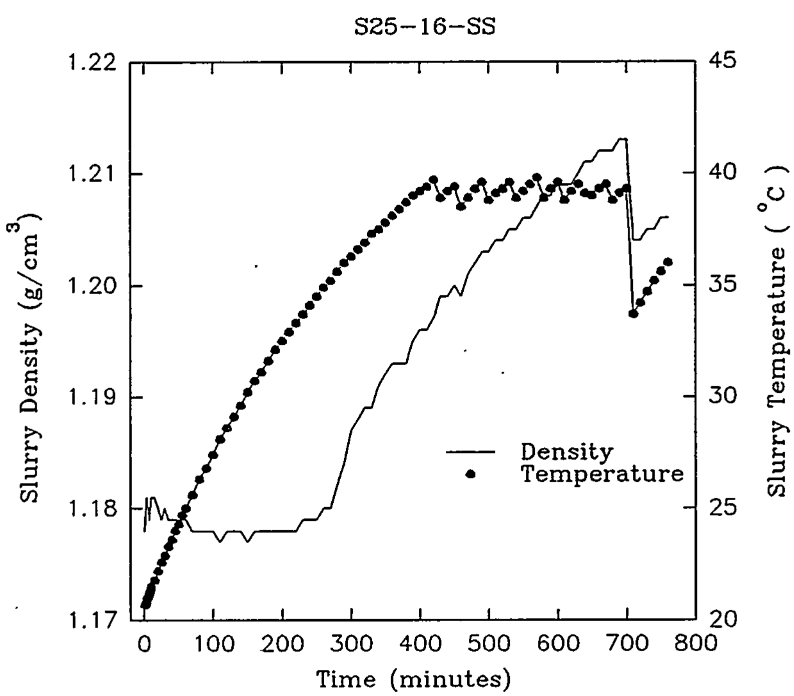

Figure 4.72. Density and Temperature (S25-16-SS)

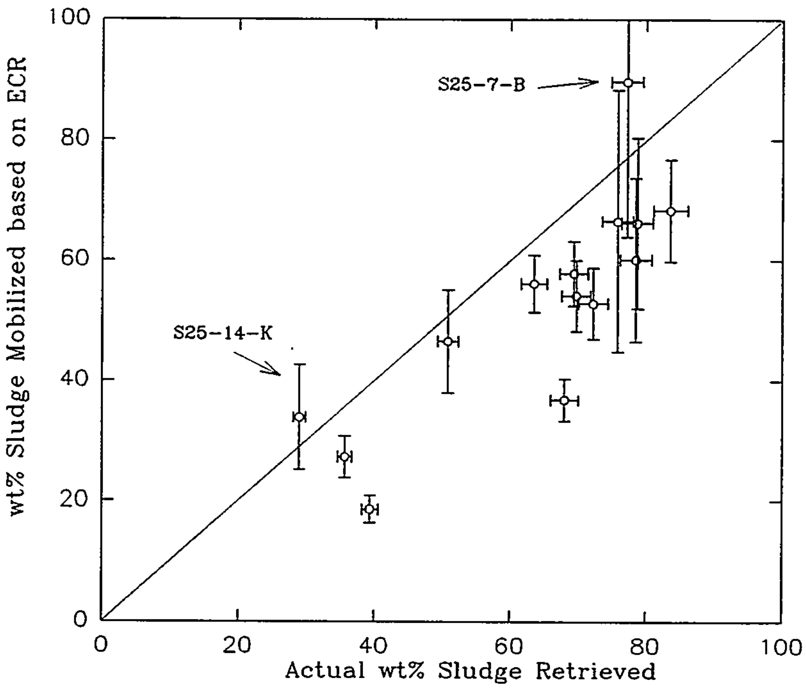

Figure 4.73. Actual wt% Retrieved vs Predicted

After each test (except S25-1-K), the mass of slurry and mass of un-mobilized sludge simulant were determined. This allows the actual wt% of sludge mobilized to be compared with that predicted by the ECR. It was noted during the previous 1/12-scale testing that the ECR tends to under-predict the fraction of sludge mobilized because the sludge banks are typically sloped rather than vertical. Table 4.2 compares the actual wt% sludge mobilized with that predicted by the ECR measurement. Also given is the estimated sludge bank angle[a] based on the difference between these two values and the wt% sludge mobilized based on the slurry density measurements.

The actual wt% retrieved compares favorably with that estimated by the ECR and the slurry density measurement for most tests. In most cases the actual wt% retrieved exceeds that predicted based on slurry density measurements. This resulted from the inclusion of small chunks of simulant in the retrieved slurry. These millimeter-to-centimeter-sized chunks did not contribute to the measured slurry density.

The bank angle for test S25-14-KI is computed to be negative due to the large amount of mobilized simulant that resettled on top of the sludge bed near the tank walls while the mixer pump jets were not being oscillated. Test S25-7-B has a negative bank angle because large (> 10 cm) chunks of simulant were "mobilized," but not mixed with the slurry so they were not retrieved when the tank was emptied.

(a) The sludge bank angle is estimated from the measured ECR and the actual wt% of sludge mobilized. The sludge bank is approximated by a planar surface rather than a conical section.

Table 4.2. Comparison of Percent Sludge Mobilized Measures

Test Number	Actual wt% Mobilized	wt% Predicted by ECR	wt% Predicted by ρ_{slurry}	Estimated Bank Angle (°)
S25-2-K	83.6	68.3	74.0	45
S25-3-K	69.4	57.8	68.3	50
S25-5-B	35.7	27.3	24.3	50
S25-6-B	75.8	66.5	66.5	58
S25-7-B	77.2	89.6	56.1	-34
S25-8-KS	78.7	66.2	72.1	74
S25-9-KS	78.5	60.1	75.9	55
S25-10-KS	72.2	52.8	72.1	50
S25-11-KN	69.7	54.1	70.2	60
S25-12-KN	50.8	46.5	57.8	71
S25-13-K	63.5	56.1	61.2	61
S25-14-KI	29.0	33.9	26.5	-40
S25-15-SS	68.0	36.8	72.1	23
S25-16-SS	29.4	18.6	28.9	40

The wt% sludge mobilized values predicted from the ECR measurements are plotted vs the actual wt% mobilized in Figure 4.73. It is seen in this figure that the ECR tends to under-predict the actual wt% of waste mobilized.

5.0 References

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Appendix A

1/25-Scale Test Plan (DST-TP-93-1) and Related Procedures

Appendix A

1/25-Scale Test Plan (DST-TP-93-1) and Related Procedures

Contained in Appendix A are copies of the test plan and test procedures that were prepared before testing commenced. The test plan (DST-TP-93-1) describes the justification for the 1/25-scale tests as well as the understanding of sludge mobilization before testing. The three test procedures detail the specific steps followed during the 1/25-scale testing as well as the simulant preparation and characterization activities.

Test Plan for
Double-Shell Tank Retrieval Project
1/25-Scale Sludge Mobilization Testing

Test Plan No. DST-TP-93-1, Revision 0

July 12, 1993

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L. E. Maples, PNL, 336 Building Manager	Date
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1.0 Introduction

The 1/25-scale testing program for the DST Retrieval Project Sludge Mobilization Task is defined in this test plan. A general description will be given of the background of the program, testing purposes, equipment and process description, and test approach. The 1/25-scale tests are being performed to determine simulant properties important to relating the effective cleaning radius (ECR) to jet parameters, expand shear strength range of existing ECR equation, develop correlations between ECR and waste simulant properties, and verify scaling parameters between 1/25-scale and 1/12-scale test systems.

2.0 Background

Millions of gallons of radioactive liquid and solid wastes are being temporarily stored in double-shell tanks (DST) on the Hanford Site in southeastern Washington. There are approximately seven different types of wastes stored in varying amounts in the 28 DSTs. These wastes must eventually be retrieved and processed to create immobile waste forms suitable for permanent disposal. Solids in some of these tanks have been settling for many years, creating a sludge layer on the tank floor. This sludge must be dispersed into the supernatant liquid to facilitate retrieval of solids from the tank.

The technology needed to mobilize the sludge layer must be developed and demonstrated to ensure successful retrieval of radioactive waste from actual DSTs. The current plan for sludge mobilization uses mixer pumps to create submerged jets of tank fluid. The two diametrically-opposed jets on each mixer pump are directed at the settled sludge to mobilize and mix the solids with the waste fluid. The mixer pump body and discharge nozzles are rotated creating moving jets of high-momentum fluid that mobilize the settled solids.

Pacific Northwest Laboratory (PNL) has previously been developing waste retrieval technology using a pilot-scale DST test facility and bench-scale test equipment. The pilot-scale facility includes a 1/12-scale geometric model of an actual DST and simulated slurry mixing pumps. The facility can be configured to represent existing arrangements of full-scale tank openings and may utilize certain configurations of internal components.

The bench-scale test equipment consists of 100 gallon tanks with stationary nozzles. This equipment was used for scoping studies and allowed more tests to be run in a shorter period of time than in the larger pilot-scale equipment.

Researchers at PNL are performing waste retrieval testing for Westinghouse Hanford Company (WHC) under the PNL project, "Development/Demonstration of Double-Shell Tank Retrieval Technology." Since the project was initiated in FY 1986, three major studies have been performed. The first two involved the investigation of sludge mobilization using simulated neutralized current acid waste (NCAW) and simulated double-shell slurry (DSS) waste. Both of these studies utilized the 1/12-scale pilot plant facility. The third study, performed using bench-scale equipment, was undertaken to investigate some unexpected discrepancies between the NCAW and DSS tests.

The primary objective of the first study was to develop a correlation to predict the effectiveness of the mixing pump in suspending NCAW solids. This correlation will aid in the design of the full-scale sludge removal system. The simulated NCAW used in this study consisted of silica flour, water, and sodium carbonate. The shear strength of the simulant sludge ranged from 4 to 18 Kdyne/cm^2 depending on the exact simulant composition and simulant age. This range was selected based on an assumed shear strength for actual NCAW sludge of 10 Kdyne/cm^2. The mixer pumps were tested in a scaled version of the expected full-scale arrangement (which utilizes two rotating pumps located on opposite sides of the tank 46 cm (18 inches) above the tank floor and 4.7 m (15.5 feet) from the nearest tank wall). These investigations indicated that the degree of NCAW sludge removal is related to the shear strength of the sludge and the jet mixer parameter U_oD, where D is the jet nozzle diameter and U_o is the fluid discharge velocity.

The second study was initiated with two objectives in mind. The first objective was to verify the correlation that was developed in the NCAW tests for a wider range of shear strengths. To meet this objective, a new simulant was developed consisting of water, salt, kaolin clay and colloidal silica (Ludox). This simulant has a shear strength that can be adjusted from 10 to as high as 180 Kdyne/cm^2. The experimental work was performed using sludge shear strengths in the range of 15-60 Kdyne/cm^2. The second objective was to evaluate a triangular-mixer pump arrangement for mobilizing DSS sludge. It was determined that the proposed triangular-mixer pump arrangement should effectively mobilize the DSS wastes. However, the correlation between the degree of sludge removal and the shear strength of the sludge was found to be significantly different than what was determined for the NCAW sludge.

Bench-scale tests were designed to investigate the possible causes of the discrepancy between the NCAW tests and the DSS tests. These tests were conducted in 380 liter (100 gallon) plastic drums in which a single, stationary nozzle had been affixed 3.8 cm (1.5 inches) from the bottom. Four different simulants were tested in this apparatus. The simulants were selected to encompass a wide range of sludge properties. Using these simulants, shear strengths ranging from about 4 to 110 Kdynes/cm^2 were tested. The bench-scale tests revealed that non-cohesive and cohesive sludges behave quite differently under the influence of a fluid jet. This suggests that different mechanisms are involved in mobilization and that different correlations would apply to these two sludge types. A method was developed to distinguish between non-cohesive and cohesive sludges.

The current 1/25-scale testing is designed to advance the current level of understanding between sludge simulant properties and the observed mobilization by fluid jets. The relevance of physical properties in addition to shear strength will be determined. In particular, the importance of tensile strength, viscoelasticity, and sludge solubility will be investigated. Once the key sludge physical properties have been identified, a more exhaustive set of 1/25-scale tests will be performed to generate correlations between the ECR and the key sludge properties. This second phase of 1/25-scale testing will be described in a future test plan.

Following development of correlations at 1/25-scale, the scaleup of these correlations will be verified by a series of 1/12-scale tests and, if necessary, several 1/4-scale tests.

The expansion of the current ECR (Effective Cleaning Radius) correlation to include higher sludge shear strengths and the effects of soluble sludge components is essential. Without this correlation, WHC may be forced to over-design the mixer pump retrieval systems, which will increase costs.

This test plan provides the methodology for performing 1/25th-scale sludge mobilization tests. These tests will be used to expand the correlations of ECR with waste simulant properties and pump operating parameters while investigating the effects of sludge simulant properties in addition to shear strength.

3.0 Theoretical Description

The following section briefly describes the theoretical background dealing with sludge mobilization. A short description of the methodology in developing the ECR equation for both mobilization by erosion and bulk mobilization is presented as well as a description of cohesive and non-cohesive sludges.

One of the objectives of the 1/25-scale testing activity is to enlarge the available amount of data for use in developing the equations necessary to determine the amount of sludge which can be mobilized in the full-scale DSTs as a function of time. Sludge mobilization by submerged jets occurs by two basic mechanisms: bulk mobilization and erosion. If the jet impacts the sludge with sufficient force, the sludge will fail in shear and large "chunks" of sludge will be mobilized at once. If the velocity of the jet is parallel to the sludge surface, there will be a shear stress at the surface of the sludge resulting from the viscous drag of the fluid. This results in mobilization by erosion.

The distance from a jet nozzle to the most distant sludge that it can mobilize is referred to as the effective cleaning radius (ECR). Accurate correlation of this parameter depends on the type of mobilization taking place.

3.1 Bulk Sludge Mobilization

For bulk mobilization of the sludge, the force of the jet must cause the sludge to fail in shear along some surface or plane of shear. If it is postulated that, on the average, there is a constant ratio between the impinging area of the fluid jet and the area of the sludge failure plane, then a balance of forces approach yields the following relationship between the sludge mobilization parameters and the ECR.

$$ECR = K_2 U_o D \left(\frac{\rho}{\tau_s}\right)^{1/2}$$

where K_2 = collection of constant terms: jet area, viscosity, etc.
U_o = nozzle velocity of the jet, cm/s
D = nozzle diameter, cm
ρ = fluid density, g/cm^3
τ_s = sludge shear strength, dyne/cm^2

The sludge shear strength is defined as the stress required to produce fracture when impressed parallel to the cross-sectional area of shear of the sludge. Shear strength is measured in units of force per unit area of sheared surface.

3.2 Sludge Mobilization by Erosion

Another mechanism by which mobilization of sludge is achieved is erosion. When the ECR no longer increases with time, the shear force created by the fluid flowing over the surface is equal to some strength property of the sludge. If this resistance to shear or tearing away of particles from the surface of the sludge is assumed to be linearly related to the bulk shear strength measured by a shear vane, then an equation can be developed for this type of mobilization. This is believed to be a reasonable assumption for cohesive sludge, but its applicability to non-cohesive sludge is less certain (See Sections 3.3 and 3.4 for a discussion of non-cohesive and cohesive sludge properties).

Determining the effective ECR for the erosion mechanism involves calculating the drag force for a turbulent fluid flowing parallel to an infinite planar solid

$$F_d = 0.036 \rho U^2 w L \left[\frac{L U \rho}{\mu} \right]^{-1/5}$$

where F_d = drag force on a flat plate, dyne
ρ = density of the fluid, g/cm^3
μ = viscosity of the fluid, g/cm-s
L = length of the plate, cm
w = width of the plate, cm
U = bulk fluid velocity, cm/s

This equation represents a simplification of the problem because the fluid jet approach is not parallel to the sludge and the sludge is not long and flat. Assuming that the drag force imposed on the sludge at the ECR is equal to the resistive force of the sludge, the following form of the ECR equation results:

$$ECR = K_5 U_o D (\rho^4 \mu)^{1/9} \tau_s^{-5/9}$$

K_5 is a collection of all the constant terms. If the jet fluid density and viscosity remain constant between different scaled tests, then μ and ρ can be collected into K_5 to give K_6 and the above equation reduces to:

$$ECR = K_6 U_o D \tau_s^{-n}$$

Using this equation as a model, experimental data are used to determine the values of K_6 and n.

Five different simulants will be tested over a range of shear stress (τ_s) from 8 to 60 Kdyne/cm^2. Other sludge simulant properties which will be varied include particle size distribution, shear wave velocity, and tensile strength.

3.3 Non-Cohesive Sludge

A given sludge can be classified as having either non-cohesive or cohesive characteristics. Non-cohesive sludge consists of tightly packed beds of individual solid particles. For such a bed of solids to deform, it is necessary for the bed to increase in volume. If the interstitial space between particles is filled with liquid, a suction will be created as the bed volume is increased. In a sludge of high solids content, the flow path for the liquid is restricted. The resulting pore suction tends to hold the particles tightly together, thereby increasing the normal forces between adjacent particles. These normal forces give rise to enhanced frictional resistance to motion within the bed of solids. This gives the sludge a high resistance to rapid deformation. As a result, a non-cohesive sludge may have a very high apparent shear strength, but have very little attraction between particles in the absence of deformation. A sludge is referred to as non-cohesive if a sizable portion of its measured shear strength is due to non-cohesive frictional effects.

3.4 Cohesive Sludge

Cohesiveness in sludges is caused by the attractive forces between particles. These forces are present in cohesive solids regardless of the applied shear and are often affected by the length of time the particles have been settling. Unlike non-cohesive sludge, the shear strength of a purely cohesive sludge does not increase during deformation of the solid. Because the shear strength of a cohesive sludge results from the attraction between individual particles, the resistance to mobilization increases with increases in the magnitude of the interparticle attractions. A sludge is considered to be cohesive if most of its measured shear strength is due to cohesive forces.

The degree of cohesiveness during 1/25-scale testing will be varied by changing the particle size distribution. As the mean particle size decreases, the sludge cohesiveness increases. As described in Section 5.0, the mean particle size will be varied from very small (bentonite/water simulant) to large (kaolin/silica/water simulant). The mean particle size of the kaolin clay and water simulant will fall somewhere between these two simulant tests. The degree of sludge cohesiveness is thought to control the resistance to mobilization by erosion as discussed above.

4.0 Objectives

The objectives of the 1/25-scale sludge mobilization tests are as follows:

- Conduct a minimum of twelve 1/25-scale tests utilizing five different non-hazardous simulant combinations. Non-dissolving, sludge simulant will be used for all but 2 tests.
- Estimate the magnitude of the effect of dissolving sludge (e.g. NCRW) on the ECR.
- Determine the ECR vs time profiles for high and low shear strength (τ_s), non-hazardous sludge simulants.
- Expand the correlations of ECR with waste simulant properties and pump operating parameters. In particular, correlations will be developed between measurable sludge properties (eg., τ_s and tensile strength) and the cohesive erosion parameters, M (erodibility) and τ_c (critical shear stress).
- Investigate the effect of indexed pump rotation, if time permits.

- Use results to investigate scaling of data between 1/25-scale and 1/12-scale test systems.

5.0 Approach

The tests will be conducted in a 1/25-scale test tank rather than in the existing 1/12-scale DST test facility. The smaller scale requires less simulant per test, will probably allow the visual determination of ECR through the bottom of the tank, and can be conducted more quickly.

Waste simulants will be formulated so that specific properties are varied. Of primary concern is the dependence of sludge mobilization on shear strength. Other sludge simulant properties to be varied and/or measured include particle size distribution, shear wave velocity, and tensile strength. If not feasible to vary each property independently, some statistical analyses may be required to formulate correlations. If needed, the statistical analyses will be documented on numbered calculation worksheets and stored in the project files. All such calculations shall receive an independent review for accuracy.

The prepared sludge simulant will be placed into the tank to a depth of 3.0±0.25 inches. The tank will then be filled to the 15.0±0.25 inch level with simulated supernate. All tests will use water as the simulated supernate except for the silica/soda ash tests which will use a soda ash solution.

During each test, the nozzle exit velocity (U_0) will be set to first a low value and then a high value. The velocity range will be from about 40 to 80 ft/sec with specific U_0 values being determined prior to each test. For each U_0 value, the ECR will be measured frequently by either observing the bottom of the tank from underneath (if this proves to be feasible) or by measuring the distance between the pump centerline and a vertical rod moved radially outward until the sludge bank is encountered. During the first 10 minutes of operation at each U_0, the ECR will be measured at 4-6 points once per minute. Following this, ECR measurements will be made once every 5 minutes for 1 hour, and then made once every 10 minutes until the ECR remains constant (<1 cm/hr) for at least 1 hour. In addition, the density of the tank slurry will be continuously measured using a digital density meter. Slurry density will also be measured by weighing a known volume of sample roughly twice per hour. The slurry density should provide a good indication of the actual fraction of the waste that has been mobilized.

It is proposed that a minimum of 12 tests be conducted (schedule permitting: 14) using 5 different sludge simulants. Table D.1 shows the proposed tests, the respective shear strength for each, and the proposed jet operating mode for each. The shear strength for each simulant will be determined using a shear vane (see procedure TP93-051-DST-001).

The first three 1/25-scale tests will be conducted using a sludge simulant composed of kaolin clay and water. The weight fraction of kaolin will be adjusted to obtain shear strengths of approximately 8, 25, and 40 kdyne/cm^2. These first 3 tests will establish a first estimate of the dependence of ECR on shear strength for non-dissolving sludge.

The 4th and 5th tests will use a kaolin/water/NaCl simulant formulated to be a reasonable first-approximation of dissolving NCRW sludge. The shear strengths of these two simulants will be approximately 30 and 50 kdyne/cm^2, respectively. The data from these two tests will provide an estimate of the magnitude of the effect that soluble components have on sludge mobilization.

Test 6 through 8 will utilize a kaolin/silica/water simulant formulated to shear strengths of approximately 8, 25, and 40 kdyne/cm^2, but having a higher mean particle size than the kaolin/water simulant used in tests 1 through 3. It is expected that these simulants will have a lower tensile strength than the respective simulants used in tests 1 through 3.

Tests 9 through 11 will be conducted with a bentonite/water simulant formulated to give 10, 35, and 60 kdyne/cm^2 approximate shear strengths. The bentonite simulant will have a much smaller mean particle size and probably a different shear wave velocity than the kaolin simulants.

Tests 12 and 13 will be done using the silica/soda ash simulant that was used in previous 1/12-scale tests. The simulants used in the 1/25-scale testing will have shear strengths of approximately 10 and 18 kdyne/cm^2. The data from these two tests will help to establish confidence in the current sludge mobilization scaleup methodology. Test 13 will only be performed if time permits.

Test 14 will utilize the same simulant as test 2 but the jet will be "indexed" (operated in a fixed position for a specified time period) rather than oscillated continuously. Tests 13 and 14 will be performed only if current scheduling permits.

The data from all 12 (possibly 13 or 14) tests described above will be analyzed to develop useful correlations of expected mixer pump performance as a function of pump operating parameters and sludge physical properties. For this, the "final" ECR values will be correlated with the test parameters. Also, the ECR vs time data will be analyzed to estimate the erodibility (M) and critical shear stress (τ_c) of each sludge simulant.

It is estimated that the tests will proceed at about 2 tests per week. Each test will require 8-10 hours to run, and intermediate times will be spent on cleanup, test preparation, and simulant characterization.

Table A.1. 1/25-Scale Test Matrix

Test Number	Simulant Composition	Shear Strength[1] ($kdyne/cm^2$)	Jet Operating Mode
1	Kaolin/Water	8	Oscillating
2	Kaolin/Water	25	Oscillating
3	Kaolin/Water	40	Oscillating
4	Kaolin/Water/NaCl	30	Oscillating
5	Kaolin/Water/NaCl	50	Oscillating
6	Kaolin/Silica/Water	8	Oscillating
7	Kaolin/Silica/Water	25	Oscillating
8	Kaolin/Silica/Water	40	Oscillating
9	Bentonite/Water	10	Oscillating
10	Bentonite/Water	35	Oscillating
11	Bentonite/Water	60	Oscillating
12	Silica/Soda ash	10	Oscillating
13*	Silica/Soda ash	18	Oscillating
14*	Kaolin/Water	25	Indexed

* Schedule Permitting

[1]Simulants will be formulated to have shear strengths within 10% of the target values with the exception of the silica/soda ash simulant which will have a 20% tolerance.

6.0 Responsibilities

Principal Investigators (PIs) - R.L. McKay, G.R. Golcar, and M.R. Powell will direct and conduct the testing. Data analysis, conclusions, and reporting will also be performed by the Pis.

Management Approval - P.A. Scott, as project manager, will approve any recommended changes in the testing strategy or schedules necessitated by unforeseen events or results.

Technician Support - Chuck Hymas will assist in the collection of data during testing. Alternate/additional technicians will be obtained, if necessary.

7.0 Equipment Description

Figure D.1 shows a schematic of the proposed test setup. The tank which will be used during 1/25-scale testing is a 3 foot diameter (2 foot high) plexiglass tank with clear sides and a clear bottom. It is proposed that the clear bottom will serve as a method for visual representation of the ECR vs time observations. The slurry will be continuously pumped using a 2 Hp centrifugal pump. A DC motor with oscillation control will be used to turn the nozzles through a 180° rotation.

The simulated mixer pump nozzles will be sized based upon a 6" full-scale nozzle diameter (1/25-scale = 0.24"). A single, centrally-located, simulated mixer pump will be mounted in the test tank such that it is capable of automatically oscillating through 180° of rotation. The oscillation rate will be scaled based on a 0.16 rpm rotation on the full-scale mixer pumps (1/25-scale = 4.2 rpm). The tank fluid will be discharged through two opposing nozzles and recovered via a suction located near the discharge nozzles. Other scaled measurements can be seen in Figure D.1.

The dry components of the various sludge simulants will be mixed with water using a Littleford Mixer located outside the 336 building.

As mentioned above, the ECR will be measured incrementally either by visual observation or by use of a vertical rod moved radially outward from the pump center line until the sludge bank is encountered. In order to facilitate this measurement, the top of the tank will be left open. The motor and other pieces of equipment will be supported using an arrangement of metal cross pieces as depicted in Figure D.1.

8.0 Hazards Assessment

Most of the materials used in these tests will be non-hazardous. Kaolin and bentonite clays are essentially inert and require only protection from nuisance dust. Dry silica flour, however, is a significant health hazard if inhaled. The kaolin and bentonite clays are obtained naturally and often contain trace amounts of free silica particles. Therefore, when handling any of the dry raw materials (clay, silica flour, or soda ash), full-face filtration masks equipped with HEPA filters will be worn by all involved personnel to avoid exposure to silica particles. All personnel using the filtration masks shall have received a mask fit and the proper training. Once the clay simulants are mixed with water, the silica dust hazard no longer exists.

The silica/soda ash solution will be basic ($pH \approx 11$). Rubber gloves will be worn when handling this mixture.

9.0 Personnel Safety

All testing and operations will conform to PNL-MA-43 (Industrial Hygiene, Occupational Safety and Fire Protection Programs), building requirements, SOPs and line management direction. Requirements associated with these tests are listed below.

1) Personnel Protective Equipment:
   Rubber gloves will be worn when handling the silica/soda ash simulant. Also, when the potential for the generation of airborne silica exists, full-face HEPA filtration masks will be worn by all involved personnel. Hardhats and safety glasses are required for access to the 336 building high bay.

2) Material Safety Data Sheets (MSDS):
   All MSDSs will be reviewed by each staff member who is involved in the tests described in this test plan.

3) Respiratory Protection Requirements:
   Filtration masks will be worn when airborne silica particles are potentially present.

4) Medical Requirements:
   All personnel handling the dry simulants shall be medically approved for the use of full-face respirators.

5) Confined Space:
   These testing activities will not involve work in a confined space. However, confined space training is required for access to the levels of the 336 building below the level where the 1/25-scale tank is located. Only qualified personnel are allowed to enter these lower levels.

6) Emergency Response:

Any emergency situation will be handled by contacting the appropriate Hanford Emergency Response Unit (Dial 375-2400).

10.0 Waste Minimization/Management

All waste generated during the course of this test will be appropriately disposed per PNL-MA-8. All material will be collected in 55 gallon drums and appropriately tested, if necessary. If the final waste volume is determined to be non-hazardous it will be sent to a non-regulated waste disposal site. It is currently anticipated that all testing will be conducted using non-hazardous, non-regulated materials.

11.0 Test Modifications and Quality Assurance

Work authorized by this test plan will be conducted in accordance with Impact Level II requirements as identified in Quality Assurance Plan No. WTC-051, Rev. 3.

All laboratory data, general observations, and details of the activities performed per this test plan will be documented in a Laboratory Record Book (LRB). The current LRB assigned to this project is BNW52465. Changes to this test plan will be documented on the "work place" record copy, and approved by the task leader as indicated by initial and date. It is important that all data records, calculations, and analyses reported from this test be documented in a sufficient manner to be traceable from the primary data and the methods and equipment used, through the assumptions and/or interpretations made, to the corresponding results reported in the summary report. For sludge mobilization testing, the majority of data will be collected on data and status log sheets and test instructions. Any additional observations, data, and remarks will be recorded in the LRB.

Change control shall be accomplished by the following methods. Changes that are considered to be major (defined as those that would affect the overall objectives) shall be approved by the same parties via revision to the test plan. Minor changes (those that are editorial, or do not change the overall objectives) shall be made by mark up of a controlled copy and signed and dated by the cognizant task manager. Minor changes are to be followed up with an official revision at a logical break point, or when there has been a total of three (3) minor changes made. The need to make minor changes is to facilitate changes needed for off-shift hours. In the front of the controlled test plan that is used for minor change mark ups, a listing of changes will be maintained.

The desk copy of the test plan will be the controlled document copy in which notations and changes in the test will be recorded. Changes may be entered only by the shift leader, responsible engineer, task leader, or the responsible investigator of the test objective. Any changes will be countersigned by the responsible engineer (can be after the fact) to indicate cognizance of the change.

12.0 Technical Procedures/Test Instructions

Technical procedures and test instructions will be used to support the activities during sludge mobilization testing. These procedures are attached to this test plan. Table D.2 lists the technical procedures to be used.

Technical Procedures Title	Procedure Number
Laboratory Testing of Simulated Sludge Characteristics	TP93-051-DST-001
Field Preparation of Non-Hazardous Sludge Simulant	TP93-051-DST-002
1/25-Scale Sludge Mobilization Testing	TP93-051-DST-003

Table A.2. 1/25-Scale Test Procedures

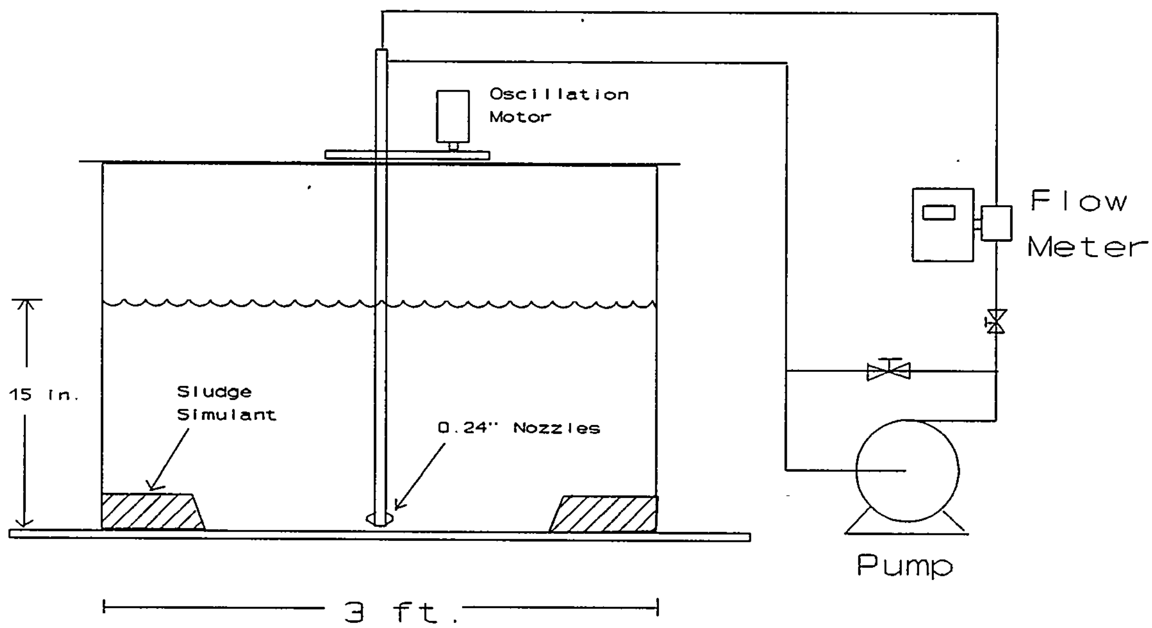

Figure A.1. Sketch of 1/25-Scale Testing Apparatus

ATTACHMENTS: TEST PROCEDURES

LABORATORY TESTING OF SIMULATED SLUDGE CHARACTERISTICS

This procedure is to be used to characterize the physical properties of the double-shell tank (DST) waste simulants used for 1/25-scale sludge mobilization testing as described in Test Plan DST-TP-93-1. The techniques described below shall be used to measure the shear strength (τ_s), tensile strength (S_t), density (ρ), and viscoelastic parameters (complex elastic modulus G^*, storage modulus G', and loss modulus G'') of the DST waste simulants. The procedure that follows will be duplicated as needed so that one copy is utilized per simulant.

<u>Shear Strength:</u>

The procedure that follows shall be repeated a minimum of four times per simulant. A separate copy of this procedure will be completed for each iteration.

Time/Date:_____/___/_____ at ____:____ Name:________________________

1. Select a vane size suitable for the shear strength range to be measured. Enter the vane dimensions here:

   vane height:_________cm vane diameter:_________cm

2. Zero the CV100 digital display with the shear vane attached to the M5 head and NOT placed in the simulant.

3. Insert the shear vane into a portion of the simulant carefully to avoid disrupting the sample.

4. Circle (a) or (b):

   (a) Vane is fully-submerged in simulant
   (b) Vane is submerged to the depth of the top of the vane blades

   The shear vane should be fully-submerged if the vane size and sample size permit doing so. A fully-submerged vane must be at least 3 vane heights below the simulant surface to ensure that the simulant surface does not move with the vane blades.

5. Select the Haake setup parameter file that applies to the vane selected in step 1. Enter the name of the file here:

   Filename:______________________________

6. Ensure that the Haake vane rotation speed is set to 0.3 rpm (0.06% of full-scale).

7. Ensure that the Haake run time is set to 2.0 minutes.

8. Ensure that the Haake CV100 electronic filter is set to 2.

9. Ensure that the Haake CV100 %τ selector is appropriately set based on the shear vane dimensions and the expected simulant shear strength.

10. Ensure that the Haake software is configured to save the data to a file. Enter the name of the data file here:
    Data Filename:___________________________

11. Activate the shear vane using the Haake software.

12. Note the magnitude of the highest point on the τ vs time plot and record this value below:
    Approximate Shear Strength:______________________ pascals

13. Remove the shear vane from the simulant and thoroughly rinse the vanes using DI water. Dab the vane dry using a paper towel.

14. Print the plot of τ vs time data and affix copies of the data in the current laboratory record book and in the 1/25-scale test data 3-ring binder.

Tensile Strength:

The procedure that follows shall be repeated a minimum of four times per simulant. It is permissible to perform all four tensile strength measurements in parallel -- that is, four separate tensiometers are loaded with simulant and then all four are measured.

1. Prepare a tensiometer for use by applying a thin coat of vacuum grease to the interface of the two halves of the tensiometer and then securing the halves together using small rubber bands.

2. Load a tensiometer with sludge simulant so that the upper portion of the tensiometer is about 1/2-full of sludge. Take care to avoid entrapping large air bubbles in the simulant or packing successive portions of simulant such that their interface coincides with the predetermined plane of failure of the tensiometer.

3. Connect the tensiometer string to the tensiometer and center the tensiometer under the first pulley.

4. Route the tensiometer string over both pulleys and carefully apply the weight of the empty water collection bottle to the tensiometer. Do this very slowly to avoid shock-loading the sample.

5. Visually ensure that the string between the upper portion of the tensiometer and the pulley is vertical. Adjust carefully, if required.

6. Establish a water flow of 100±5 ml/min through the water addition tube.

7. Direct the water flow into the water collection vessel.

8. Gently hold the baseplate of the tensiometer secure to the lab bench while adding the water.

9. Terminate water addition when the simulant "fails" in a tensile mode.

10. Determine the mass of the water collection vessel (still containing water) and the mass of the upper portion of the tensiometer (containing simulant). Record these masses below:

    Water Collection Vessel:__________g   Upper Portion:__________g

11. Remove the simulant from the tensiometer halves and clean the tensiometer.

12. Use the following equation to calculate tensile strength. Record calculation and result in appropriate Laboratory Record Book.

$$S_t = \frac{4\,(M - M_t - 20\,grams)\,g}{\pi D_t^2}$$

where:

S_t = tensile strength, dynes/cm^2
M = mass of 1000-ml bottle and water, g
M_t = mass of upper portion of tensiometer (including simulant), g
g = acceleration of gravity, 980 cm/s^2
D_t = diameter of tensiometer simulant interface, 3.35 cm

Simulant Density:

The density of each sludge simulant and each supernate will be measured prior to testing using the following procedure. Four density measurements shall be taken on each simulant.

1. Pour or pack the 100±0.5ml density flask full of simulated sludge or supernate and secure the flask lid.

2. Zero the digital balance.

3. Place the 200g "calibration" weight on the balance and record the as found reading here:

   Balance Reading (200g mass):________________g

4. Place the empty density flask on the balance and record the reading:

   Balance Reading (density flask):__________________g

5. Place the filled density flask on the balance and record the reading:

   Balance Reading (density flask + simulant):__________________g

6. Remove the density flask and place the 200g "calibration" weight on the balance.

7. Verify that the balance reads within 0.02g of the reading recorded in step 3. If not, repeat steps 3-7.

8. Repeat steps 3-7 three more times and enter the requested data here:

1) 200g mass reading:__________________g
   Density Flask:_____________________g
   Density Flask + Simulant:___________g

2) 200g mass reading:__________________g
   Density Flask:_____________________g
   Density Flask + Simulant:___________g

3) 200g mass reading:__________________g
   Density Flask:_____________________g
   Density Flask + Simulant:___________g

9. Use the following equation to calculate density. Record calculation and result in appropriate Laboratory Record Book.

$$\rho = \frac{M_t - M_f}{V}$$

where:

ρ = density of simulant, g/ml
M_t = mass of density flask + simulant, g
M_f = mass of density flask
v = volume of flask, 100 ml

Viscoelastic Properties:

The following procedure shall be followed when determining the viscoelastic properties of the sludge simulants.

1. Connect the plate-and-plate sensor to the Haake CV20.

2. Activate the oscillation software by typing "osc" from the directory c:\haake.

3. Load the plate-and-plate setup parameters into computer memory.

4. Place a small quantity of sludge simulant between the plates.

5. Execute a frequency sweep from .5 to 10 Hz at a strain of 1° over a period of 5 minutes. Enter the data filename here:

   Frequency sweep filename:______________________________

6. Execute a stain sweep from 0.1° to 10° at a frequency of 1 Hz over a period of 5 minutes. Enter the data filename here:

   Strain sweep filename:_________________________________

7. Thoroughly clean the plates prior to storing them.

Once the raw data have been stored, the viscoelastic properties of the simulant are obtained by using the Haake software to generate any required plots and perform the necessary calculations. Copies of the key graphs of the data shall be affixed in the Laboratory Record Book.

FIELD PREPARATION OF NON-HAZARDOUS SLUDGE SIMULANTS

This procedure shall be followed when preparing the simulants to be utilized during 1/25-scale sludge mobilization testing in the 336 building as outlined in the Test Plan DST-TP-93-1. Five different types of sludge simulant will be required for the 1/25-scale testing. Because these different simulant types require different preparation techniques, this procedure is composed of 5 separate procedures - one each for the different simulant types.

Kaolin/Water Simulant:

This procedure shall be used when preparing "kaolin/water" sludge simulant.

Time/Date:_____/___/_____ at ___:____ Name:_________________________

1. Obtain the target simulant composition from the cognizant engineer and enter the data in the table below:

Weight % Kaolin in Simulant:____________ wt %

Material	Quantity (lb)
Kaolin Clay	
Water	
Total:	

2. Ensure that the Littleford simulant mixer is clean.

CAUTION: Air filtration masks shall be worn when working with dry kaolin clay to prevent the inhalation of the small amount of free silica dust particles present in the kaolin clay.

3. Weigh out enough clay to produce a 100 lb batch of simulant (wt% kaolin times 1 lb).

4. Pour approximately half of the kaolin weighed out in step 3 into the Littleford mixer.

5. Weigh out enough water to produce a 100 lb batch of simulant (100 lbs minus weight of clay determined in step 3).

6. Add the water measured in step 5 to the Littleford Mixer.

7. Activate the Littleford Mixer.

8. After 1 minute of mixer operation, slowly add the remaining portion of the clay weighed out in step 3.

9. Allow the mixer to operate for at least 10 minutes following the completion of step 8.

10. Position a suitable container under the Littleford mixer, then open the mixer effluent hatch. The simulant will drop out of the mixer and into the container.

11. Close the mixer hatch.

12. Collect approximately 500 ml of simulant for physical property characterization.

13. Repeat steps 3-12 until the amount of simulant specified in step 1 has been prepared.

14. Clean the mixer using water. Collect the rinse water in a suitable waste container.

Bentonite/Water Simulant:

This procedure shall be used when preparing "bentonite/water" sludge simulant.

Time/Date:_____/__/_____ at ____:____ Name:________________________

1. Obtain the target simulant composition from the cognizant engineer and enter the data in the table below:

   Weight % bentonite in Simulant:____________ wt %

Material	Quantity (lb)
Bentonite Clay	
Water	
Total:	

2. Ensure that the Littleford simulant mixer is clean.

CAUTION: Air filtration masks shall be worn when working with dry bentonite clay to prevent the inhalation of the small amount of free silica dust particles present in the clay.

3. Weigh out enough clay to produce a 100 lb batch of simulant (wt% bentonite times 1 lb).

4. Pour approximately half of the bentonite weighed out in step 3 into the Littleford mixer.

5. Weigh out enough water to produce a 100 lb batch of simulant (100 lbs minus weight of clay determined in step 3).

6. Add the water measured in step 5 to the Littleford Mixer.

7. Activate the Littleford Mixer.

8. After 1 minute of mixer operation, slowly add the remaining portion of the clay weighed out in step 3.

9. Allow the mixer to operate for at least 10 minutes following the completion of step 8.

10. Position a suitable container under the Littleford mixer, then open the mixer effluent hatch. The simulant will drop out of the mixer and into the container.

11. Close the mixer hatch.

12. Collect approximately 500 ml of simulant for physical property characterization.

13. Repeat steps 3-12 until the amount of simulant specified in step 1 has been prepared.

14. Clean the mixer using water. Collect the rinse water in a suitable waste container.

Kaolin/Silica/Water Simulant:

This procedure shall be used when preparing "kaolin/silica/water" sludge simulant.

Time/Date:______/___/______ at ____:____ Name:________________________

1. Obtain the target simulant composition from the cognizant engineer and enter the data in the table below:

Weight % kaolin in Simulant:____________ wt %

Weight % silica in Simulant:____________ wt %

Material	Quantity (lb)
Kaolin Clay	
Min-U-Sil 30 silica flour	
Water	
Total:	

2. Ensure that the Littleford simulant mixer is clean.

CAUTION: Air filtration masks shall be worn when working with dry kaolin clay and the Min-U-Sil 30 silica flour to prevent the inhalation of silica particles.

3. Weigh out enough clay to produce a 100 lb batch of simulant (wt% kaolin times 1 lb).

4. Weigh out enough silica to produce a 100 lb batch of simulant (wt% silica times 1 lb).

5. Pour approximately half of the clay weighed out in step 3 and half of the silica weighed out in step 4 into the Littleford mixer.

6. Weigh out enough water to produce a 100 lb batch of simulant (100 lbs minus total weight of kaolin and silica determined in steps 3 and 4).

7. Add the water measured in step 6 to the Littleford Mixer.

8. Activate the Littleford Mixer.

9. After 1 minute of mixer operation, slowly add the remaining portions of the clay weighed out in step 3 and the silica weighed out in step 4.

10. Allow the mixer to operate for at least 10 minutes following the completion of step 8.

11. Position a suitable container under the Littleford mixer, then open the mixer effluent hatch. The simulant will drop out of the mixer and into the container.

12. Close the mixer hatch.

13. Collect approximately 500 ml of simulant for physical property characterization.

14. Repeat steps 3-12 until the amount of simulant specified in step 1 has been prepared.

15. Clean the mixer using water. Collect the rinse water in a suitable waste container.

Kaolin/Salt/Water Simulant:

This procedure shall be used when preparing "kaolin/NaCl/water" sludge simulant.

Time/Date:_____/___/_____ at ____:____ Name:_________________________

1. Obtain the target simulant composition from the cognizant engineer and enter the data in the table below:

Weight % kaolin in Simulant:____________ wt %

Weight % NaCl in Simulant:____________ wt %

Material	Quantity (lb)
Kaolin Clay	
$NaCl_{(s)}$	
Water	
Total:	

2. Ensure that the Littleford simulant mixer is clean.

CAUTION: Air filtration masks shall be worn when working with dry kaolin clay to prevent the inhalation of the small amounts of free silica particles that may be present.

3. Weigh out enough clay to produce a 100 lb batch of simulant (wt% kaolin times 1 lb).

4. Weigh out enough NaCl to produce a 100 lb batch of simulant (wt% salt times 1 lb).

5. Pour approximately half of the clay weighed out in step 3 and half of the salt weighed out in step 4 into the Littleford mixer.

6. Weigh out enough water to produce a 100 lb batch of simulant (100 lbs minus total weight of kaolin and salt determined in steps 3 and 4).

7. Add the water measured in step 6 to the Littleford Mixer.

8. Activate the Littleford Mixer.

9. After 1 minute of mixer operation, slowly add the remaining portions of the clay weighed out in step 3 and the salt weighed out in step 4.

10. Allow the mixer to operate for at least 10 minutes following the completion of step 8.

11. Position a suitable container under the Littleford mixer, then open the mixer effluent hatch. The simulant will drop out of the mixer and into the container.

12. Close the mixer hatch.

13. Collect approximately 500 ml of simulant for physical property characterization.

14. Repeat steps 3-12 until the amount of simulant specified in step 1 has been prepared.

15. Clean the mixer using water. Collect the rinse water in a suitable waste container.

Silica/Soda Ash Simulant:

This procedure shall be used when preparing "silica/soda ash" sludge simulant.

Time/Date:_____/__/_____ at ___:____ Name:____________________

1. Obtain the target simulant compositions from the cognizant engineer and enter the data in the table below:

Weight % Min-U-Sil 30 in Simulant:______________ wt %

Weight % Soda Ash in Simulant:______________ wt %

Weight % Sand in Simulant:____________ wt %

Weight % N-130 Polymer (flocculent):____________ wt %

Weight % Water in Simulant:____________ wt %

Material	Quantity (lb)
Min-U-Sil 30	
Soda Ash	
Sand	
N-130 Clarifloc	
Water	
Total:	

3. Fill a steel drum with the specified quantity of water.

4. Add the quantity of N-130 polymer solution specified in step 2 to the water while agitating.

CAUTION: Avoid contact with the soda ash and the soda ash solution. Soda ash is a mild caustic and can irritate the skin. Rubber gloves shall be worn when handling the soda ash.

5. While wearing rubber gloves, add the soda ash to the solution while stirring. Sprinkle the soda ash onto the surface slowly. Avoid dropping in clumps of soda ash as these will be very difficult to dissolve.

CAUTION: Air filtration masks shall be worn when working with dry Min-U-Sil 30 silica flour to prevent the inhalation of silica particles.

6. Slowly add the Min-U-Sil 30 silica flour to the mixture while agitating.

7. Slowly add the sand to the mixture.

8. Allow the tank to mix for 5 minutes, then collect 4 samples for physical property measurements.

9. Cover the physical property samples to prevent evaporation of water.

10. Transfer the silica/soda ash slurry to the 1/25-scale tank.

11. Cover the 1/25-scale tank to prevent evaporation of water from the simulant.

12. Clean the simulant makeup vessel thoroughly.

1/25-SCALE SLUDGE MOBILIZATION TESTING

This procedure shall be used to perform the 1/25-scale sludge mobilization tests as described in the 1/25-scale Test Plan DST-TP-93-1. The testing will involve the measurement of the amount of simulated sludge mobilized by a single, centrally-located, simulated mixer pump. The effective cleaning radius (ECR) will be used to quantify the amount of sludge mobilized. The ECR will be measured frequently during the test so that an ECR vs time profile can be generated. As a check on the ECR measurements, the slurry density will be monitored during the test. Based on the sludge and supernate densities, the density profile (with respect to time) can be calculated from the plot of ECR vs time. Likewise, the ECR profile (with respect to time) can be calculated from the plot of measured density vs time.

Test ID #:____________________ Date:____________ Time:___________

Names of Test Operators:____

____

Simulant Type:____

Nozzle Exit velocities to be tested:

1) _________________ m/s = __________ gpm total flow

2) _________________ m/s = __________ gpm total flow

1. Record the initial supernate density as measured by the digital density meter:_____________________ g/ml

2. Record the initial supernate density as measured by the 100 ml stainless steel density flask:______________________ g/ml

3. Lower the simulated mixer pump into the sludge simulant so that the nozzle centerline is 1.8±0.2 cm above the tank floor.

4. Activate the mixer pump oscillation electronics and adjust the speed and oscillation times so that the pump oscillates through a 180° rotation at a rate of 4.2±0.2 rpm (unless indexed pump movement is being tested).

5. Open the pump recirculation valve completely (V-1).

6. Close the mixer pump flow control valve (V-2).

7. Ensure that the centrifugal pump has been primed.

8. Turn on the centrifugal pump.

9. Open valve V-2 and close valve V-1 sufficiently to obtain the desired total flow rate (recorded above). Note the time at which this is done in the table below.

10. Record the ECR and density vs time data in the tables below until the rate of change of the measured ECR is less than 1 cm/hour for at least 1 hour. "Time=0" is established in step #9 for the first U_0 setting. (use copies of page 5 of this procedure for times exceeding 240 minutes).

11. Once the ECR growth rate is less than 1 cm/hour for at least 1 hour at all measured locations, valves V-1 and V-2 shall be adjusted as necessary to obtain the second desired flow rate. When this adjustment is made, a new "Time=0" is recorded on a new copy of the tables that follow.

12. Continue to record the required data until the ECR growth rate is less than 1 cm/hour for at least 1 hour at all measured locations.

13. Deactivate the centrifugal pump.

14. Pump the slurry in the 1/25-scale tank into a waste container (steel drum).

15. Take measurements and generate a detailed sketch of the observed remaining sludge bank. Also take photographs of the sludge bank.

16. Remove any remaining sludge from the tank and flush all piping with clean water.

1/25-Scale Testing Data Table									
Test No:			Date:			Time=0 at :			
Time (min)	ECR_a	ECR_b	ECR_c	ECR_d	ECR_e	ECR_f	ECR_g	ECR_h	ρ_{slurry} (g/ml)
0									
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
15									
20									
25									
30									
30	Slurry Density measured by 100 ml flask: g/ml								
35									
40									
45									
50									
55									
60									
60	Slurry Density measured by 100 ml flask: g/ml								

1/25-Scale Testing Data Table									
Test No:			Date:			Time=0 at :			
Time (min)	ECR_a	ECR_b	ECR_c	ECR_d	ECR_e	ECR_f	ECR_g	ECR_h	ρ_{slurry} (g/ml)
70									
80									
90									
90	Slurry Density measured by 100 ml flask: g/ml								
100									
110									
120									
120	Slurry Density measured by 100 ml flask: g/ml								
130									
140									
150									
150	Slurry Density measured by 100 ml flask: g/ml								
160									
170									
180									
180	Slurry Density measured by 100 ml flask: g/ml								
190									
200									
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210	Slurry Density measured by 100 ml flask: g/ml								
220									
230									
240									
240	Slurry Density measured by 100 ml flask: g/ml								

<table>
<tr><th colspan="10">1/25-Scale Testing Data Table</th></tr>
<tr><td colspan="3">Test No:</td><td colspan="3">Date:</td><td colspan="4">Time=0 at :</td></tr>
<tr><td>Time (min)</td><td>ECR_a</td><td>ECR_b</td><td>ECR_c</td><td>ECR_d</td><td>ECR_e</td><td>ECR_f</td><td>ECR_g</td><td>ECR_h</td><td>ρ_{slurry} (g/ml)</td></tr>
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<tr><td></td><td colspan="9">Slurry Density measured by 100 ml flask: g/ml</td></tr>
</table>

Appendix B

Sludge Bank Profiles

Appendix B

Sludge Bank Profiles

The profile of the sludge bank as observed from beneath the 1/25-scale tank was sketched following each test. Typically, two sketches were made per test. The first was performed just before changing from the first jet flow rate to the second flow rate. The second sketch was made following the completion of the test at the second flow rate. In the figures that follow, this difference is denoted by either a (1) or a (2) following the test number. For example, the plot below shows the sludge bank profile following the second jet flow rate of test S25-1-K. Thus, the figure title reads S25-1-K (2). No sketch was made for the first flow rate of S25-1-K. Sketches for each flow rate of all the remaining tests were made.

All radial distances in the following figures are given in centimeters from the tank center. The ECRs are 2.2 cm less than the distances shown in the figures due to the distance between the pump centerline and the nozzle exit. Zero degrees (at 3 o'clock position) has been assigned to the "ECRa" radial line scribed on the 1/25-scale tank bottom. The ECRb line is at 45° (1:30 position), ECRc is at 90° (12 o'clock position), and so on. The sludge bank profiles are shown in the figures as would be observed from a position above the tank looking downward. The 1/25-scale mixer pump nozzles were oscillated through 180° between 112.5° and 292.5° (between the 5:15 and 11:15 positions). The tank radius is 45 cm, as shown in the figures. Note that ECRs were measured at 45° increments wile the figures below contain lines at 30° increments. These lines are for reference purposes only.

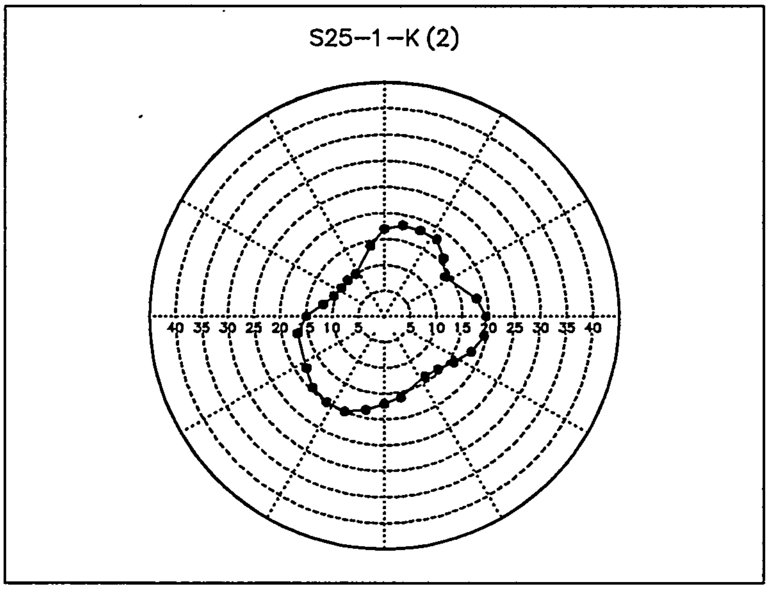

Figure B.1. Final Sludge Bank Profile for S25-1-K, $U_oD = 491\ cm^2/s$

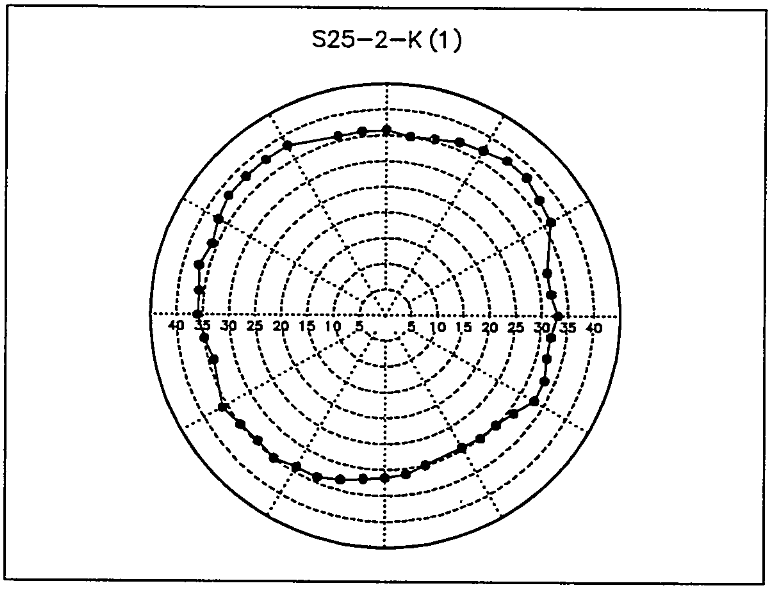

Figure B.2. Final Sludge Bank Profiles for S25-2-K, $_{o}D = 579\ cm^2/s$

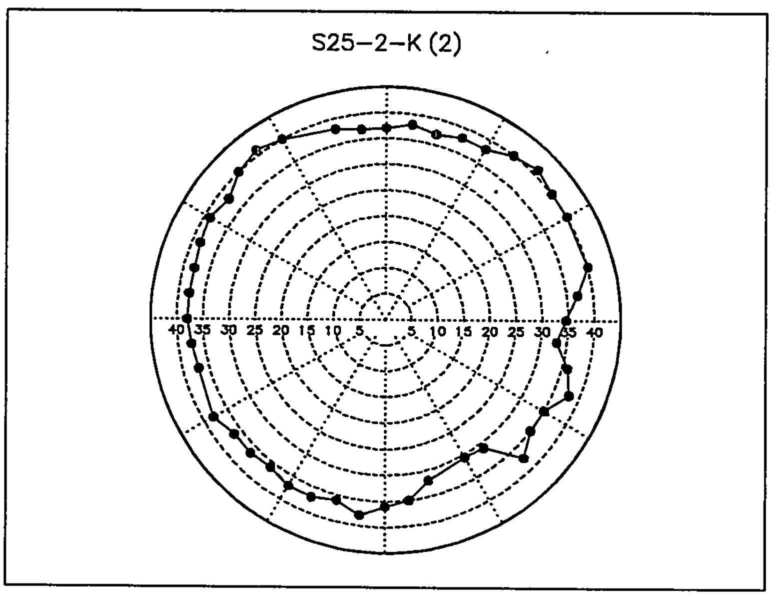

Figure B.3. Final Sludge Bank Profile for S25-2-K, $_{o}D = 676\ cm^2/s$

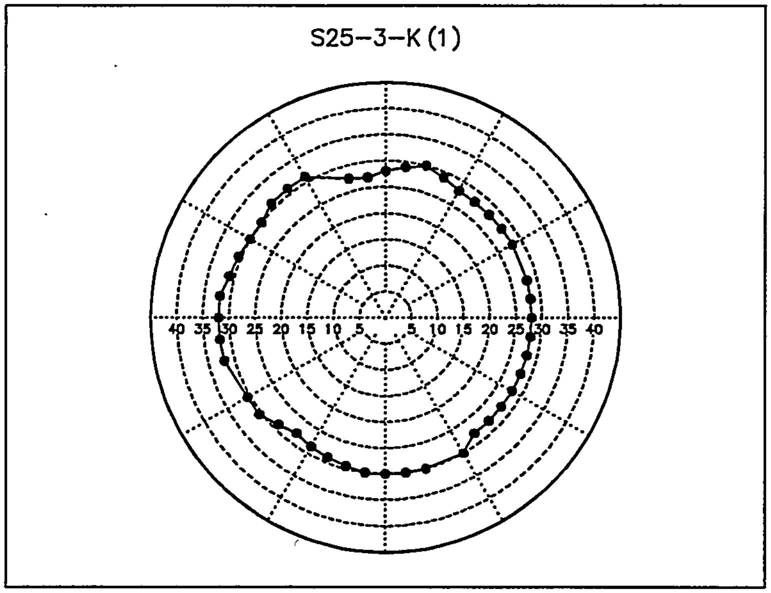

Figure B.4. Final Sludge Bank Profile for S25-3-K, $U_oD = 579\ cm^2/s$

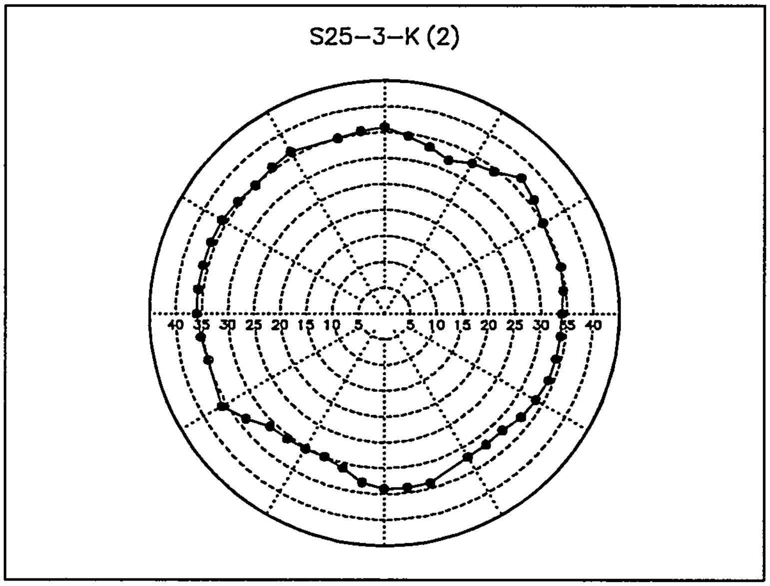

Figure B.5. Final Sludge Bank Profile for S25-3-K, $U_oD = 676\ cm^2/s$

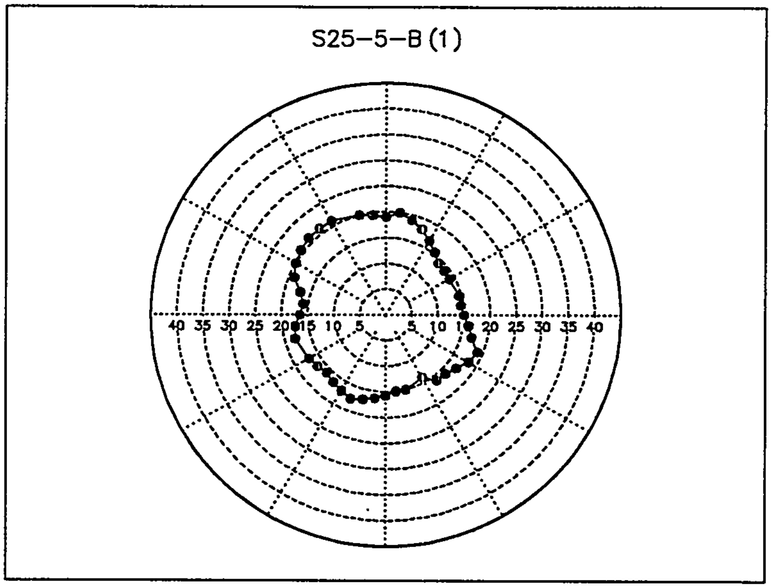

Figure B.6. Final Sludge Bank Profile for S25-5-B, $U_0D = 542\ cm^2/s$

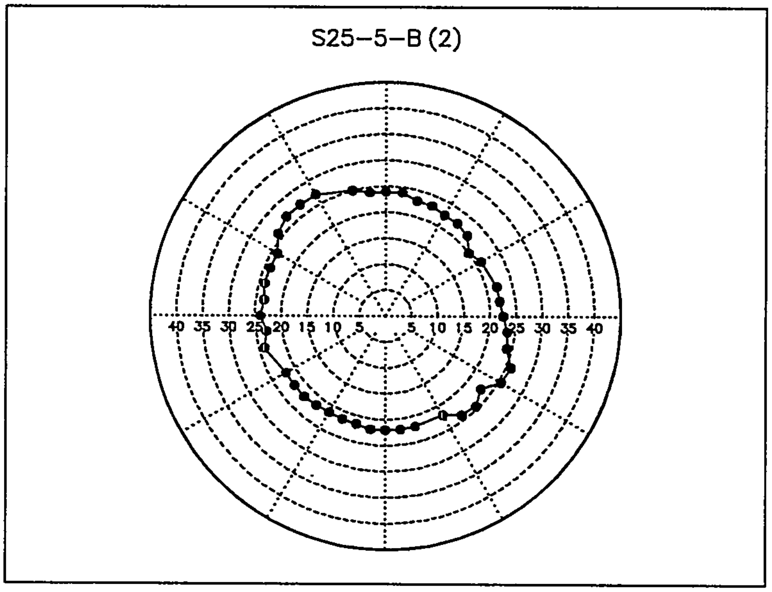

Figure B.7. Final Sludge Bank Profile for S25-5-B, $U_0D = 814\ cm^2/s$

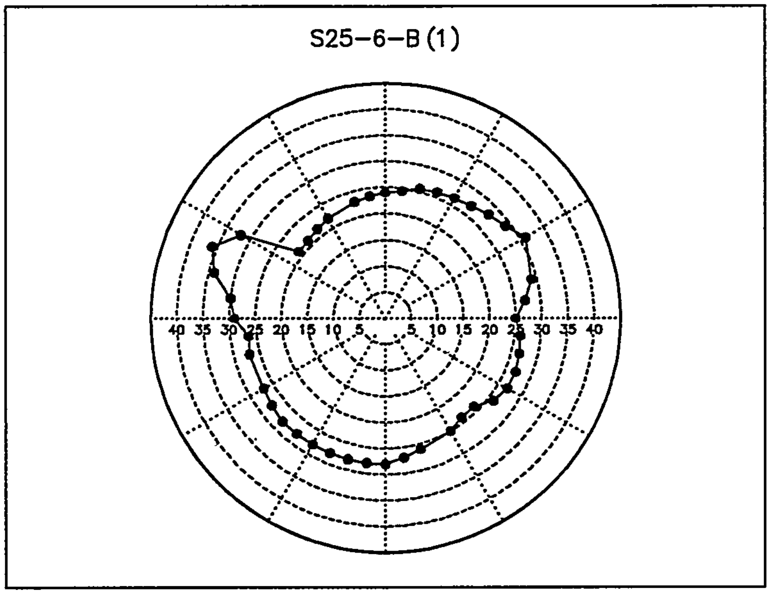

Figure B.8. Final Sludge Bank Profile for S25-6-B, $U_oD = 814\ cm^2/s$

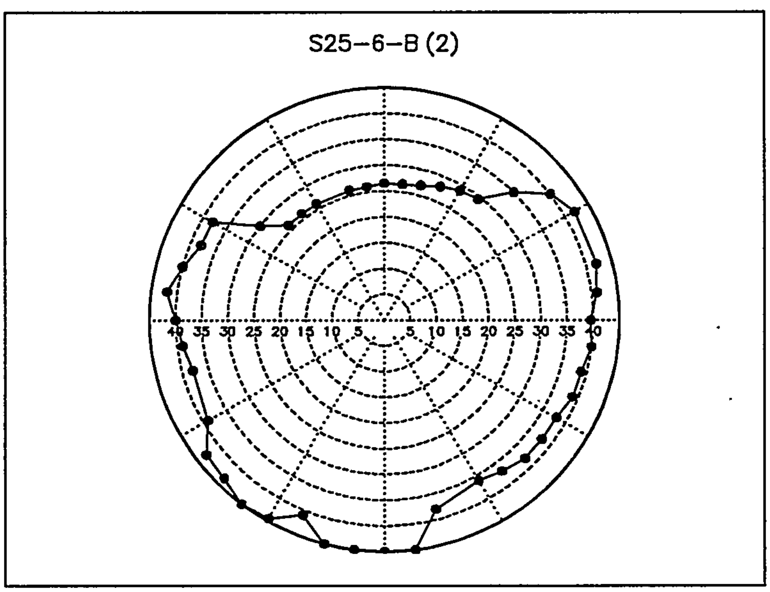

Figure B.9. Final Sludge Bank Profile for S25-6-B, $U_oD = 1153\ cm^2/s$

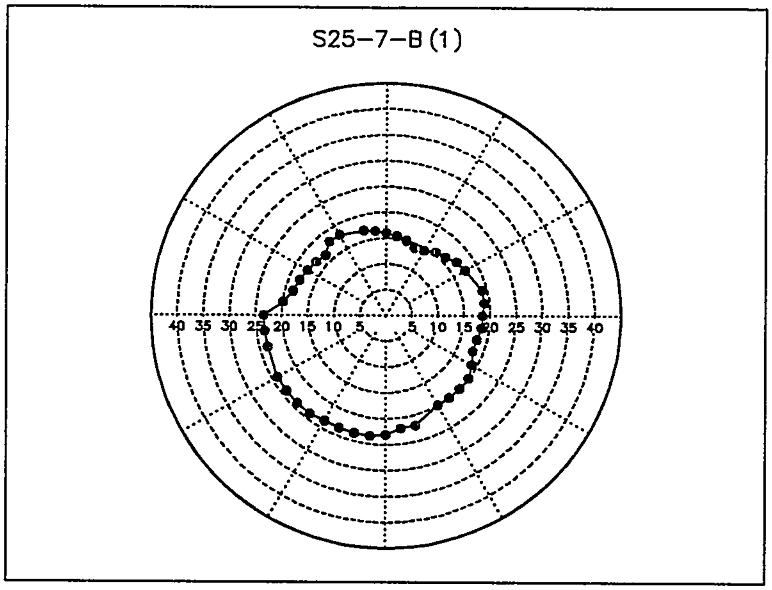

Figure B.10. Final Sludge Bank Profile for S25-7-B, $U_oD = 270\ cm^2/s$

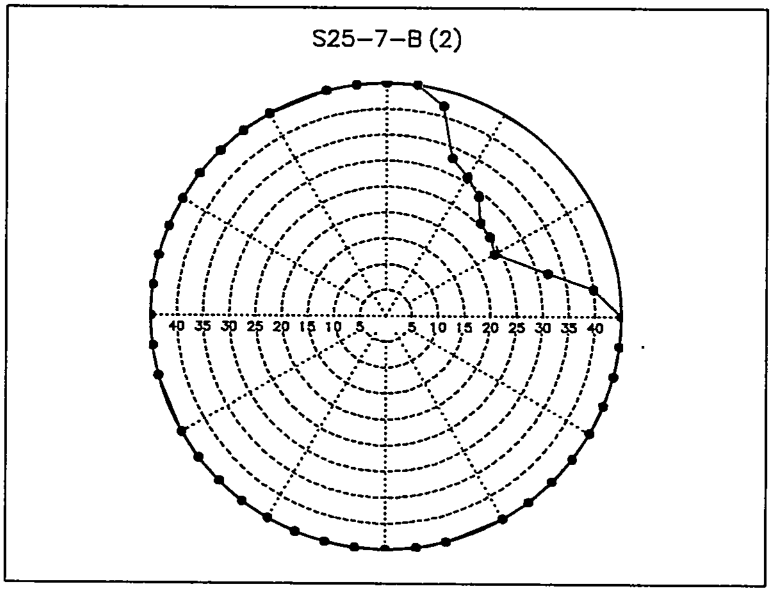

Figure B.11. Final Sludge Bank Profile for S25-7-B, $U_oD = 474\ cm^2/s$

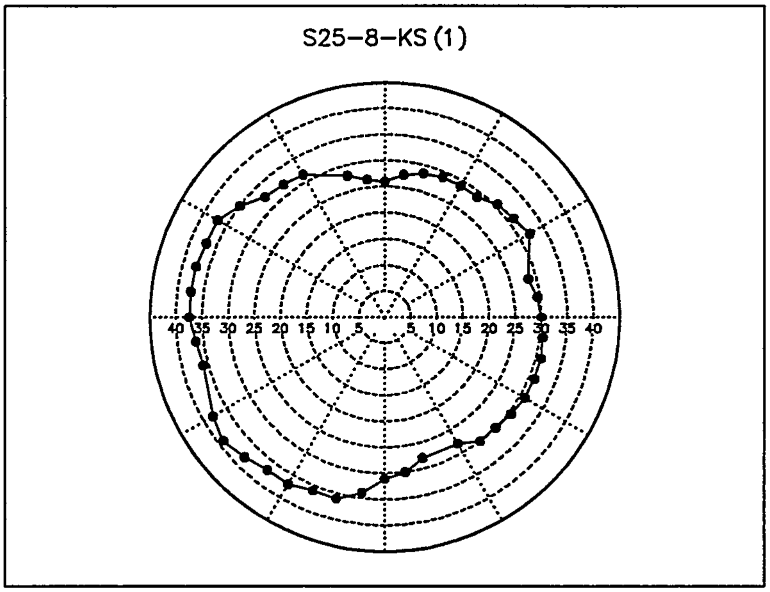

Figure B.12. Final Sludge Bank Profile for S25-8-KS, $U_oD = 474\ cm^2/s$

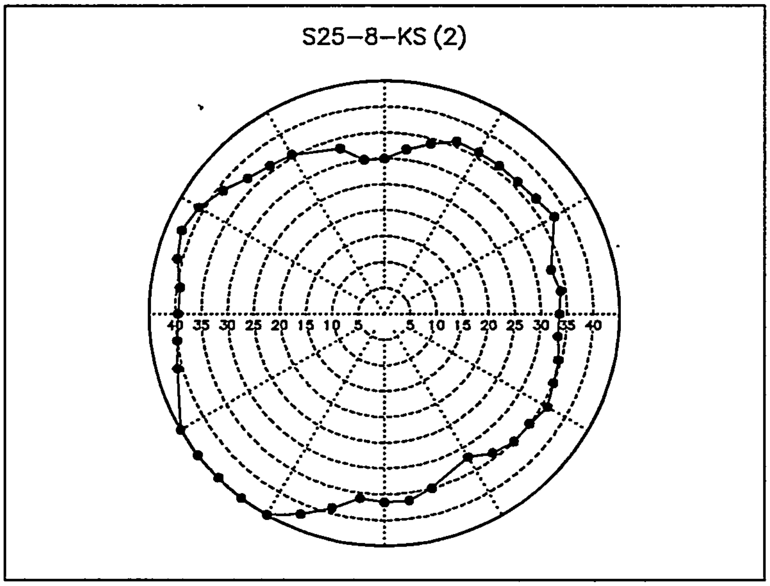

Figure B.13. Final Sludge Bank Profile for S25-8-KS, $U_oD = 576\ cm^2/s$

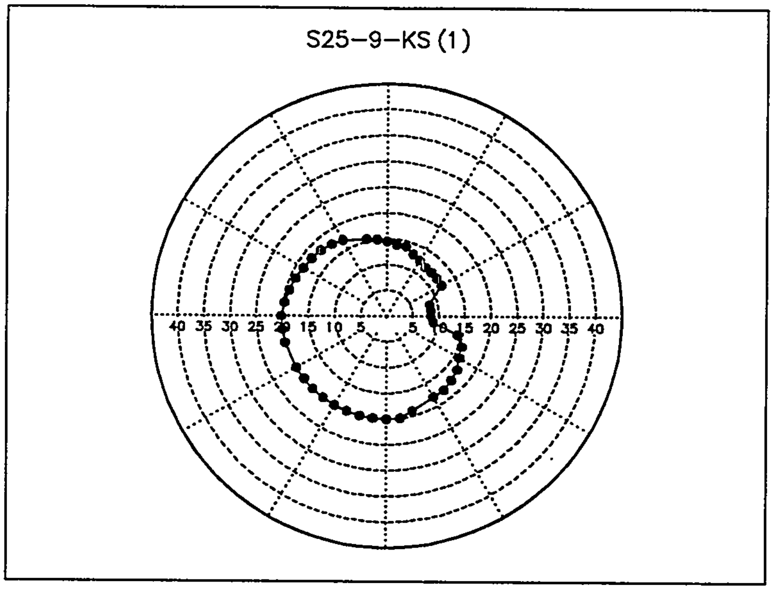

Figure B.14. Final Sludge Bank Profile for S25-9-KS, $U_0D = 304\ cm^2/s$

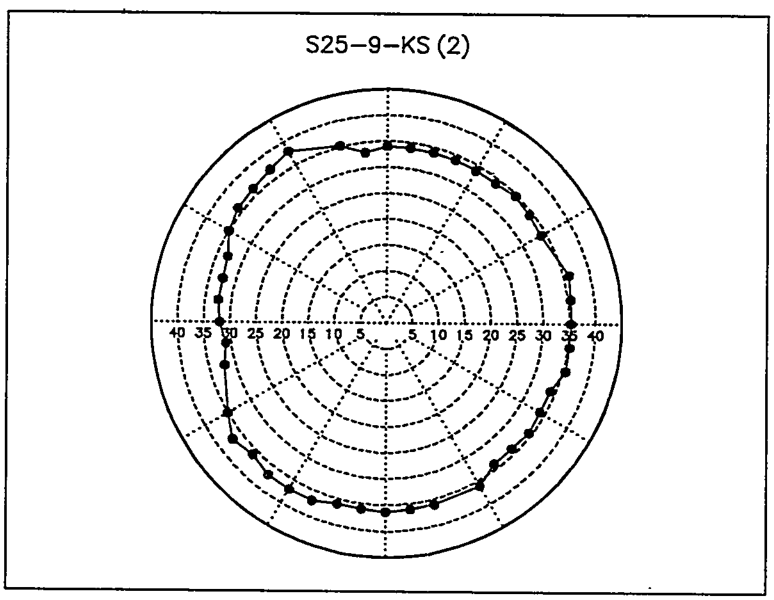

Figure B.15. Final Sludge Bank Profile for S25-9-KS, $U_0D = 576\ cm^2/s$

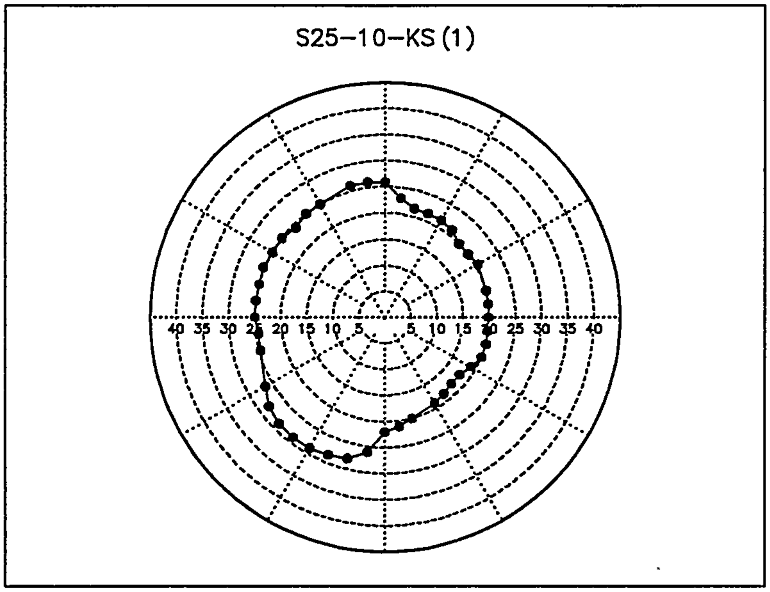

Figure B.16. Final Sludge Bank Profile for S25-10-KS, $U_oD = 406\ cm^2/s$

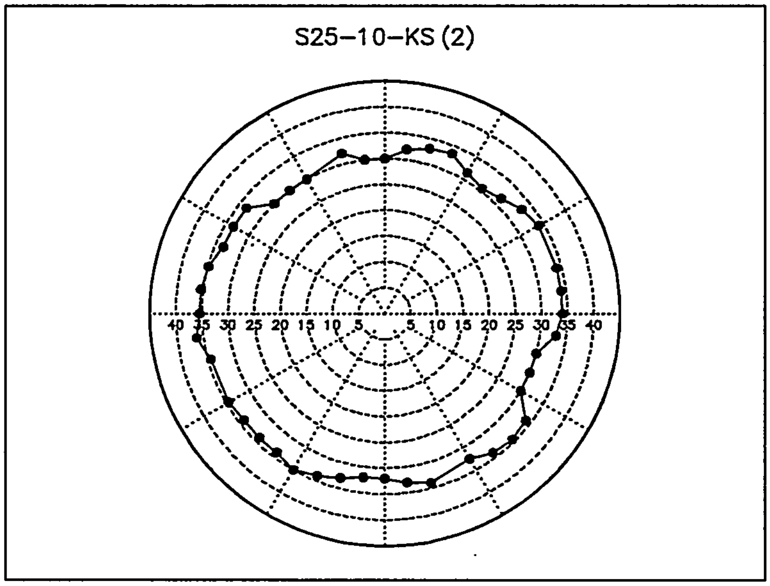

Figure B.17. Final Sludge Bank Profile for S25-10-KS, $U_oD = 610\ cm^2/s$

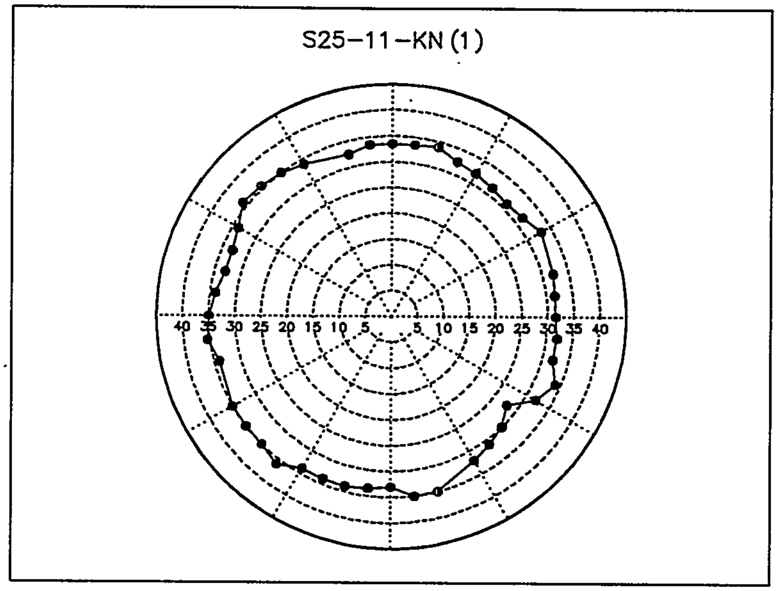

Figure B.18. Final Sludge Bank Profile for S25-11-KN, $U_0D = 406\ cm^2/s$

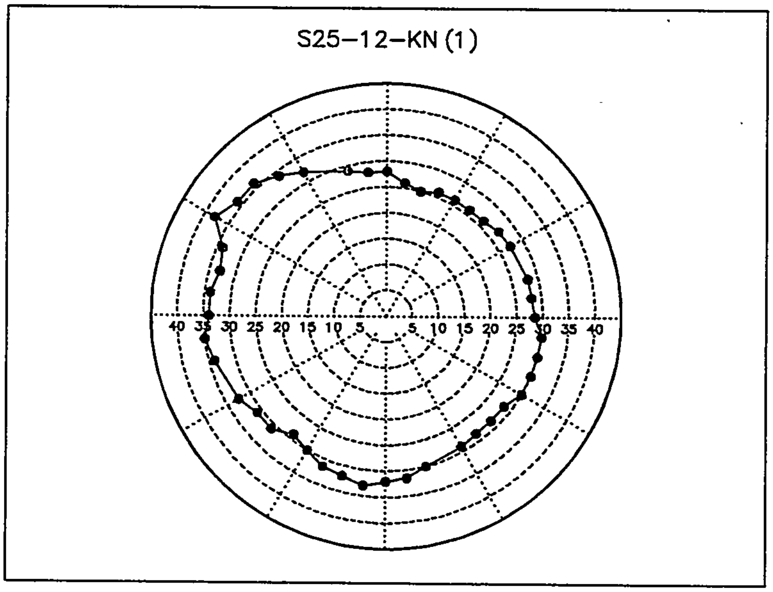

Figure B.19. Final Sludge Bank Profile for S25-12-KN, $U_0D = 406\ cm^2/s$

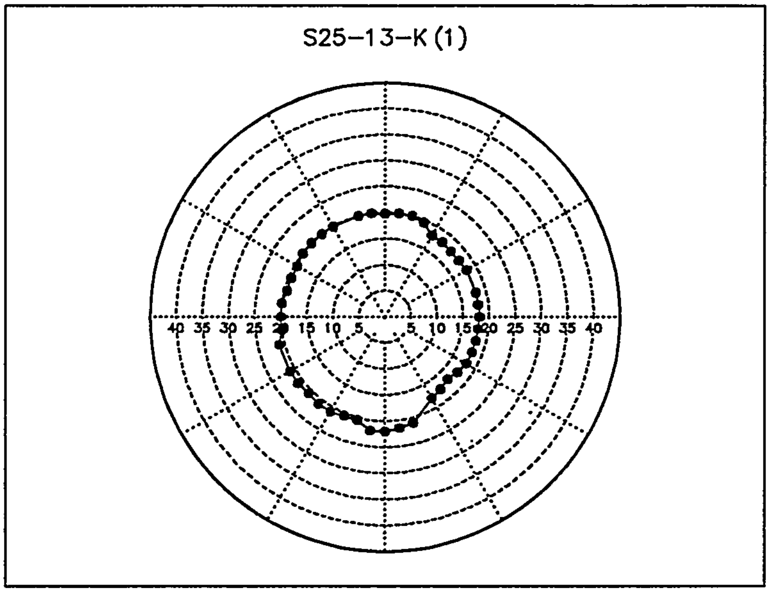

Figure B.20. Final Sludge Bank Profile for S25-13-K, $U_0D = 304\ cm^2/s$

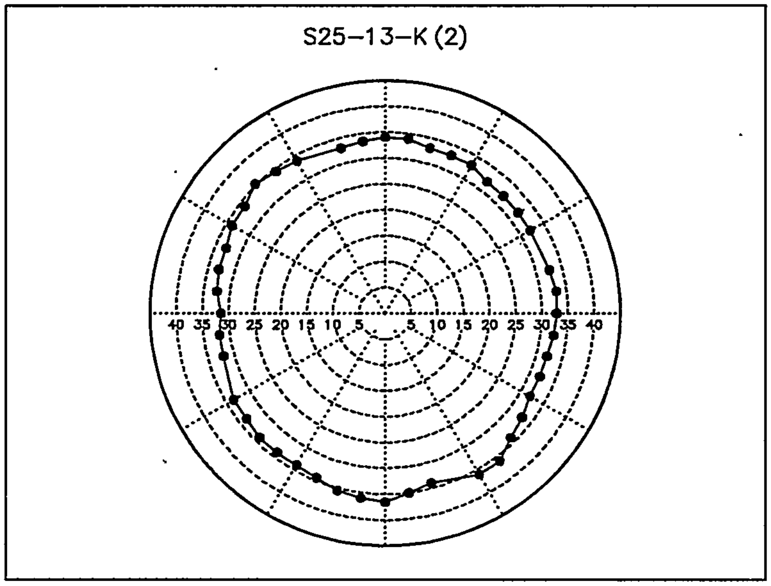

Figure B.21. Final Sludge Bank Profile for S25-13-K, $U_0D = 579\ cm^2/s$

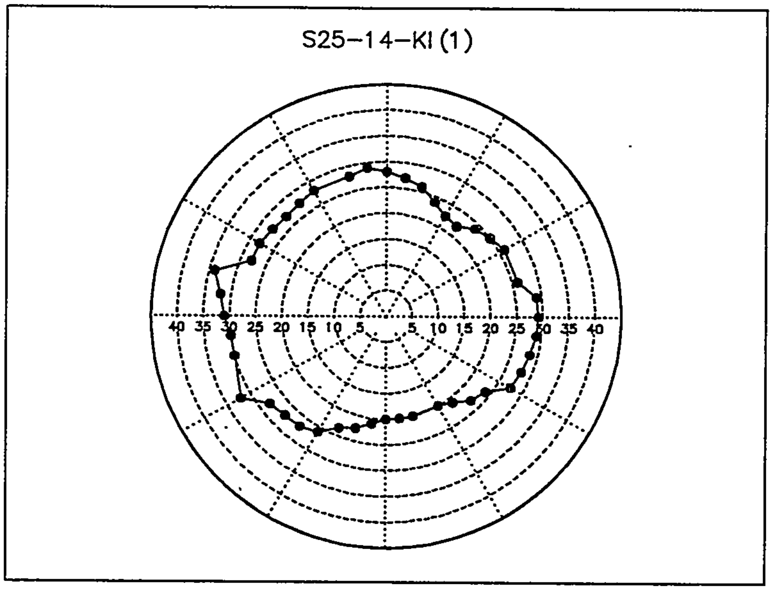

Figure B.22. Final Sludge Bank Profile for S25-14-KI, $U_0D = 406\ cm^2/s$

Test S25-14-KI involved the use of indexed pump column rotation. The sketch shown above was made after the sludge had been mobilized using the typical 180° oscillating jets.

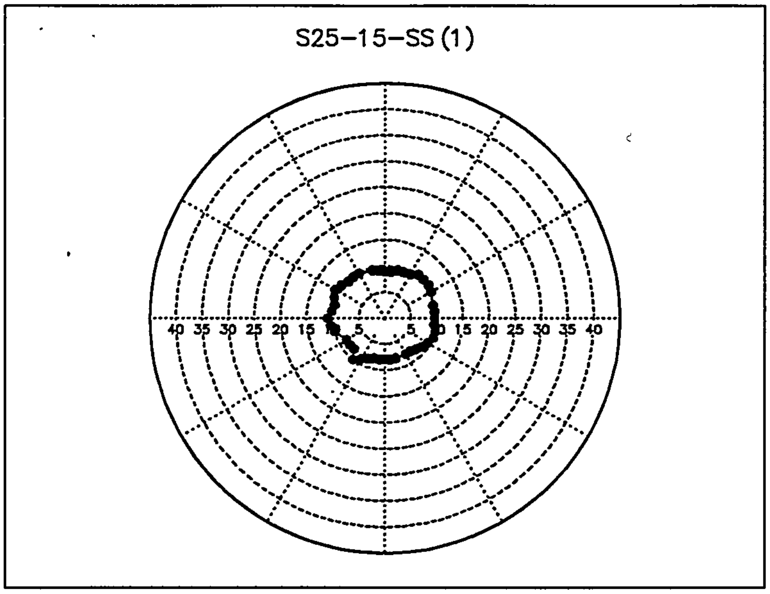

Figure B.23. Final Sludge Bank Profile for S25-15-SS, $U_oD = 437\ cm^2/s$

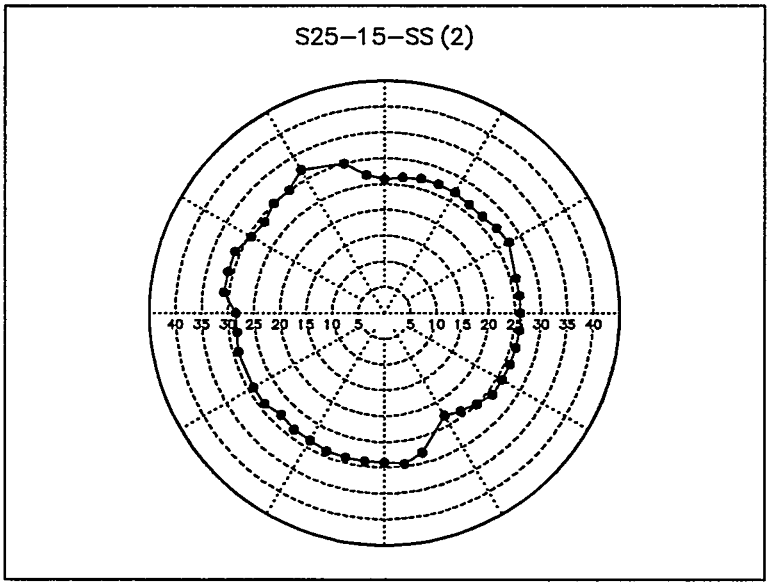

Figure B.24. Final Sludge Bank Profile for S25-15-SS, $U_oD = 836\ cm^2/s$

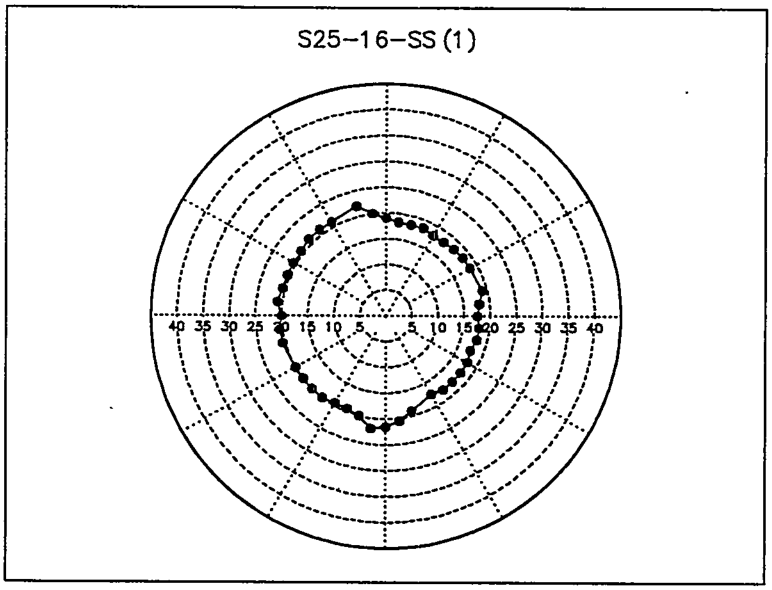

Figure B.25. Final Sludge Bank Profile for S25-16-SS, $U_oD = 547\ cm^2/s$

Appendix C

Photographs of 1/25-Scale Apparatus

Appendix C

Photographs of 1/25-Scale Apparatus

Photographs of the 1/25-scale test facility are given in Figures C.1 through C.4. Figure C.1 is a view of the entire 1/25-scale test facility. Figure C.2 shows the inside of the plexiglass tank and the base of the simulated mixer pump. The two, 2-hp centrifugal irrigation pumps, magnetic flowmeter, and associated piping are shown in Figure C.3. A closeup of the mixer pump nozzle and intake is given in Figure C.4.

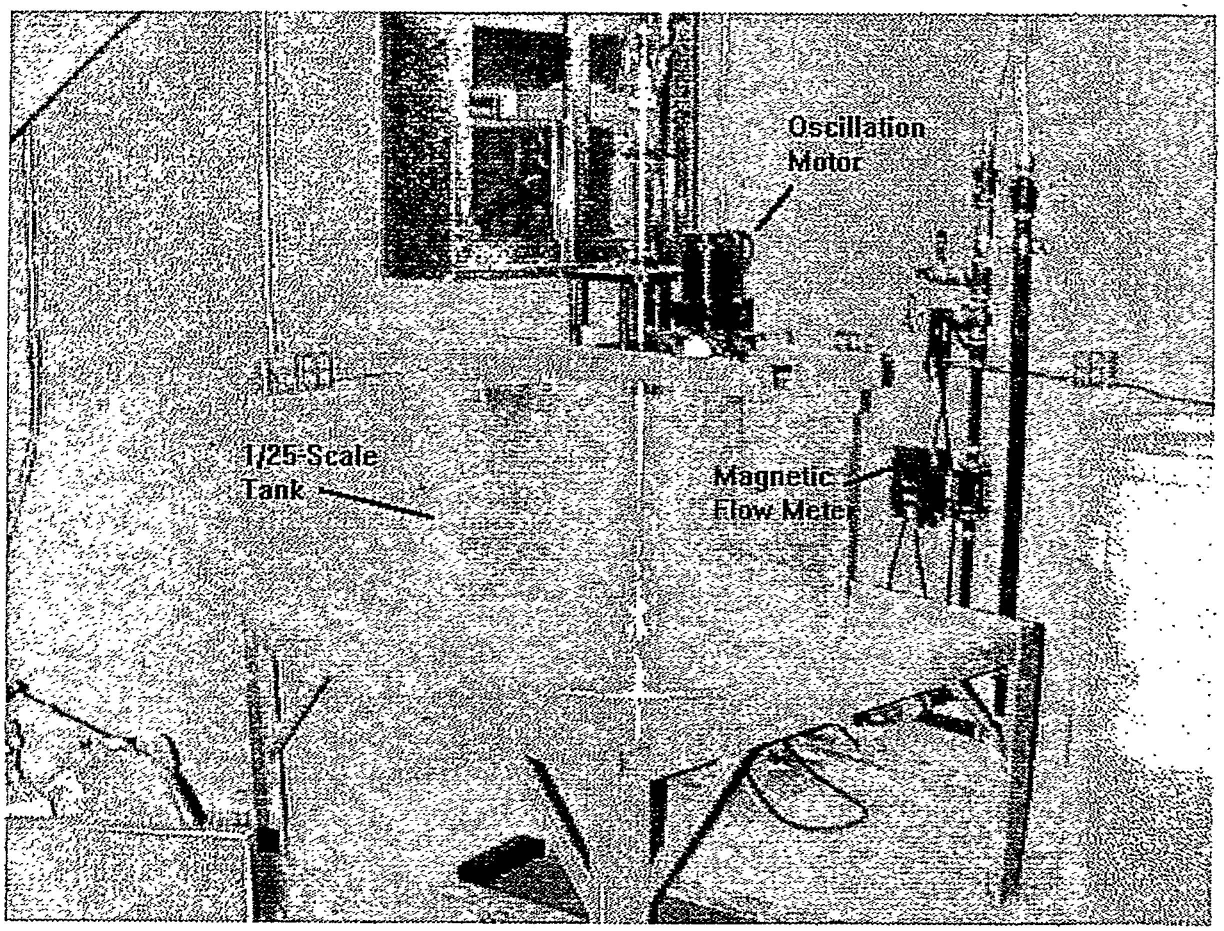

Figure C.1. Photograph of 1/25-Scale Tank and Support Equipment.

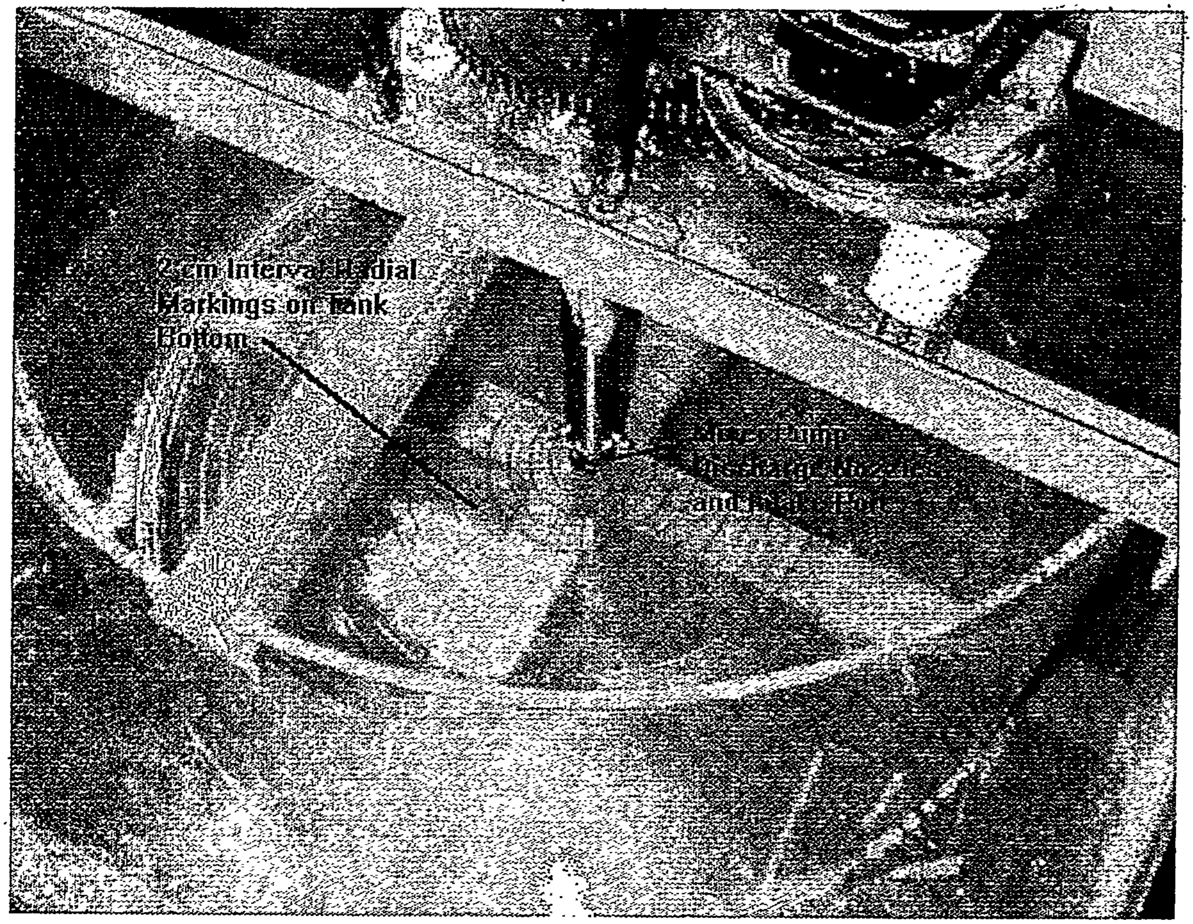

Figure C.2. Photograph of 1/25-Scale Tank and Mixer Pump.

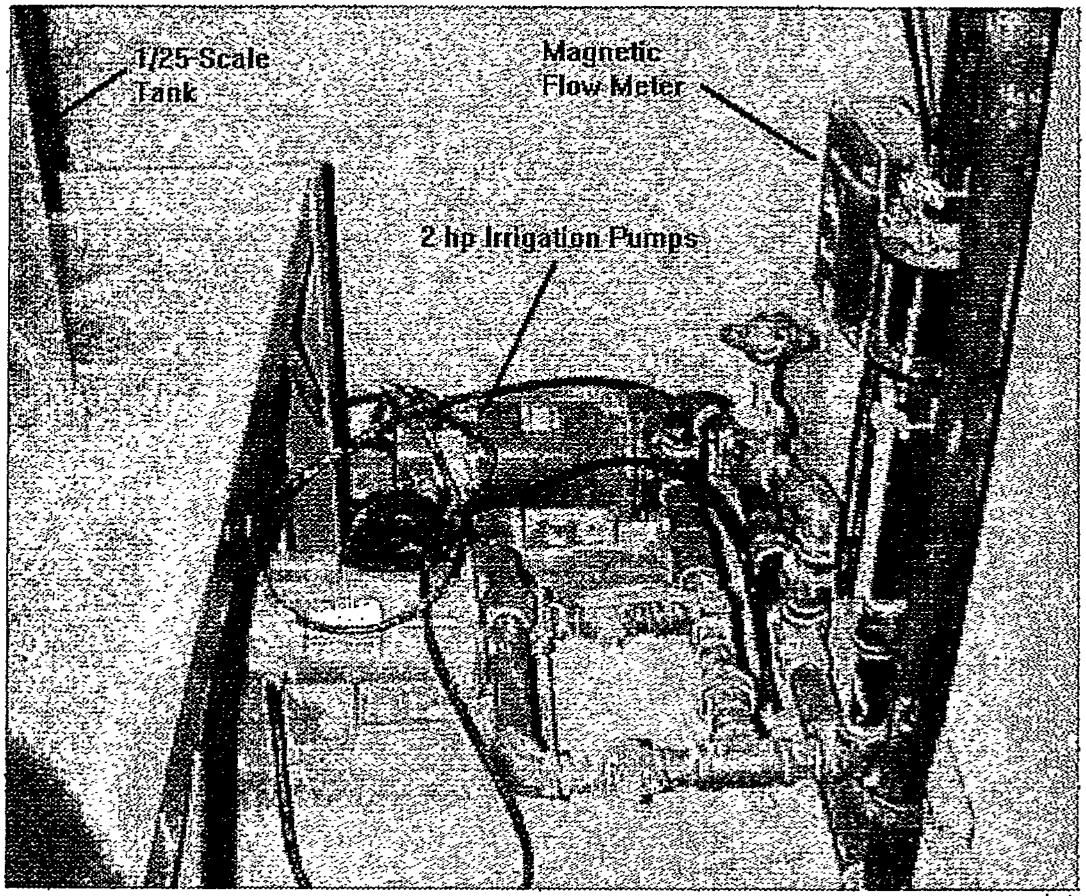

Figure C.3. 1/25-Scale Centrifugal Pumps and Flow Meter. 2 hp centrifugal irrigation pumps with brass impellers were used.

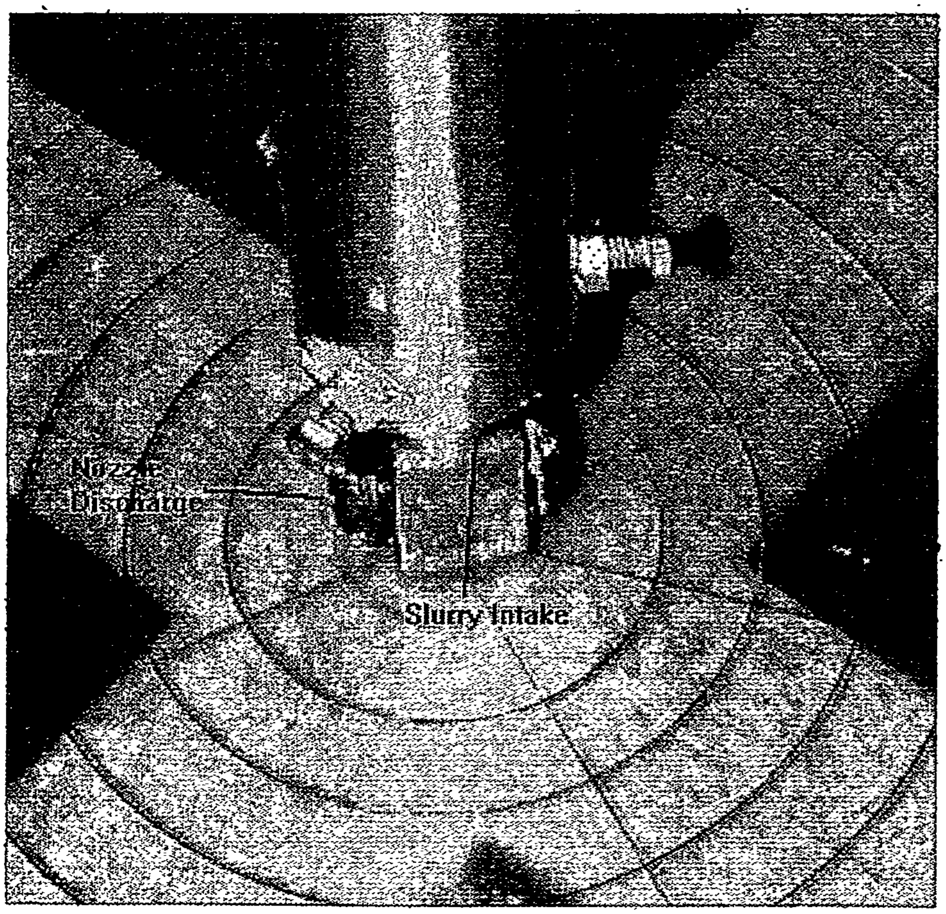

Figure C.4. View of 1/25-Scale Mixer Pump Nozzles and Intake

Appendix D

Description of Cohesive Erosion Model Computer Program

Appendix D

Derivation of Cohesive Erosion Model Predictive Equations

The erosion equation for cohesive soils is given by Parchure and Mehta (1985) as

$$E = M \left[\frac{\tau_w}{\tau_c} - 1 \right] \times u(\tau_w - \tau_c) \tag{D.1}$$

where
E = erosion rate, kg/m^2s
M = erodibility constant, kg/m^2s
τ_w = imposed wall stress on soil surface, N/m^2
τ_c = critical shear stress of soil, N/m^2
$u(\alpha)$ = unit step function, $u(\alpha) = 0$, for $\alpha < 0$
$u(\alpha) = 1$, for $\alpha \geq 0$

For a wall jet, $\tau_w|_{z=0}$ is obtained from a rough fit of data given in Figure 13-29 of Turbulent Jets, Rajaratnam 1976. The functional form shown is rather arbitrary, but it does match Rajaratnam's data over the range of interest:

$$\tau_w|_{z=0} = 0.02782\rho_{slurry} \left[\frac{U_o D}{x} \right]^2 \left[8.5 \left[1 - \exp\left[\frac{1.1284\frac{x}{D} + 12}{-17} \right] \right] - 2 \right] \tag{D.2}$$

where
$\tau_w|_{z=0}$ = shear stress on the wall at some axial position (x) along the z=0 plane (see below)
ρ_{slurry} = slurry density, kg/m^3
U_o = nozzle exit velocity, m/s
D = nozzle inside diameter, m
x = axial position, m
z = direction normal to nozzle axis and parallel to wall, m

The coordinate system is shown in Figure D.1.

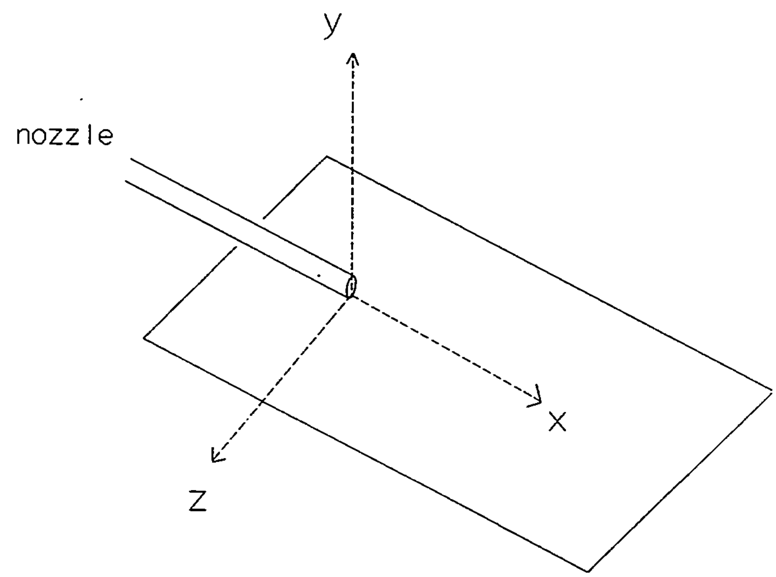

Figure D.1. Coordinate System Definition

Figure 13-32 of Rajaratnam (1976) presents data which give the variation of τ_w with z (in Figure 13-32) as:

$$\frac{\tau_w|_z}{\tau_w|_{z=0}} = \exp\left[-63.63\left(\frac{z}{x}\right)^2\right] \tag{D.3}$$

Combining this equation with the correlation for $\tau_w|_{z=0}$ gives equation D.4

$$\tau_w(x,z) = 0.02782\rho_{slurry}\left[\frac{U_oD}{x}\right]^2\left(8.5\left[1-\exp\left(\frac{1.1284x/D+12}{-17}\right)\right]-2\right)\left[\exp\left[-63.63\left(\frac{z}{x}\right)^2\right]\right] \tag{D.4}$$

The effect of slurry viscosity has not been included, but at large Reynolds numbers the behavior of a turbulent jet is largely independent of viscosity. The equation for τ_w given above was determined using data for submerged water jets.

The equation for drag force on a flat plate exposed to a turbulent boundary layer gives $\tau_w \propto \mu^{0.2}$ (Bird et al. 1960). A factor of 3.0 increase in μ results in a 25% increase in τ_w. This might be the case but more investigation would be worthwhile. The behavior of turbulent wall jets has been shown to be independent of Reynolds number (provided that Re is sufficiently high).

The variation of τ_w as the fluid jet encounters and is redirected by the eroding sludge bank is difficult to determine. Therefore, it is assumed that the shear stress acting on a particular portion of sludge area is about equal to the τ_w that the floor would experience if the sludge were absent. Note that the magnitude of τ_w has been taken to be a function of only x and z. Variations of τ_w with the height of the sludge bank have been neglected.

Because no erosion takes place in the areas of the sludge bank where $\tau_w < \tau_c$, there exists a limited region (shaded in the diagram below) where erosion can take place (i.e., $\tau_w > \tau_c$ in this region). The distances marked z_c are a measure of the breadth of the erosion region.

z_c is calculated by finding the z at which $\tau_w = \tau_c$ at the x of interest. Setting Equation (D.4) given above equal to τ_c and solving for z gives

$$z_c = x\left[\frac{1}{63.63}\ln\left[\frac{\rho_{slurry}U_o^2\left[8.5\left[1-\exp\left[\frac{1.1284(x/D)+12}{-17}\right]\right]-2\right]}{35.945\tau_c(x/D)^2}\right]\right]^{\frac{1}{2}} \quad \text{(D.5)}$$

Next the average erosion rate over the arc of the sludge bank encompassed by $-z_c \le z \le z_c$ is estimated (see Figure D.2). Neglecting the curvature of the sludge bank, E_{avg} is given by:

$$E_{avg}(x) = \frac{1}{2z_c}\int_{-z_c}^{z_c}E(x,z)dz = \frac{1}{z_c}\int_0^{z_c}E(x,z)dz \quad \text{(D.6)}$$

where E_{avg} is the average rate of material removal over the area of the sludge bank where $\tau_w > \tau_c$. In order to compute the overall erosion rate, the E_{avg}

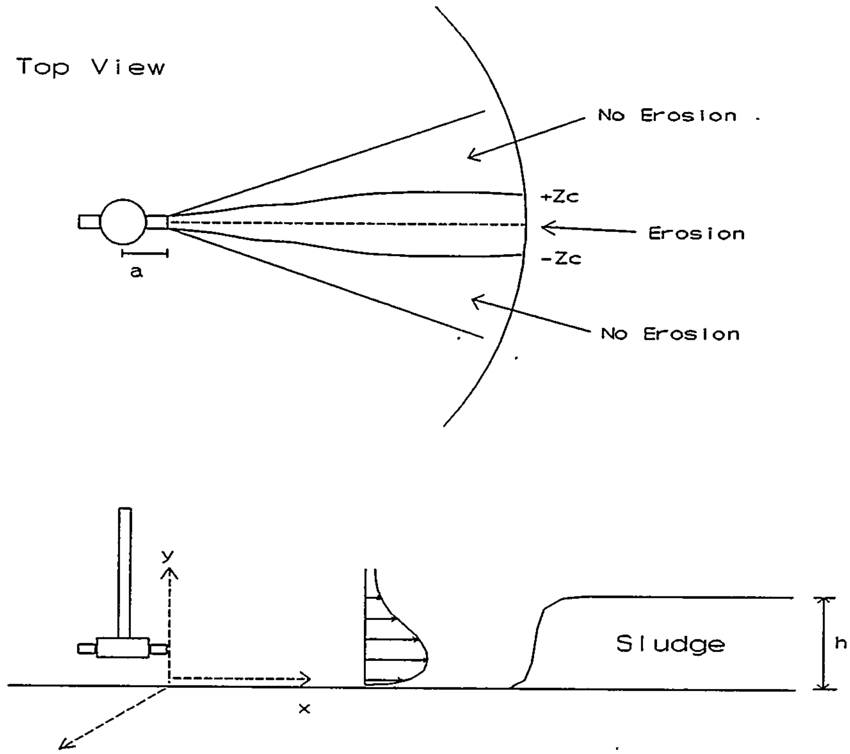

Figure D.2. Erosion Zone Defined by z_c

value given in Equation (D.6) must be multiplied by the ratio of the area of eroding sludge to the total available sludge bank area.

The angle of the arc of sludge undergoing erosion is given approximately by

$$\theta = 2\tan^{-1}\left[\frac{z_c}{x+a}\right] \tag{D.7}$$

where 'a' is the distance between the mixer pump centerline and the nozzle exit (see Figure D.2). x is the distance between the nozzle and the sludge bank.

The fraction of eroding sludge is then given by

$$\frac{2}{\pi}\tan^{-1}\left[\frac{z_c}{x+a}\right] \tag{D.8}$$

assuming two diametrically opposed nozzles per mixer pump.

The instantaneous erosion rate of material (in kg/s) throughout the tank is given by

$$(2\pi(x+a)h)\frac{2}{\pi}\tan^{-1}\left[\frac{z_c}{x+a}\right]E_{avg} \tag{D.9}$$

where 'h' is the height of the sludge bank.

The ECR (equal to x) at any time (t) is given by

$$ECR = x = \int_0^t (2\pi(x+a)h)\frac{2}{\pi}\tan^{-1}\left[\frac{z_c}{x+a}\right]\frac{E_{avg}}{\rho_{sludge}}\cdot\frac{dt}{2\pi(x+a)h} \tag{D.10}$$

which simplifies to

$$ECR = \frac{2}{\pi\rho_{sludge}}\int_0^t \tan^{-1}\left[\frac{z_c}{x+a}\right]E_{avg}\,dt \tag{D.11}$$

A value for E_{avg} is obtained by:

$$E_{avg} = \frac{1}{z_c}\int_0^{z_c}\frac{M}{\tau_c}(\tau_w-\tau_c)dz = -M+\frac{M}{z_c\tau_c}\int_0^{z_c}\tau_w\,dz \tag{D.12}$$

where (from equation D.2),

$$\int_0^{z_c}\tau_w dz = 0.02782\rho_{slurry}\left[\frac{U_0D}{x}\right]^2\left[8.5\left[1-\exp\left[\frac{1.1284(x/D)+12}{-17}\right]\right]-2\right]\int_0^{z_c}\exp\left[-63.63\left[\frac{z}{x}\right]^2\right]dz$$

(D.13)

where

$$\int_0^{z_c}\exp\left[-63.63\left[\frac{z}{x}\right]^2\right]dz \approx \sum_{i=0}^{\infty}\left[z_c^{2i+1}\exp(gz_c^2)(-g)^i\frac{2^i}{\prod_{j=1,odd}^{2i+1} j}\right] \qquad (D.14)$$

where $g = -63.63/x^2$.

About 10 terms of the sum provide sufficient accuracy for calculations.

References

Bird, R. B., W. E. Stewart, and E. N. Lightfoot. 1960. *Transport Phenomena*. John Wiley & Sons, New York.

Parchure, Trimbak M., and Ashish J. Mehta. 1985. "Erosion of Soft Cohesive Sediment Deposits." *J. of Hydraulic Engineering*, 111(10):1308-1326.

Rajaratnam, N. 1976. *Turbulent Jets*. Elsevier Scientific Publishing Co., New York

Computer Code to Implement Equations D.12 through D.14

The following computer program was used to determine the erodibility (M) and critical shear stress (τ_c) for each of the 1/25-scale tests. This program runs in Microsoft Quick C. The experimental data are obtained from a file called "input.dat" which contains two columns. The first column is time in minutes and the second column is ECR in meters. The user is prompted for all other input data. The output M and τ_c values are contained in "output.fil".

```
/*  This program will simulate the growth of the ECR in a DST based
    on the input specification of the pump and the sludge properties.
    Sludge properties are specified in terms of the sludge erodibility
    (M) and the sludge critical shear stress (tc).  These two parameters */
/*  are used in soil science to describe the erosion of cohesive soils
        -- Mike Powell  3A256  376-2334  9/14/93

/* ***************************************************************
        Begin Program
  ****************************************************************/

/*  get necessary libraries */
  #include <stdio.h>
  #include <float.h>
  #include <math.h>

/*  Define variable types  */

  int i,j,k,cnt,zz,capture,ii,jj,kk,numdata,middl,done[4][4],ch;
  int capture2;
  float m,tc,x,z,tf,psld,psn,pslr,u0,d,t,ecr,sum,tw[27],a,zc,eavg,decr;
  float tmin,ts,g,gg,prod,twmax,tuo[10],ttm[10],tdat[100],edat[100];
  float resids[4][4],mmat[4],tcmat[4],mins,mnew,mold,tcold;
  float tcnew,macc,tcacc,vsn,vsldg,rtank;

/*  DEFINITION OF SELECTED VARIABLES  */

/*   i,j,k,ii,jj,kk :  counter integers
    cnt : counter used to count the iterations between result outputs
    zz, capture, capture2, ch : dummy variables/counters
    numdata:  the number of data points in the file input.dat
    done[4][4]:  array which keeps track of which M and tc combinations
      have been evaluated, 1==yes, 0==no.
    middl: dummy variable which determines how convergence has been reached
    m:  sludge erodibility, units of kg/m2s
    tc:  sludge critical shear stress, units of Pascals
    x: axial position, distance from nozzle exit, meters
    z: direction perpendicular to x-dirn and parallel to tank floor, meters
```

tf: time at which to terminate calculations, entered as minutes but immediately converted to seconds
psld: sludge density, kg/m3
pslr: slurry density, kg/m3
psn: supernate density, kg/m3
u0: average nozzle exit velocity, m/s
d: inside diameter of nozzle, meters
t: cumulative mobilization time, seconds
ecr: effective cleaning radius (equal to x), meters
sum: dummy variable used to evaluate integrals, etc.
tw[27]: vector of wall stress values, no longer used
a: distance between pump centerline and nozzle exit, meters
zc: critical z distance, that is, the value of z where tw falls below tc, zc is in meters
eavg: average erosion rate, kg/m2s
decr: rate of ecr growth, meters per second
tmin: cumulative mobilization time in minutes
ts: time step used in calculations, seconds
g: dummy variable
gg: dummy variable
prod: dummy variable
twmax: wall stress evaluated at z=0 and x=x, kg/ms2
tuo[]: vector of u0 values, used to step up u0, m/s
ttm[]: vector of times at which corresponding u0's occur, seconds
tdat[]: vector of input data times, seconds (input as minutes)
edat[]: vector of input ecr values, meters
resids[][]: matrix of sum of square residuals determined by the various fits using the M's and tc's in mmat[] and tcmant[]
mmat[]: vector of erodibilities to try during optimization loop
tcmat[]: vector of tc values to try during optimization loop
mins: dummy variable
mnew: new M value determined by optimization loop
mold: previous M value used by optimization loop
tcnew: new tc value determined by optimization loop
tcold: previous tc value used by optimization loop
rtank: tank radius, meters
vsldg: sludge volume (initial) m3
vsn: supernate volume (initial) m3
psld: sludge density kg/m3
psn: supernate density kg/m3
macc: percentage by which to vary M during optimization
tcacc: percentage by which to vary tc during optimization */

```
main ()
 {
 FILE  *fp,*fp2,*fp3;


  /*  set initial values and constants  */

    rtank=0.45;
    t = 0.;
    cnt=0;
    mold=-1.;
    tcold=-1.;
    middl=0;

  /*  Get input parameters from the keyboard  */

    printf("\n\n");
    printf("  Enter erodibility constant M (kg/m2s) = ");
    scanf("%f",&m);
    printf("  Enter critical shear stress Tc (kg/ms2) = ");
    scanf("%f",&tc);
    m=m/tc;
    printf("  Enter Uo (m/s) = ");
    scanf("%f",&u0);
    printf("  Do you want Uo to change? (1=y/0=n)  ");
    scanf("%d",&ch);
    printf(" \n");
    if(ch==1) {
   printf("  How many more Uo's?  ");
   scanf("%d",&i);
   printf(" \n");
   for (j=1;j<i+1;j++) {
     printf("  Enter Uo, begin time:  ");
     scanf("%f,%f",&tuo[j],&ttm[j]);
     ttm[j]=ttm[j]*60.;
     }
   }
   tuo[0]=u0;
   ttm[0]=0.;
   ttm[i+1]=5.0e8;
    printf("  \n");
    printf("  Enter D (m) = ");
    scanf("%f",&d);

    /*  assuming that potential core very quickly removes sludge,
      ECR will instantly grow to about 8.0*d, therefore...  */
    x=8.0*d;
```

```
printf("  Enter end time (minutes):  ");
scanf("%f",&tf);
tf=tf*60.;
printf("  Enter time step for calculations (min):  ");
scanf("%f",&ts);
ts=ts*2;
printf("  Enter distance between nozzle exit and pump CL (m):  ");
scanf("%f",&a);
printf("  Enter % to vary M by in search:  ");
scanf("%f",&macc);
printf("  Enter % to vary Tc by in search:  ");
scanf("%f",&tcacc);
printf("  Enter Sludge Density (kg/m3):  ");
scanf("%f",&psld);
printf("  Enter Supernate Density (kg/m3):  ");
scanf("%f",&psn);
printf("  Enter Sludge volume (m3):  ");
scanf("%f",&vsldg);
printf("  Enter Supernate volume (m3):  ");
scanf("%f",&vsn);
printf("\n\n");
capture=0;
capture2=0;

zz = 1;

/*  Get input data set to optimize M and tc on  */
/*  The input data file must be called input.dat and be located
  in the current default directory.  There must be two columns
  of data, Time (minutes) in the first column and ECR (meters)
  in the second column.  The two values should be separated by
  a blank space.  */
/*  The last line in the file input.dat should have time equal to
  -1.0 and ECR equal to any number.  */

if ((fp2=fopen("c:\input.dat","r"))!=NULL) {
/* read in vectors of input data */
/* make sure that last line in input.dat is -1.0 */

i=1;
tdat[0]=0;
edat[0]=a;
while (tdat[i-1]!=-60.) {
  fscanf( fp2, "%f %f \n", &tdat[i],&edat[i]);
  tdat[i]=tdat[i]*60.;
  i=i+1;
  }
/*  once here, all data has been read */
```

```
  fclose(fp2);
  }
  numdata=i-2;
  /*  numdata equal the number of points in the data set */
  /*  print out the data set in full  */
  for (i=1;i<numdata+1;i++) {
   printf(" T = %f , ECR = %f \n",tdat[i],edat[i]);
   }
  for (i=1;i<4;i++) {
   for (j=1;j<4;j++) {
    done[i][j]=0;
    }
   }

  capture=0;


while ((capture!=1)&&(capture2!=2)) {

  /* generate matrix of M's and tc's to try first  */
  mmat[1]=(100.-macc)*m/100.;
  mmat[2]=m;
  mmat[3]=(100.+macc)*m/100.;
  tcmat[1]=(100-tcacc)*tc/100.;
  tcmat[2]=tc;
  tcmat[3]=(100+tcacc)*tc/100.;
  for (ii=1;ii<4;ii++) {
  printf(" mmat[%d] = %f , tcmat[%d] = %f \n",
    ii,mmat[ii],ii,tcmat[ii]);
  }

for (ii=1;ii<4;ii++) {
  for (jj=1;jj<4;jj++) {
 /*  if done[ii][jj]==1 then this combination of m and tc has
     already been tried  */
 if (done[ii][jj]!=1) {
 u0=tuo[0];
 m=mmat[ii];
 tc=tcmat[jj];
 kk=1;
 resids[ii][jj]=0.;
 zz=1;
 t=0.;
 x=8.*d;
 cnt=0;
 if ((m>12)&&(ts>30)) ts=30.;
 if ((m>25)&&(ts>2)) ts=2.;
```

```
/* ECRDAT.ASC is the name of the output file */
if ((fp=fopen("c:\ecrdat.asc","w"))!= NULL) {

fprintf(fp," m = %f , tc = %f \n",m,tc);
fprintf(fp," ii = %d , jj = %d \n",ii,jj);

/* begin loop of numerical integration for the current
 combination of m and tc      */


while (t<tf+1) {

/* check to see if u0 has been changed to a new value */
if ( t >= ttm[zz] ) {
  u0 = tuo[zz];
  zz=zz+1;
  }
/* compute slurry density */

 gg = pow((x+a)/rtank, 2);
 pslr = (vsn*psn+vsldg*psld*gg)/(vsn+vsldg*gg);


/* compute zc */
 sum = (-1./63.63)*log((tc*35.945*x*x/(d*d))/(pslr*u0*u0
     *(8.5*(1.-exp((1.1284*x/d+12.)/(-17.)))-2.)));
 zc = x*pow(sum,0.5);
 twmax = 0.02782*pslr*u0*u0*d*d/(x*x)*(8.5*(1.-exp((1.1284*
        x/d+12.)/(-17.)))-2.);

/* compute integral of tw from 0 to zc using the first 15 terms
   of an infinite series */
   sum = 0.;
   g = -63.63/(x*x);
   for (i=0;i<16;i++) {
      j = 1;
      prod = 1.;
      while (j<2*i+2) {
     prod = prod * j;
     j = j + 2;
      }
      sum = sum + pow(zc,2*i+1)*exp(g*zc*zc)*pow(g,i)*pow(-1.,i)
         * pow(2.0,i) / prod;

   }
```

```
/* compute eavg  */

   eavg = -m+(m/(zc*tc)) * 0.02782*pslr*(u0*d/x)*(u0*d/x)*
     (8.5*(1.-exp((1.1284*x/d+12.)/(-17.)))-2.) * sum;


/* compute decr/dt  */
   sum=zc/(x+a);
   decr=(0.6366)*atan(sum)*eavg/psld;

/* Increment ecr and time */
   x = x + decr*ts;
   t = t + ts;
   cnt = cnt + 1;

/* add residual to current residual position */
    if (t==tdat[kk]) {
      resids[ii][jj]=resids[ii][jj]+pow((x-edat[kk]),2);
      tmin=t/60.;
      printf(" Match: Time= %f, Predicted= %f, Measured= %f \n",
           tmin,x,edat[kk]);
      kk=kk+1;
      }

/* print out results if at an increment of .5*ts minutes */
    if (cnt==30) {
    tmin=t/60.;
    printf("   Time = %f , ECR = %f , Tw max = %f \n",tmin,
          x,twmax);
    printf("   tc = %f , M = %f \n",tc,m);
    printf("   ii = %d , jj = %d , pslr = %f \n",ii,jj,pslr);
    printf("\n");
/*    if (capture2==1) { */
      if (1==1) {
      fprintf(fp,"  %f   %f \n",tmin,x); }
    cnt=0;
    }
}

fclose(fp);

 }
/* once gets here, has completed current iteration */
 } /* end of if on done matrix */
} /* end of for jj loop */
} /* end of for ii loop */

/* once gets here has completed current resids matrix */
```

```
/* time to compute minimum m and tc combo then try again */

mins=resids[1][1];
i=1;
j=1;

for (ii=1;ii<4;ii++){
for (jj=1;jj<4;jj++) {
 printf(" resids[%d][%d] = %f \n",ii,jj,resids[ii][jj]);
 if (resids[ii][jj]<mins) {
  i=ii;
  j=jj;
  mins=resids[i][j];
 }
}
}
/*  at this point, mmat[i] and tcmat[j] give least sum of squares
 residuals  */
mnew=mmat[i];
tcnew=tcmat[j];
printf(" i = %d , j = %d \n",i,j);
if ((mnew==mold)&&(tcnew==tcold)) capture=1;
if ((mnew==mmat[2])&&(tcnew==tcmat[2])) {
capture=1;
middl=1;
}
mold=m;
tcold=tc;
m=mnew;
tc=tcnew;
/* clear done matrix in preparation for next set of iterations */
for (ii=1;ii<4;ii++) {
for (jj=1;jj<4;jj++) {
 done[ii][jj]=0;
 }
}

/*  Now put 1's into the positions of the new done matrix that
 have already been tried.  This prevents the program from
 re-running any particular m and tc combination  */

if ((i==1)&&(j==1)) {
done[2][3]=1;
done[2][2]=1;
done[3][2]=1;
done[3][3]=1;
resids[2][3]=resids[1][2];
resids[3][2]=resids[2][1];
```

```
resids[3][3]=resids[2][2];
resids[2][2]=resids[1][1];
}
 if ((i==1)&&(j==2)) {
for (ii=3;ii>0;ii--) {
  done[2][ii]=1;
  done[3][ii]=1;
  resids[3][ii]=resids[2][ii];
  resids[2][ii]=resids[1][ii];
  }
  }
 if ((i==1)&&(j==3)) {
done[2][1]=1;
done[2][2]=1;
done[3][1]=1;
done[3][2]=1;
resids[2][1]=resids[1][2];
resids[3][1]=resids[2][2];
resids[3][2]=resids[2][3];
resids[2][2]=resids[1][3];
}
 if ((i==2)&&(j==1)) {
for (ii=1;ii<4;ii++) {
  done[ii][2]=1;
  done[ii][3]=1;
  resids[ii][3]=resids[ii][2];
  resids[ii][2]=resids[ii][1];
  }}
 if ((i==2)&&(j==3)) {
for (ii=1;ii<4;ii++) {
  done[ii][1]=1;
  done[ii][2]=1;
  resids[ii][1]=resids[ii][2];
  resids[ii][2]=resids[ii][3];
  }}
 if ((i==3)&&(j==1)) {
done[1][2]=1;
done[1][3]=1;
done[2][2]=1;
done[2][3]=1;
resids[1][2]=resids[2][1];
resids[1][3]=resids[2][2];
resids[2][3]=resids[3][2];
resids[2][2]=resids[3][1];
}
 if ((i==3)&&(j==2)) {
for (ii=1;ii<4;ii++) {
  done[1][ii]=1;
```

```
    done[2][ii]=1;
    resids[1][ii]=resids[2][ii];
    resids[2][ii]=resids[3][ii];
    }}
   if ((i==3)&&(j==3)) {
  done[1][1]=1;
  done[1][2]=1;
  done[2][1]=1;
  done[2][2]=1;
  resids[1][1]=resids[2][2];
  resids[1][2]=resids[2][3];
  resids[2][1]=resids[3][2];
  resids[2][2]=resids[3][3];
  }
   if (capture==1) capture2=capture2+1;

   } /* end of giant loop */
  /* once here have converged to between two results */
  /* optimized m and tc values are put into "output.fil" */

    if ((fp3=fopen("c:\output.fil","a"))!=NULL) {
  if (middl==1) {
    printf(" Results:  M = %f , Tc = %f \n",m,tc);
    fprintf(fp3,"Results:  M = %f , Tc = %f \n",m,tc);
    }
  if (middl!=1) {
  printf ("Results:  M between %f and %f \n", mold,m);
  printf ("           Tc between %f and %f \n",tcold,tc);
  fprintf (fp3,"Results:  M between %f and %f \n",mold,m);
  fprintf (fp3,"           Tc between %f and %f \n",tcold,tc);
  }
  fclose(fp3);
    } /* end of fopen */
}  /* end of program */
```