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FINAL REPORT

Industrial Concise Version

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Rheology Testing of Fernald K-65 Waste Residue Slurry

Prepared for

Fluor Daniel Fernald
Fernald Environmental Management Project

M.A. Ebadian, Ph.D. and F. Mao, Ph.D.

Hemispheric Center for Environmental Technology
Florida International University

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INFORMATION ONLY

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FINAL REPORT
INDUSTRIAL CONCISE VERSION

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NOMENCLATURE

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C	concentration
D	tube diameter
dp/dl	pressure gradient
F	flow rate
f	friction factor
K	resistance factor
l	test section length
P	pressure
Re	Reynolds number
T	temperature
u	flow velocity
V	velocity

Greek

ΔP	pressure drop
ρ	density
μ	dynamic viscosity
ε	tube wall roughness

Subscript

b	bend
d	downward
e	effective
h	horizontal
s	straight section
u	upward

EXECUTIVE SUMMARY

The project was initiated based on "Statement of Work for Rheology Testing of Waste Residue Slurry" provided by Fluor Daniel Fernald (FDF) through Clark Atlanta University, Agent. According to this statement, a Project Specific Plan (PSP) was prepared by the Hemispheric Center for Environmental Technology at Florida International University and approved by FDF. The project has been conducted according to the PSP and was started in September 1997.

In accordance with the PSP, the main objective of the project was to develop rhelogical and hydraulic data for the K-65 materials using a radioactive test loop and to develop a surrogate formulation that would duplicate the rhelogical and physical attributes of the K-65 materials as nearly as practical. The tests of the attributes included pressure drop measurement, physical property measurement, settling behavior determination, and particle size characterization.

Since radioactive material was involved, the test loop for K-65 material slurries was built in a glove box constructed in an enclosed radioactive laboratory. Another test loop, the cold loop identical to the hot loop, was built in a regular laboratory for surrogate testing and development. After completion of loop construction, instrumentation, water flow calibration tests were conducted. The calibration results were analyzed and compared to the data published in industrial handbook. These tests demonstrated that both loops have satisfactory measurement and control performances that mimic each other in data results.

The first series of test conducted the pressure drop measurements of K-65 slurries under the specified operating conditions of:

- Slurry temperature: 4, 25, and 40 C°
- Slurry compositions: 5, 25, and 40 wt % of K-65 materials without Bentonite.
  5, 25, and 40 wt % of K-65 materials with 5 wt % Bentonite
  5, 25, and 40 wt % of K-65 materials with 10 wt% Bentonite
- Slurry flow velocity: 2, 4, and 8 feet per second.

During the testing, the pressure drops of the slurry across four test sections of the loop were measured. These included upward vertical test section with bend, downward vertical test section, horizontal test section, and horizontal test section with bend. The absolute pressure at the exit of the slurry pump and that at the entrance of the slurry tank were also measured. The pressure drops along the four test sections were plotted and correlated as a function of the slurry velocity. The friction factor was calculated from the measured pressure drops and correlated as a function of calculated Reynolds number.

Upon completion of the hot loop testing, the physical properties of K-65 material slurry were measured under the three-temperature points with different solids concentrations. These properties included pH, density, and viscosity. The density and the viscosity of the slurry were plotted and correlated as a function of solids concentration at each temperature level. The settling behaviors such as settling distance, settling velocity, and the weight ratio of settled solids to the total slurry were measured, calculated, and plotted as function of settling time. Particle size

distribution results were also acquired for most of the slurry samples and the results were illustrated by the particle size distribution curves.

Based on the K-65 material testing and measurement results, and the K-65 compositions, a proper physical surrogate formulation for the K-65 material was developed through several testing-modification tries. The surrogate slurries were prepared based on the formulation and tested in the cold loop and the pressure drops were measured under the same operation conditions as above mentioned for the K-65 materials. The physical properties, settling behaviors, and particle size analysis were then performed for the surrogate evaluation and comparison with the K-65 materials. The developed surrogate proved to have fairly consistent pressure drops and physical properties with the K-65 material under identical operating conditions.

From the experimental measurement and the mathematical correlation, some of the major conclusions can be summarized as follows:

1. The physical surrogate can be used as a substitute for K-65 silo material for testing and demonstration under the operating conditions used in this study.
2. The regressed pressure gradient or friction factor correlation can be used to predict the flow resistance in the flow velocity range. The following pressure gradient correlation is recommended for prediction of pressure drop in straight section of the pipeline.

$$\frac{dp}{dl} = (0.07945 + 0.2736C_k^{1.389} + 0.1347C_b^{0.4148})u^{1.65} / d^{1.35}$$

3. The minimum transporting velocity ranges from 0.5-1.5 ft/s depending on the concentration. Based on the 1-inch tube testing and settling tests, the ideal slurry condition for pipeline transportation is 25% K-65 silo material and 5% bentonite in the velocity range from 4 ft/s to 8 ft/s.
4. The settling behavior of the slurry can be identified with three settling layers: clear supernate, cloud suspension, and settled phase. The interfaces between these layers have been detected and the settling distances have been measured. The bentonite in the slurry can slow down the particle settling velocity and reduce the weight ratio of the settled solid to the total slurry. No supernate and cloud layers could be observed when10 wt% bentonite was present in the K-65 and surrogate slurries.
5. For K-65 material, the particle size analysis indicates that the particles in supernatant are in the range of 2-15 μm without bentonite and 2-10 μm with 5% bentonite. The particles in top of the settled phase can be as large as 25 μm for lower concentration and 40 μm for higher concentration. Therefore, the bentonite did help the K-65 settling. This was supported by the observation in the settling tests. For surrogate slurry, similar particle size distribution was found.

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1.0 OBJECTIVE

The objective of this project was to acquire the rheological and hydraulic data for slurries of K-65 materials combined with bentonite clay. The information is meant to be used as technical reference for designing slurry retrieval, transfer, and processing systems.

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2.0 EXPERIMENTAL AND INSTRUMENTATION

2.1 PHYSICAL PROPERTY MEASUREMENT

Temperature. Property measurements were taken at three temperatures: 4°C, 25°C, and 40°C.

Viscosity. A rheometer Model RI-1-L (Serial No: 6292) from Rheology International Shannon Ltd. was used to measure slurry viscosity. The manufacturer has calibrated the viscometer using viscosity standards traceable to the National Institute of Standards & Technology (NIST).

Density. Two methods were used for determining the density of the K-65 samples. The first method consisted of weighing each sample and calculating the density for the known sample volume. The second method was to use a set of hydrometers provided by Fisher Scientific for determining the densities of those samples with low solids concentration and solids settling that would not affect the measurements.

pH. A Corning pH-meter (electrode type) was used for sample pH analysis.

3.0 K-65 DATA

The K-65 samples were prepared either in a bottle as fresh samples or taken from the test loop as pumped samples. The convention used for naming the sample is as follows:

> Sample Naming: K65: K-65 slurry; 25, 35, 40: Slurry concentration in wt %; 5 or 10: Bentonite concentration in wt %; P: Sample taken from packing leak; F: Sample prepared before running experiment (Fresh); T: Sample taken from slurry tank.

3.1 PHYSICAL PROPERTIES

Table 3.1.1 presents the physical properties of K-65 and bentonite slurries measured in this work.

Table 3.1.1.
Physical properties of K-65 and bentonite slurries

Sample	Density, g/cm^3			pH			Viscosity cP		
Name	**4°C**	**25°C**	**40°C**	**4°C**	**25°C**	**40°C**	**4°C**	**25°C**	**40°C**
K65-5-T	1.00	1.01	1.00	8.78	8.92	8.97	3	2.5	2.4
K65-25-P	1.12	1.10	1.11	7.69	7.93	7.27	9	8	11.5
K65-25-F	**	1.11$^+$	**	**	7.35	**	**	**	**
K65-35-P	***	1.06$^+$	***	7.87	7.83	7.70	***	***	***
K65-35-T	1.17	1.17	1.16	7.95	7.89	7.68	16	17	21
K65-40-T	1.25	1.23	1.22	7.82	7.68	7.40	71	108	115
K65-40-F	**	1.29$^+$	**	**	7.65	**	**	**	**
K65-5-5-T	1.04	1.04	1.04	8.29	7.41	7.59	11	16	17.7
K65-25-5-T	1.21	1.20	1.18	8.20	7.82	7.62	100	104	199
K65-40-5-T	1.75	1.72	1.71	8.22	7.89	7.76	668	577	558
K65-5-10-T	1.28	1.30	1.32	8.42	8.36	8.24	246	255	258
K65-25-10-T	1.49	1.53	1.54	8.07	7.89	7.91	273	334	371

+ These values are approximates because samples either were not enough or settled too fast (Fresh).

* Numbers in parentheses indicate spindle number and speed (RPM).

** Freshly prepared samples do not give good viscosity and density readings since they settle fast.

*** Sample quantity was not enough for viscosity and density determination.

The measured results indicate that the temperature effect on the K-65 slurries is not significant for the test conditions.

3.2 DENSITY

Figure 3.2.1 plots the density versus K-65 concentrations for K-65 slurries with and without bentonite.

A general correlation was developed for density estimation.

$$\rho_e = 900C_t^2 + 230C_t + 997.9 \quad (1)$$

$40^oC \geq T \geq 4^oC$, $0.10 \geq C_b$ when $0.25 \geq C_s \geq 0.05$, and $0.05 \geq C_b$ when $C_s = 0.40$

where:

ρ_e = slurry effective density, Kg/m^3;

C_t = the concentration of total solids including K-65 and bentonite.

Note: In the equation, 0.25 means 25% solid in slurry. The density could also be calculated with the unit of lb/ft^3 by multiplying these coefficients in the above equation by 0.0625.

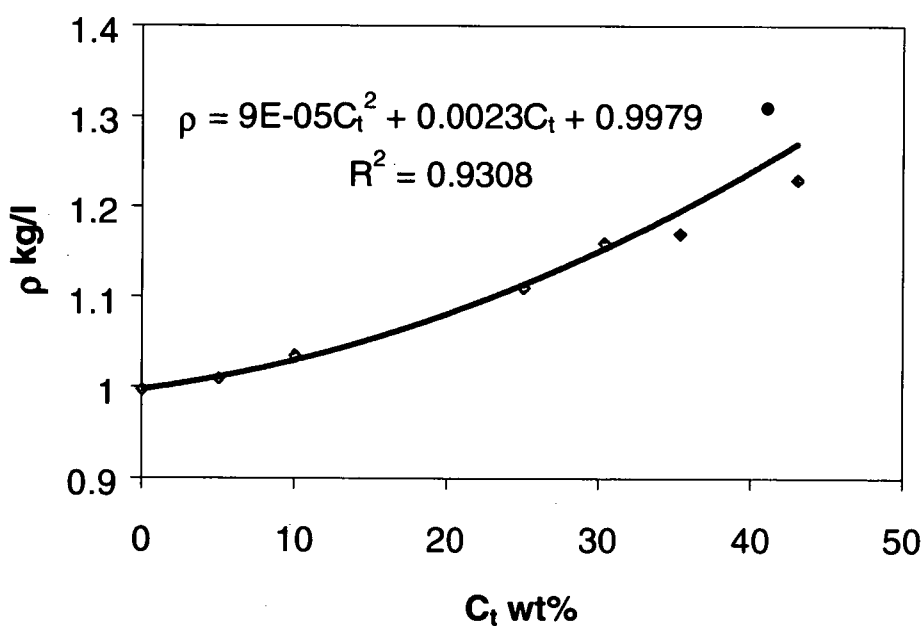

Figure 3.2.1. Density versus K-65 concentration for K-65 slurries with and without bentonite.

3.3 VISCOSITY

Figure 3.3.1 plots the viscosity versus K-65 slurries with and without bentonite.

The viscosity of the K-65 and bentonite slurries was correlated and is an exponential function of K-65 hot material concentration.

Without bentonite:

$$\mu_e = 1.2065e^{9C}, \quad T = 25^{\circ}C, \quad 0.40 \geq C_s \geq 0.05 \tag{2.1}$$

With 5% bentonite:

$$\mu_e = 8.266e^{11.24C}, \quad T = 25^{\circ}C, \quad 0.40 \geq C_s \geq 0.05 \tag{2.2}$$

where:

μ_e = slurry viscosity, cP

C_s = slurry concentration, wt%.

These two correlations are for room temperature at 25°C. The viscosities for the 10% bentonite slurries are very high, and few data are available to make a correlation.

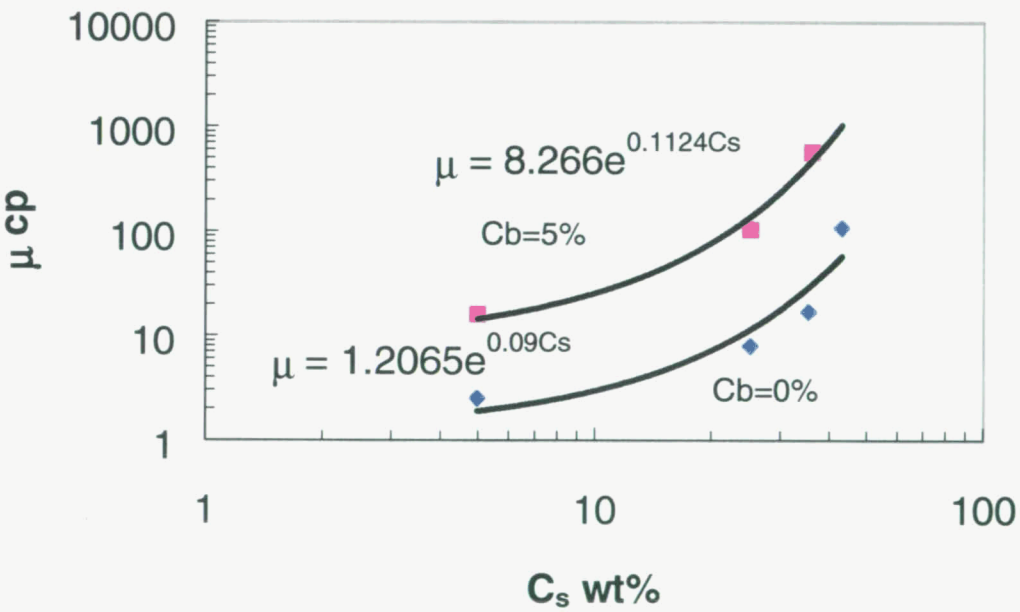

Figure 3.3.1. Viscosity versus K-65 concentration for K-65 slurries with and without bentonite.

3.4 PH

No variation patterns of the pH values of the K-65 slurry samples can be observed from the measured data. The pH values range from 7.2 to 9.0 for all samples.

3.5 PARTICLE SIZE ANALYSIS

3.5.1 Particle Counter

To evaluate the size and distribution of particles in K-65 materials from Fernald Silos 1 and 2, determinations were carried out using a particle counter. The instrument was fitted with a laser sensor capable of determining particles in the 2μm to 400μm size range.

3.5.2 Measurement Method

The particle counter was provided with a manufacturer-supplied calibration curve for the sensor, covering a particle size range from 2μm to 400μm. Calibration was carried out according to ASTM F658-87 87 with monosized latex spheres traceable to NIST. Samples were tested at flow rates of 60ml/min, corresponding to the flow rate used during calibration.

Table 3.5.2.1 presents measurement data of the Fluor Daniel Fernald particle size estimation of K-65 silo material.

Table 3.5.2.1.
Fluor Daniel Fernald particle size estimation of K-65 silo material

Mesh Size	Particle Size, μm*	Percent Retained on Sieve
80	≥180	48.25
200	≥ 75	30.46
325	≥ 45	7.2
400	≥ 38	1.3
635	≥ 20	5.4
Pan	≤ 20	5.2

* Particle-mesh size correlation based on ASTM E-11- 98

3.5.3 Particle Size Analysis Results

The curves in Figure A.1.1 to Figure A.1.11 in Appendix A indicate the results after subtraction of a water background count. In all cases the background count was so low compared to the sample count that it was insignificant and would not have needed to be applied. However, it was carried through in the reporting process.

3.5.4 Particle Analysis Chart Sample

In order to compare the relative particle sizes of the various K-65 samples, the data were presented as a plot of the population percentage greater for each size. As a reference, the size of the particle whose population was greater than 50% was arbitrarily taken as indicative of the sample.

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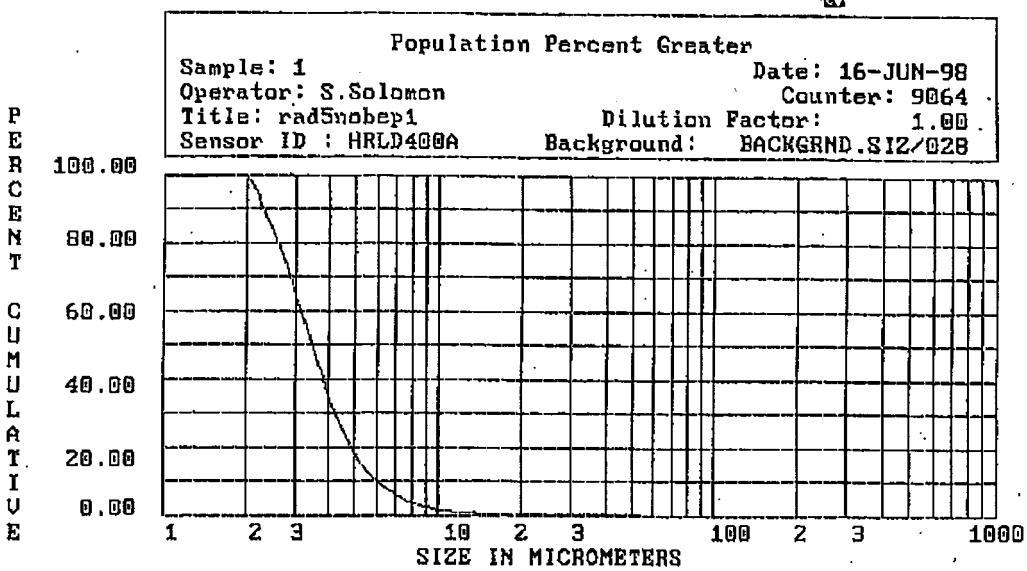
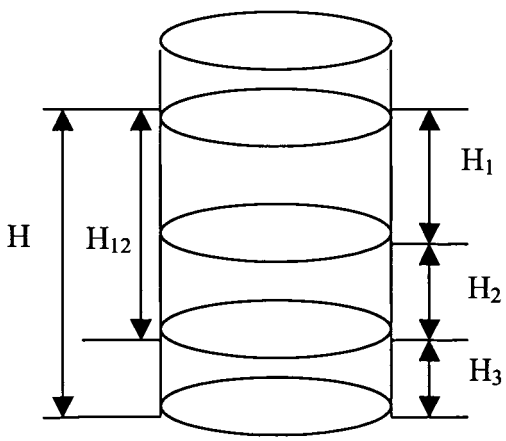


Figure 3.5.4.1 Unpumped K-65 slurry without bentonite supernatant of settled material, at 10 mm depth, undiluted.

Note: Similar charts are presented in Appendix A for all samples.

3.6 SLURRY PARTICLE SETTLING

The particle-settling phenomenon has been observed and measured in settling bottles. The settling velocity was determined by examining the movement of the settled interface along with the settling time. The following diagram defines the settling portions and distances in the settling bottle and the equation was used to calculate the settling velocity:



H = Total sample height
H_1 = Height of clear layer
H_2 = Height of cloudy layer
H_3 = Settled layer
$H_{12} = H_1 + H_2$
Settling Velocity =
H_{12} / Settling Time

Figure 3.6.1. Sample bottle diagram.

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3.7 WEIGHT RATIO OF SOLIDS IN THE SETTLED PHASE

The weight ratio of solids in the settled phase to the total solids in the sample could be calculated by the following equation:

$$W_3/W = (\text{Total solids} - \text{Solids in suspension})/\text{Total solids} \quad (4.1)$$

$$= (V\rho W - V_2\rho_2 W_2)/V\rho W \quad (4.2)$$

$$= 1 - (V_2/V)\,(\rho_2/\rho)\,(W_2/W) \quad (4.3)$$

$$= 1 - (H_2/H)\,(\rho_2/\rho)\,(W_2/W) \quad (4.4)$$

where:

W_3 = weight percentage of solids in settled phase, wt.%

V = sample volume

ρ = sample density

W = solids concentration of sample, wt.%

V_2 = volume of suspension layer

ρ_2 = density of suspension layer

W_2 = solids concentration of suspension layer, wt.%.

3.8 SETTLING VELOCITIES AND WEIGHT RATIO DATA

Figure 3.8.1 shows the settling velocity changing with time. The velocity was calculated from the measurements of settling distance (H_{12}) and the settling time. In Figure 3.8.2 the weight ratio of the settled solid to the total solids in the sample was indicated as a function of time. The ratio was determined by the method described in section 3.7.

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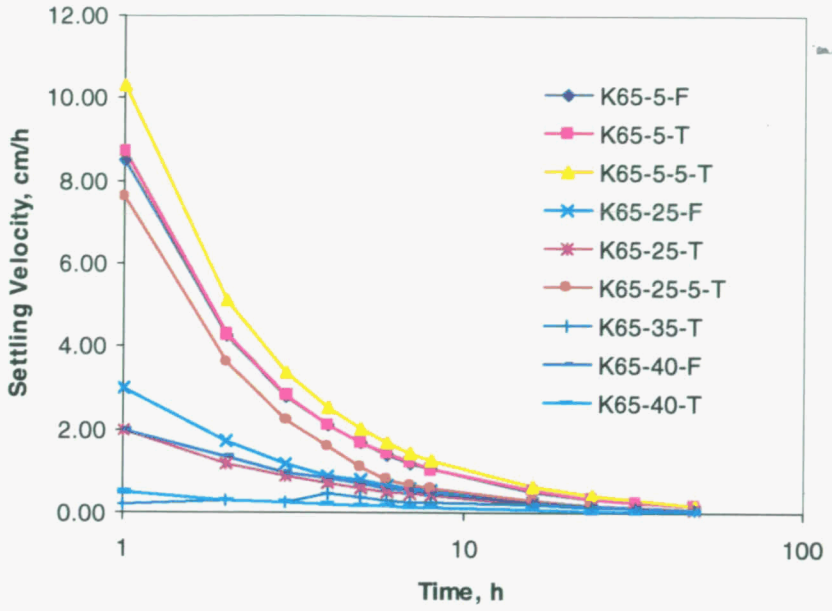

Figure 3.8.1. Settling velocity versus time for K-65 slurries with and without bentonite.

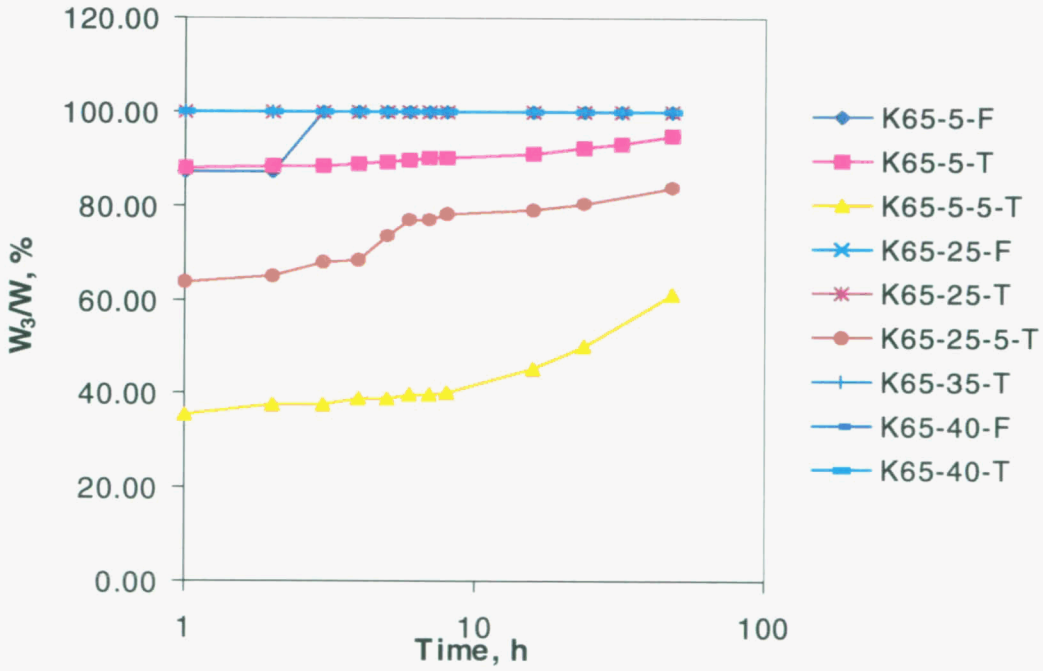

Figure 3.8.2. Weight ratio of settled solids to total solids for K-65 slurries with and without bentonite.

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All of the measured settling distances, the ratios of the distances to the total sample height, and the calculated settling velocities, and the weight ratio results are shown in the tables of Appendix B.

All of the settling distances, including the total distance over all settling time and the actual distance over the settling periods between two recorded times, have been plotted in Figures C.1.1-C.1.9 and Figures C.2.1-C.2.15 in Appendix C.

4.0 PRESSURE DROP TESTING LOOPS

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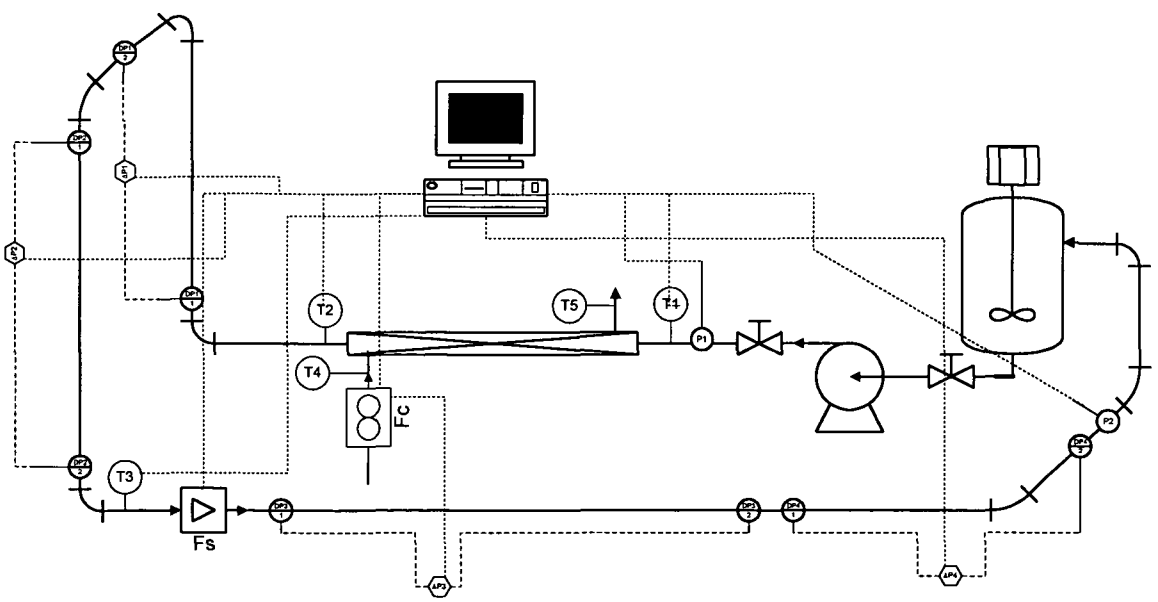
Two pipeline and testing systems have been built for the rheological and flow resistance tests of K-65 and its surrogate slurries. One of the main purposes of these tests was to verify pressure drop characteristics between K-65 and the prepared surrogates. The first system used to test slurries containing K-65 radioactive material was built inside a glove box. A second identical system was used to test the surrogate slurry (see figures 4.1 through 4.3). These two systems were designed and built to meet the following requirements:

- The system can measure flow resistance of K-65 and its surrogate slurry flowing in different pipeline system components, which include horizontal and vertical straight pipe and 90-degree bends.
- The system can measure different flow velocities ranging from 2 to 8 ft/s without plugging and different temperature levels ranging from 4° to 40°C.
- The system's pressure transmitters and connection lines must be capable of handling a slurry flow with up to 40% solids.
- The system's pump station must be capable of pumping dense sand slurry of up to 40% solids for three months and longer.
- The data acquisition system should be able to collect all sensor readings automatically and store them in a data file for further analysis.
- All measurement sensors must meet all testing condition requirements and signal ranges with adequate accuracy and stability.



ΔP1 = Upward vertical test section with bend. ΔP2 = Downward vertical test section. ΔP3 = Horizontal test section. ΔP4 = Horizontal test section with bend.

Figure 4.1. Diagram of the pressure drop test loops.

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Each system is formed by two subsystems: the pipeline flow system and the instrumentation and data acquisition system. The pipeline system includes slurry reservoir tank, pump station, heat exchanger, straight vertical section (77.5 in), straight horizontal section (77.5 in), vertical section with bend, horizontal section with bend, and flow control valves. The bend radius is 5 times the tube diameter.

Table 4.1.
Measurement uncertainties

Parameter	Uncertainty	Notes
Density	± 3%	Combination of uncertainties of weighting and volume measuring .ASTM Standard E100
Friction factor & resistance factor	± 3.8%	Calculated
Static pressure	±1.5 InH2O (±1% FSO)	Instrument limits
pH	± 0.01 pH	Specified by the manufacturer
Pressure drop	±0.25%	Measured
Reynolds number	±2.5%	Calculated
Temperature	±0.5%	Measured
Velocity	±1.0%	Measured
Viscosity	± 5%	Maximum uncertainty reported by the manufacturer

Figure 4.2. Test system for silo material slurry.

Figure 4.3. Test system for surrogate slurry.

4.1 PRESSURE DROP DATA REDUCTION METHOD

For the slurry pressure drop tests, initial readings of the pressure transmitters were set to zero when the loop was filled with water. The gravity heads had to be added or deducted from the initial readings for the vertical up-flow and down-flow test sections. The data reduction process is conducted using the SI units. All readings were converted to the SI units at beginning of the reduction process.

The pressure gradient is calculated for the straight horizontal test section.

$$\left.\frac{dP}{dl}\right|_h = \frac{\Delta P_h}{l_h} \tag{5.1}$$

Then the pressure drop across the bend is calculated by subtracting the pressure drop of the straight portion from the total pressure drop of the horizontal test section with bend.

$$\Delta P_b = \Delta P_h - \left.\frac{dP}{dl}\right|_h l_s \tag{5.2}$$

The pressure drop in the straight vertical upward flow section can be determined by subtracting the pressure drop across a bend from the total pressure drop of the vertical test section with bend.

$$\Delta P_{us} = \Delta P_u - \Delta P_b \tag{5.3}$$

The data are presented in the form of pressure gradient versus flow velocity. The results are also presented in dimensionless form. Based on the pressure drop testing data and the measured

physical properties, the flow Reynolds number and friction factor are calculated. The Reynolds number and friction factor are defined as

$$Re^* = \frac{\rho_e u d}{\mu_e} \tag{5.4}$$

$$f = \frac{(\Delta P / L)d}{\frac{1}{2}\rho_e u^2} \tag{5.5}$$

where:

u = average flow velocity

d = inner diameter of the tube

L = length of the test section

ΔP = pressure drop across the test section

ρ = slurry density

μ = dynamic viscosity of the slurry calculated based on the measured data.

The pressure drop across the bend is presented in the form of resistance factor versus Reynolds number. The resistance factor can be defined as

$$K = \frac{\Delta P_b}{\frac{1}{2}\rho_e u^2} \tag{5.6}$$

The density and viscosity of slurry is correlated with the concentration of hot material or surrogate, the concentration of bentonite, and slurry temperature.

$$\rho = f(C_b, Cs, T) \tag{5.7}$$

$$\mu = f(C_b, Cs, T) \tag{5.8}$$

Water flow calibration tests were conducted for the cold loop and the hot loop. The calibration results showed a great consistency between the present data and the prediction by a common correlation [2]:

$$f = \frac{0.25}{\left[\log\left(\frac{1}{3.7(d/\varepsilon)} + \frac{5.74}{Re^{0.9}}\right)\right]} \tag{5.9}$$

The roughness of the tube is selected as 0.001mm for a commercial stainless steel tube.

4.2 PRESSURE DROP RESULTS AND CORRELATION

Based on the measurement data, the pressure drop data for different test sections are presented in two ways. First, the relationship of the pressure drop gradient versus flow velocity was analyzed and presented for all test cases in the hot loop and the cold loop. The test results are also presented in dimensionless form as the relationship of friction factor versus slurry flow Reynolds number so they might be used in extrapolations for different tested conditions. Moreover, some correlations were provided. It should be noted that there is a high risk of underestimation when test data from a smaller tube diameter is used to predict those for a larger tube diameter, especially for the solid-liquid, two-phase slurry flow, where the phase separation exists. The suggested correlations can be used only with the physical property data as measured in this project. Table 4.2.1 documents the compositions of the silo material slurry.

The pressure drop tests have been done for K-65 material slurries with and without bentonite. When bentonite was required in the slurry, it was directly and slowly added into the well-mixed K-65 materials and water accompanied by mixing. The added amounts were calculated based on the specified concentration.

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Table 4.2.1.
Silo material slurry compositions

Slurry	Water kg	K-65 kg	Bentonite kg	K-65 %	Bentonite %
5% K-65	18.256	1.21 (0.8)	0	4.97	0
25% K-65	18.304	8.358 (0.8)	0	25.08	0
35% K-65	18.304-0.489 =17.815	8.358-0.223+5.954 =14.089 (0.8)	0	35.33	0
40% K-65	17.815-0.49 =17.324	14.089-0.389+6.446 =20.146 (0.8)	0	43.01	0
5%-K 5%-B	15.71	2.46 (0.40)	0.952	5.15	4.98
25%-K 5%-B	15.71-0.4108	2.46 (0.4)-0.064(0.4)+7.052 (0.8)	0.952-0.025+0.384	25.33	5.03
40%-K 5%-B	15.30-0.4178	2.396(0.4)+7.052(0.8)-0.152(1.0)+6.512(0.8)	1.311-0.030+0.304	36.12	4.91
5%-K 10%-B	17.95	1.34(0.8)	2.15 kg	5%	10%
	7.666	10.838(0.4)+0.666(0.8)	2.13	22.8	10%

Notes: K-65 material has 20% moisture. Dry K-65 density 2.7 Kg/l, the water density 1.0Kg/l. K=K-65 material, B=BentoGrout™ material.

All the hot loop pressure drop data and dimensionless results are attached in Appendix A and Appendix B, respectively. In following sections, the temperature, orientation, and concentration effects on the pressure gradient are discussed. The dimensionless results are then presented, and some correlations are suggested.

4.3 TEMPERATURE EFFECT

In general, as the temperature increases, the pressure gradient or bend resistance decreases as shown on Figures 4.3.1-4.3.4. It is well known that the water viscosity decreases with temperature increase. It is the main reason for this phenomenon. The reverse effect occurs at the low velocity and high solid concentration, as the case of u = 2.0 ft/s for the 25% K-65 and 5% bentonite slurry (Figure 4.3.2). When the velocity is low for very high solid concentration, the particle interaction influences the friction flow resistance. The interaction becomes stronger as the temperature becomes higher. However, the temperature effects on either case are small compared with the velocity variation effect.

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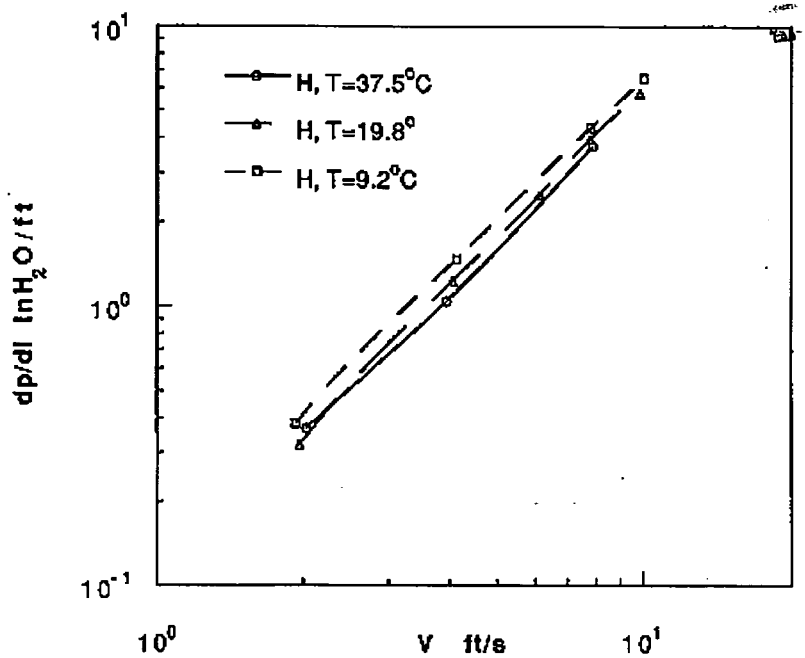

Figure 4.3.1. Pressure gradient of 25% K-65 slurry in horizontal test sections.

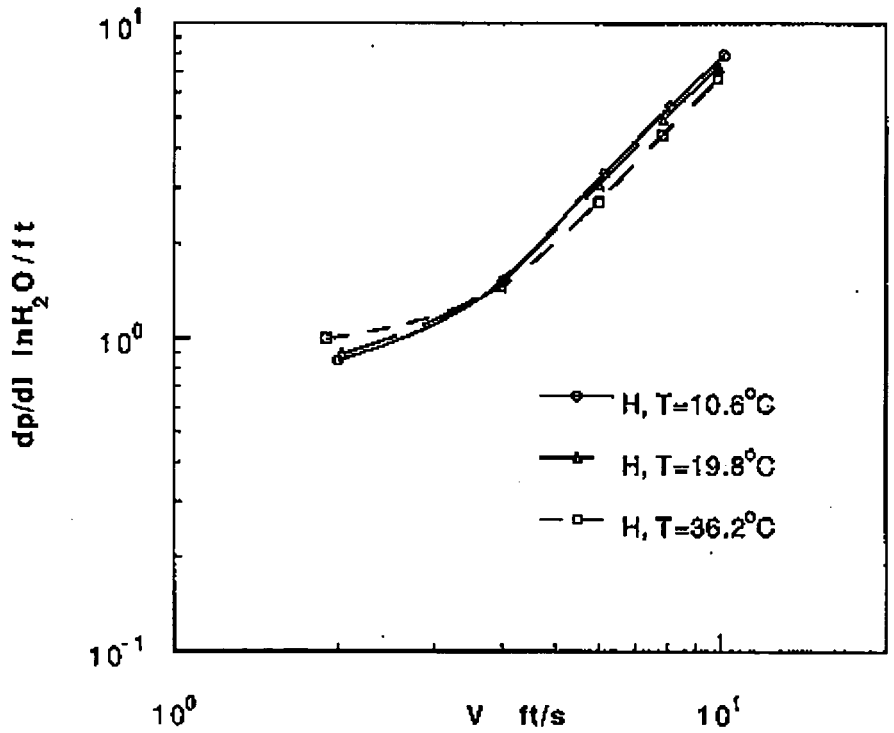

Figure 4.3.2. Pressure gradient of 25% K-65 slurry with 5% bentonite in horizontal test section.

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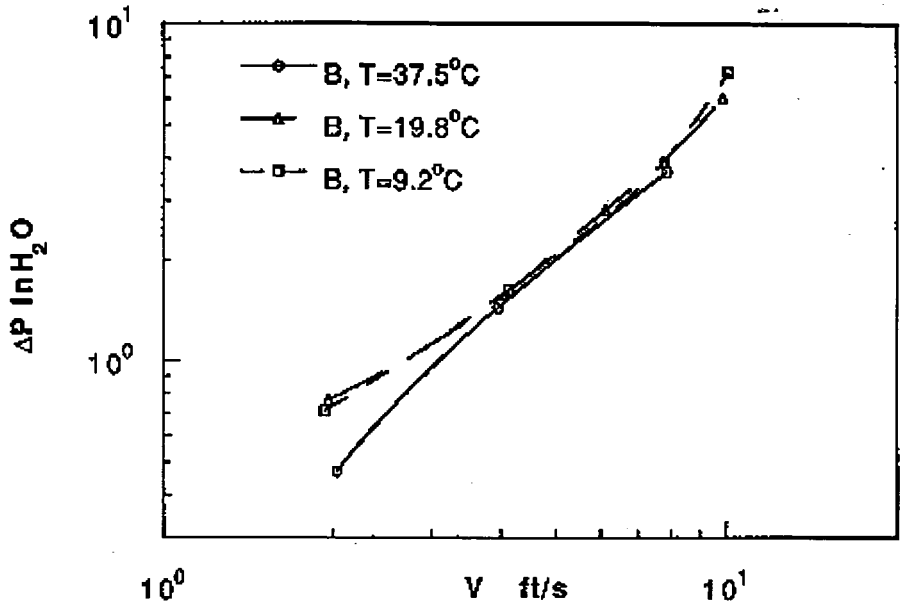

Figure 4.3.3. Pressure drop across the bend of 25% K-65 slurry.

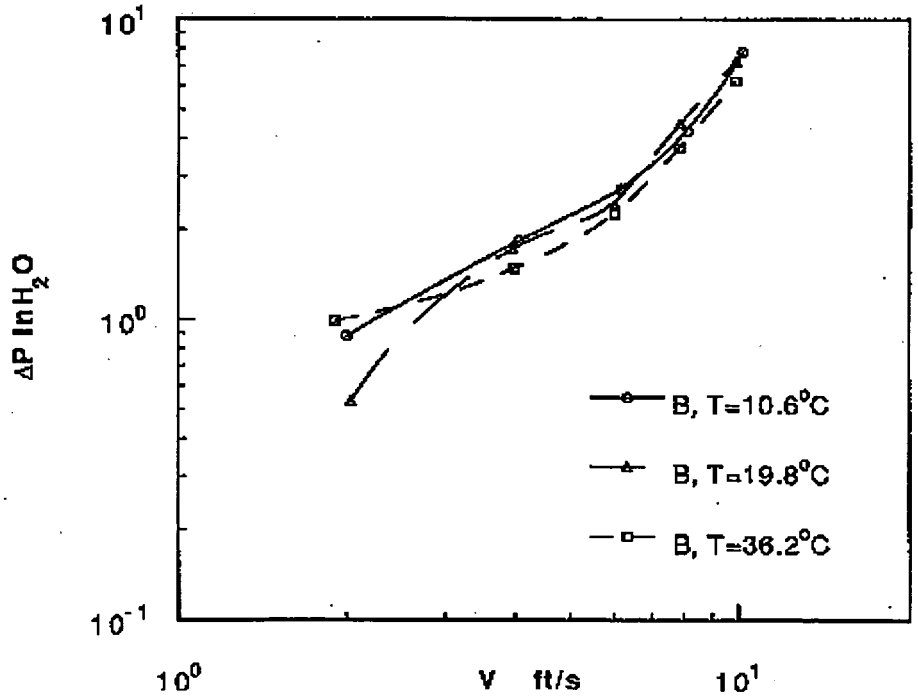

Figure 4.3.4. Pressure drop across the bend of 25% K-65 slurry with 5% bentonite.

4.4 CONCENTRATION EFFECT

The slurries with different concentrations of silo material and bentonite were tested. The effects of both silo material concentration and bentonite concentration on the pressure drop are examined here. The pressure gradients versus flow velocity in the horizontal test section at different silo material concentrations are plotted in Figure 4.4.1 without bentonite and Figure 4.4.2 with bentonite. Figure 4.4.3 and Figure 4.4.4 show the pressure drop across the bend for the corresponding cases; the pressure gradient and bend resistance increase as the silo material concentration increases.

In Figure 4.4.1 and Figure 4.4.2, when the solid concentration is low, the pressure gradient has a power-law relationship with flow velocity - straight line in dual-log graphic (less than 35% silo material without bentonite, or 5% silo material with 5% bentonite), or only at high velocity range (4 ft/s to 10 ft/s for 25% silo material with 5% bentonite). In the non-power-law range, even a slight drop of pump head can cause a dramatic drop of flow rate or plugging. Therefore, it is suggested that the pipeline should be running in the power-law range. For example, for the 25% silo material slurry with 5% bentonite, the loop should run at least 4 ft/s. For higher concentrations the critical velocity would be higher, in other words, a higher pump head.

The bentonite concentration influences the flow resistance in the same way. The pressure gradient curves of different bentonite concentrations for the 5% silo material slurry are shown in Figure 4.4.5. However, the bentonite concentration has a more sensitive effect than silo material concentration.

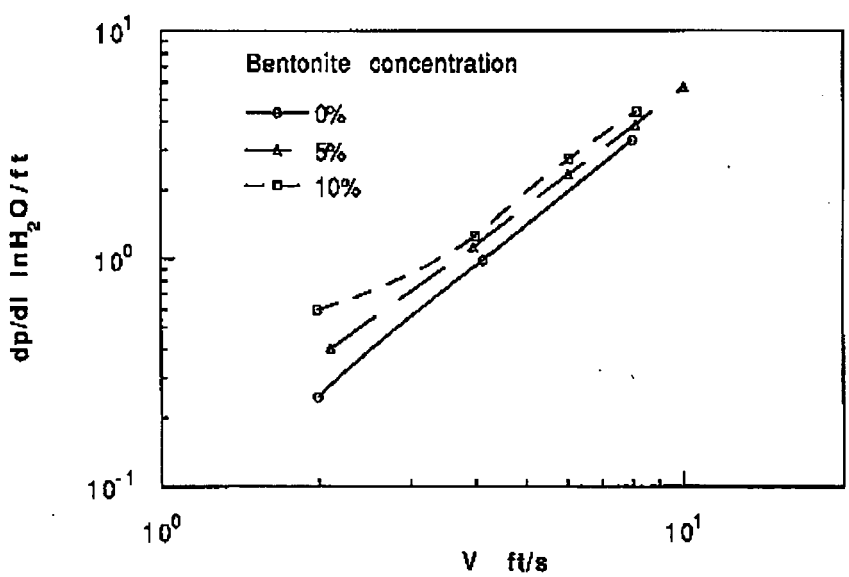

Figure 4.4.1. Concentration effect on pressure gradient of K-65 slurry without bentonite in horizontal test section.

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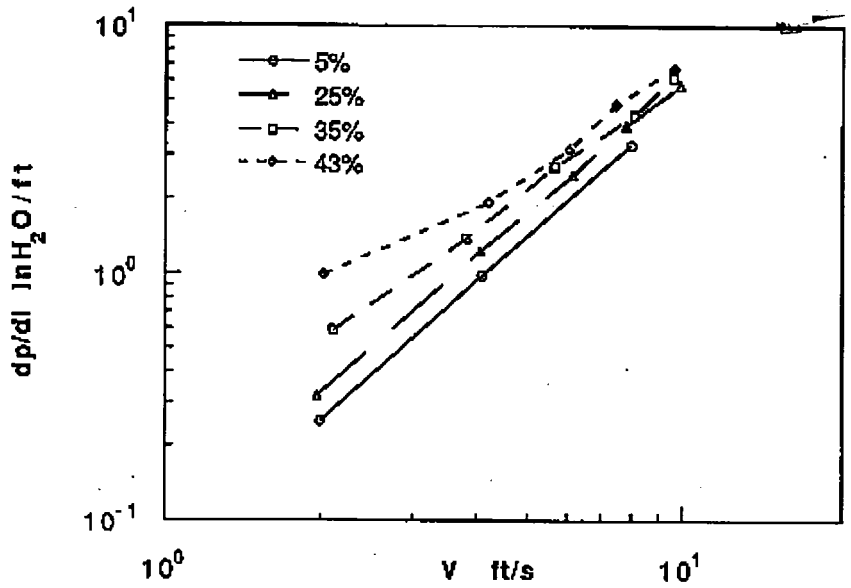

Figure 4.4.2. Concentration effect on pressure gradient of K-65 slurry with 5% bentonite in horizontal test section.

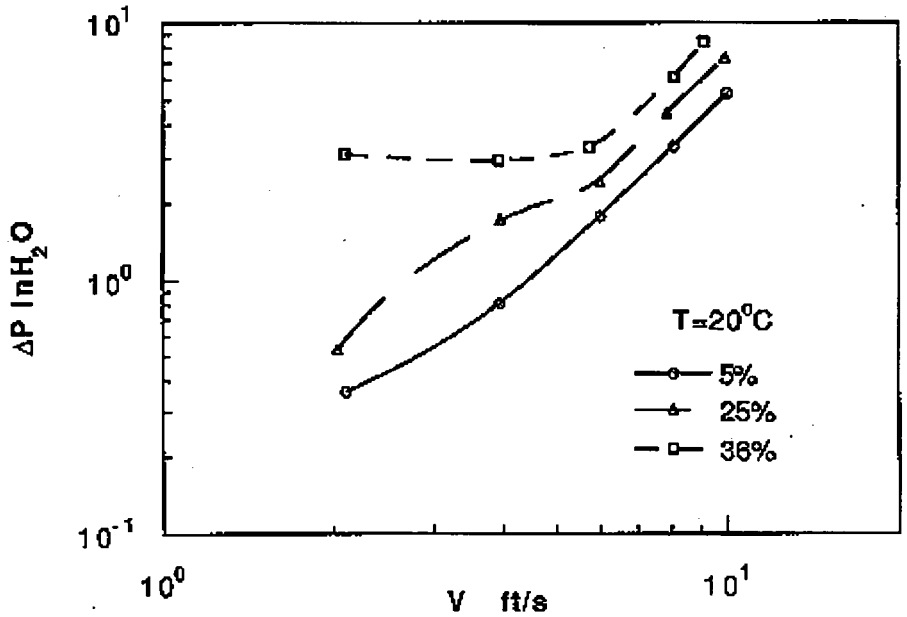

Figure 4.4.3. Concentration effect on pressure drop across the bend of K-65 slurry without bentonite.

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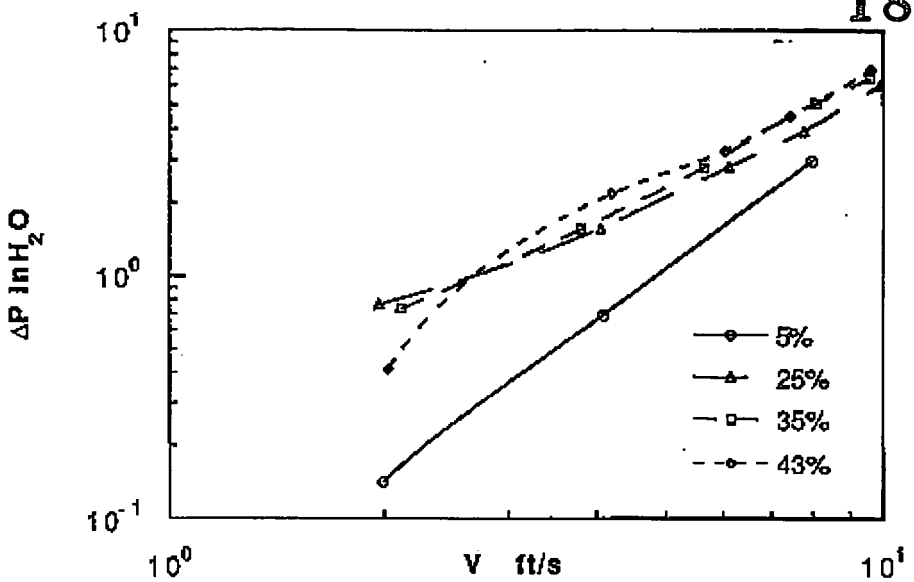

Figure 4.4.4. Concentration effect on pressure drop across the bend of K-65 slurry without bentonite.

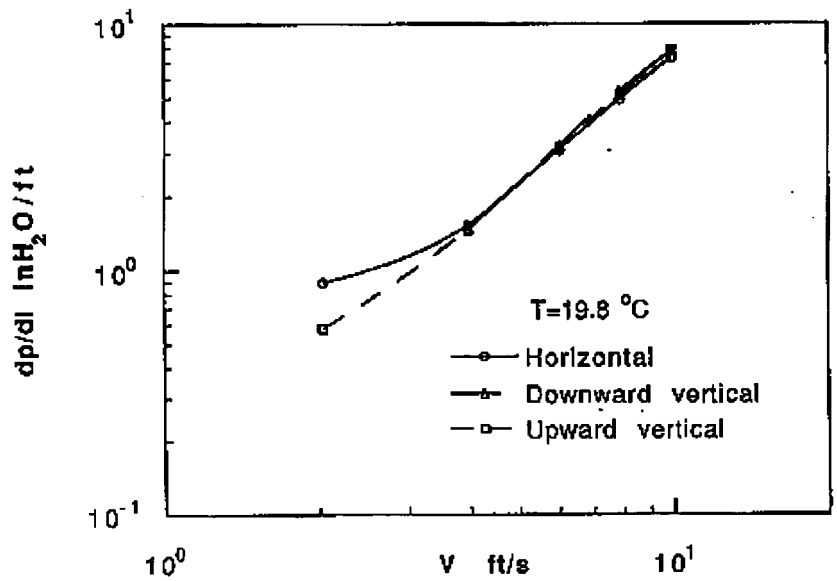

Figure 4.4.5. Bentonite concentration effect on pressure gradient of 5% K-65 slurry in horizontal test section.

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4.5 ORIENTATION EFFECT

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The pipeline orientation effect on the flow resistance can be observed from Figure 4.5.1 and Figure 4.5.2. At high flow velocity, the pressure gradients are the same for horizontal, downward vertical, and upward vertical sections. At low velocity, the difference arises. The differences come from the fact that the flow is not homogeneous any more. The phase separation may happen in the vertical sections. More details about phase distribution need specific experimental investigation.

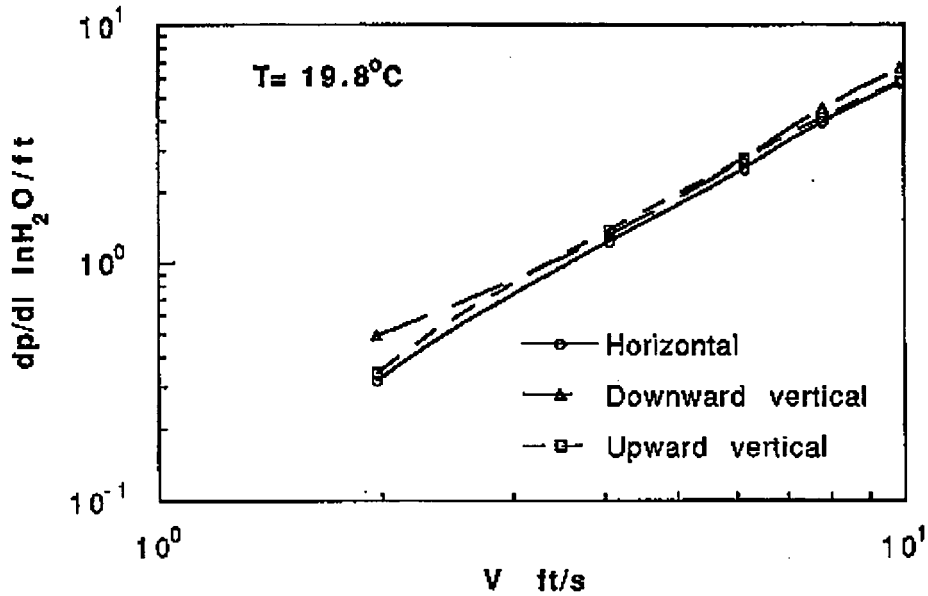

Figure 4.5.1. Flow orientation effect on pressure gradient of 25% K-65 slurry without bentonite.

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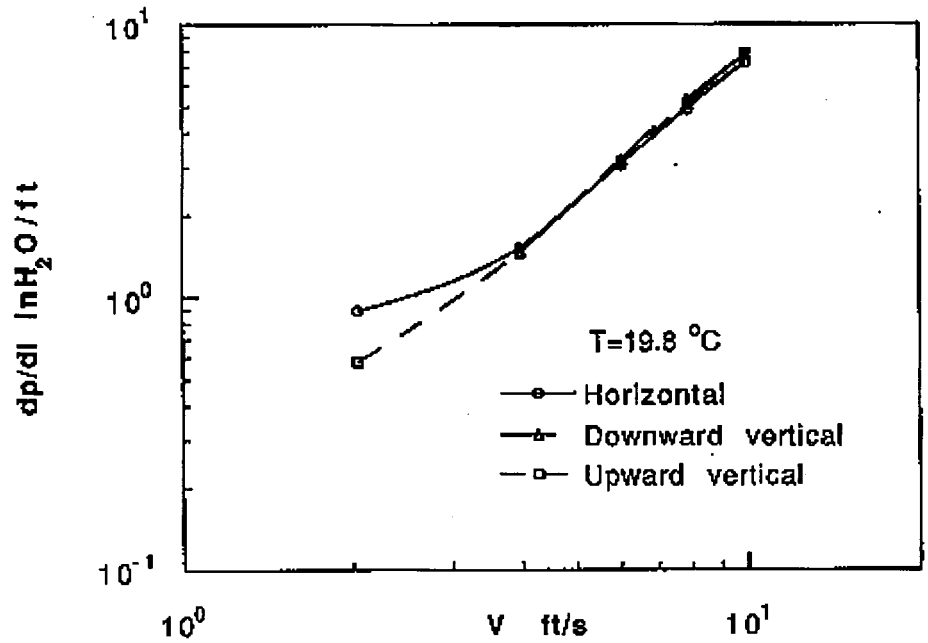

Figure 4.5.2. Flow orientation effect on pressure gradient of 25% K-65 slurry with 5% bentonite.

4.6 PRESSURE DROP CORRELATION

4.6.1 Pressure Gradient Correlations

When the solid concentration is low, the pressure gradient has a power-law relationship with flow velocity. The power-law range is recommended for pipeline system running condition. Efforts were made to regress a general correlation between pressure gradient and flow velocity. The following correlation was obtained.

$$\frac{dp}{dl} = \left(0.07945 + 0.2736\ C_k^{1.389} + 0.1347\ C_b^{0.4148}\right)u^{1.65} \qquad (6.1)$$

The equation was correlated in the following test condition.

$$C_b = 0,\ 0.25 \geq C_k \geq 0.05, \quad 10 \geq u \geq 2; \quad \text{and} \quad 0.40 \geq C_k > 0.25, \quad 10 \geq u \geq 4 \qquad (6.2)$$

$$C_b = 0.05, \quad C_k = 0.05, \quad 10 \geq u \geq 2; \quad \text{and} \quad C_k = 0.25, \quad 10 \geq u \geq 4 \qquad (6.3)$$

where:

dp/dl has the unit of inches of H_2O/ft,
the velocity takes the unit of ft/s,
Cb and Ck are the concentration of bentonite and K-65 material in decimal number, respectively.

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In the power-law range, the f = f(Re) relationship should exist for different pipe diameters. Therefore, the pressure gradient for the larger tube diameter can be predicted using the following modified equation.

$$\frac{dp}{dl} = (0.07945 + 0.2736C_k^{1.389} + 0.1347C_b^{0.4148})u^{1.65}/d^{1.35} \qquad (6.4)$$

d takes the unit of inch. The power-law range may be different for a larger diameter tube than it is for a one-inch tube.

The comparison between experimental data and prediction from the correlation is shown in Figure 4.6.1.

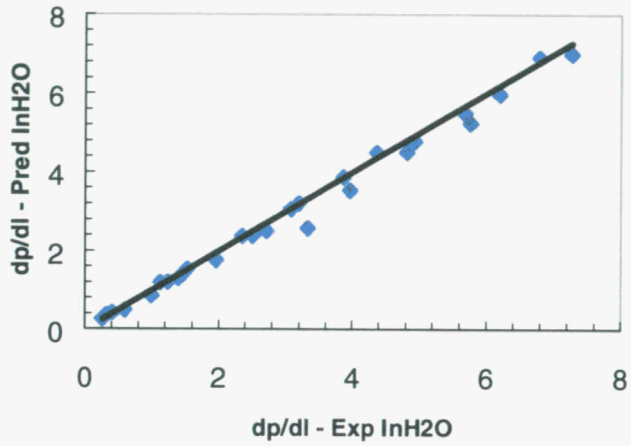

Figure 4.6.1. Comparison of experimental data prediction for K-65 slurry without bentonite.

4.7 FRICTION FACTOR AND RESISTANCE FACTOR

The following friction factor and bend resistance factor correlations are proposed for prediction.

$$f = 144.4\,Re^{*-1.856} \qquad K = 236.85\,Re^{*-1.298} \qquad Re^* \le 100 \qquad (7.1)$$

$$f = 0.0355\,Re^{*-0.0432} \qquad K = 0.8186\,Re^{*-0.124} \qquad 100 < Re^* < 2.0 \times 10^4 \qquad (7.2)$$

The proposed equations are regressed based on the experimental data of K-65 and bentonite slurries in the following range:

$$0.05 < C_s < 0.40, \qquad 0.0 < C_b < 0.05 \qquad (7.3)$$

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$$0.05 < Cs < 0.25, \qquad 0.0 < C_b < 0.10 \tag{7.4}$$

The testing data points and the correlations are shown in Figures 4.7.1 and 4.7.2 for comparison.

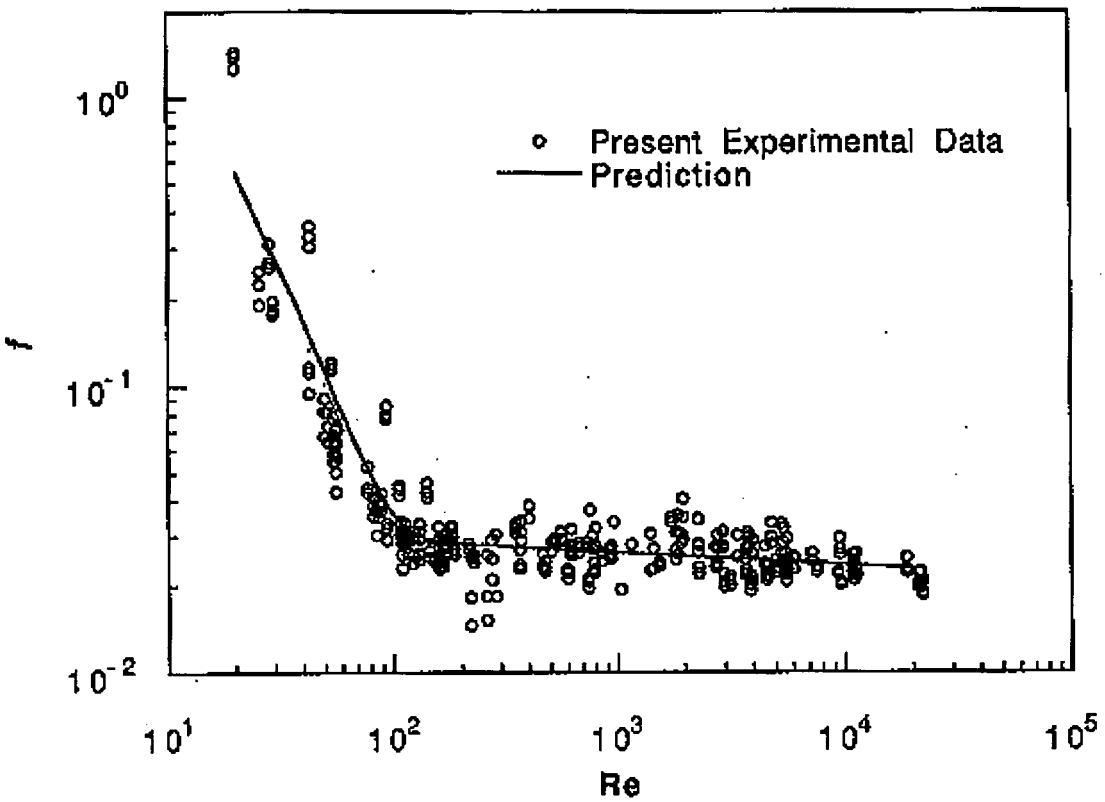

Figure 4.7.1. Experimental results and correlation of friction factor in straight section.

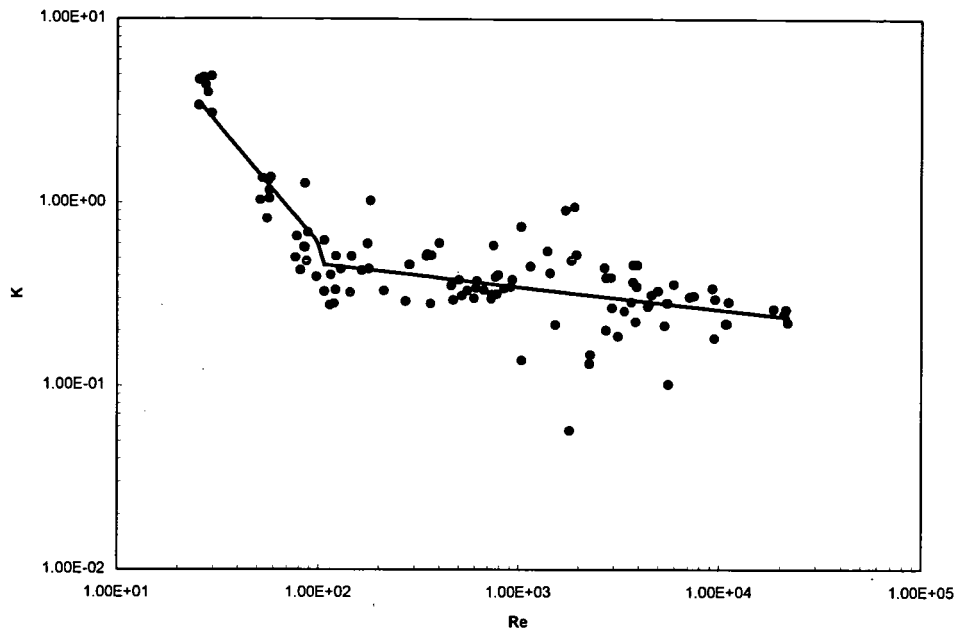

Figure 4.7.2. Experimental results and correlation of resistance factor of the bend.

5.0 SURROGATE DEVELOPMENT

5.1 SURROGATE FORMULAS

Physical surrogates were developed to simulate the rheological and hydraulic properties of the K-65 materials. Testing was conducted in the cold loop identical to the hot loop. Two surrogate formulations have been developed and tested in the cold loop. Table 5.1.1 shows the composition of each surrogate. The sand and the soil were provided by a local vendor. The sand is a fine construction sand. The soil is a topsoil manufactured by VitaGreen Inc. The soil compositions of sand, peat, and suspended materials have been identified by washing, drying, and weighing. The identified results and other information are shown in Table 5.1.2. Based on the particle size information provided by FDF, the sand and the soil have been ground and sieved into particles with the size distribution shown in Table 5.1.3.

Table 5.1.1.
Formula of surrogate #1 and #2 (wt% dry)

Materials	Surrogate #1 (wt.%)	Surrogate #2 (wt.%)
Sand	40	44.5
Soil	40	44.5
Diatomaceous Earth	11	5
Al_2O_3	3	3
Fe_2O_3	3	3
$CaCO_3$	1.5	0
$MgCO_3$	1.5	0

Table 5.1.2.
Soil information

Brand	VitaGreen		
Manufacture	VitaGreen Inc., Florida		
Composition	**Sand**	**Peat**	**Suspension**
Weight (gram)	151.5	29.44	19
Wt. %	75.7	14.7	9.6

Table 5.1.3.
Particle size data of sand and soil in the surrogate

Particle Size	Sand (wt %)	Soil (wt %)
1 mm	10	10
Mash # 60	18	18
Mash # 80	27	27
Mash # > 80	45	45

Surrogate #1 was initially prepared and tested in the cold loop. The pressure drop measurements of this surrogate were compared to those obtained from the hot loop using K-65 materials. The results were consistent when the surrogate concentration is in the range from 5% to 25% without and with 5% bentonite. As the bentonite concentration was increased to 10% for the 5% surrogate slurry, the cold loop was plugged, which was not observed in the hot loop under the same condition. The chemicals $CaCO_3$ and $MgCO_3$ presenting in surrogate #1 are assumed to interact with the bentonite to cause the plugging. Based on this consideration, surrogate #2 had been developed and tested without these two chemicals. The pressure measurements with surrogate #2 are also consistent with that of K-65 materials when the bentonite concentration in the surrogate is 5 % with 5, 25, and 40 % surrogates. Additionally, the pressure drop of the surrogate #2 mixture of 5% surrogate with 10% bentonite is consistent with that of the K-65 materials.

5.1.1 Physical Property Data

The physical properties of surrogates such as pH, density, settling velocity, and viscosity have been measured at three temperatures of 4, 25, and 40°C for both surrogate #1 and #2. The measurement methods and instruments used for these properties are the same as those used for the K-65 materials. These measured property data are shown in Table 5.1.1.1. The sample naming convention appears at the bottom of the table.

Table 5.1.1.1.
Surrogate slurry physical properties

Sample Name	Density, g/cm^3			pH			Viscosity, cP		
	4°C	25°C	40°C	4°C	25°C	40°C	4°C	25°C	40°C
S1-5-F**	1.04	1.03	1.02	8.83	8.79	8.63	1.7	2.1	1.8
S1-5-T	0.99	0.99	0.98	8.79	8.58	8.48	1.9	3.3	2.3
S1-5-5-F	1.05	1.05	1.02	8.27	8.83	8.47	14.2	14.4	15.6
S1-5-5-T	1.05	1.04	1.02	8.62	8.72	8.32	8.6	10.4	12.4
S1-5-10-F	1.12	1.11	1.15	8.86	9.04	8.82	411	481	514
S1-5-10-T	1.12	1.12	1.13	8.86	8.82	8.69	421	516	575
S2-5-F	**1.00**	**1.01**	**0.97**	**7.52**	**7.46**	**7.28**	**1.5**	**1.9**	**2**
S2-5-5-F	**1.04**	**1.03**	**1.06**	**8.53**	**8.49**	**8.32**	**12.5**	**13.3**	**14.4**

Table 5.1.1.1.
Surrogate slurry physical properties (continued)

Sample Name	Density, g/cm³			pH			Viscosity, cP		
	4°C	25°C	40°C	4°C	25°C	40°C	4°C	25°C	40°C
S2-5-5-T	**1.02**	**1.02**	**1.03**	**8.54**	**8.43**	**8.25**	**10.7**	**11.3**	**11.9**
S2-5-10-T	**1.05**	**1.06**	**1.05**	**8.66**	**8.33**	**8.24**	**312**	**315**	**378**
S1-25-F	1.16	1.13	1.14	8.93	8.52	8.30	10.1	12.4	13.6
S1-25-T	1.09	1.08	1.07	8.88	8.55	8.33	10	10.8	12.6
S1-25-5-F	1.27	1.27	1.25	8.66	9.06	8.41	76.1	78.7	83.7
S1-25-5-T	1.29	1.26	1.27	8.66	9.00	8.47	91.4	97.3	107
S1-25-10-F	1.29	1.28	1.27	8.87	8.65	8.58	1664	1689	1793
S1-25-10-T	1.25	1.23	1.24	8.38	8.36	8.4	1496	1596	1631
S2-25-F	**1.16**	**1.15**	**1.16**	**7.80**	**7.29**	**7.08**	**10**	**10.7**	**10.8**
S2-25-5-F	**1.19**	**1.18**	**1.16**	**7.63**	**7.85**	**7.12**	**72.8**	**75.5**	**83.5**
S2-25-5-T	**1.16**	**1.14**	**1.15**	**7.57**	**7.73**	**7.23**	**86**	**91.1**	**98.4**
S2-25-10-F	**1.27**	**1.25**	**1.24**	**7.69**	**7.33**	**7.09**	**1263**	**1387**	**1428**
S2-25-10-T	**1.23**	**1.19**	**1.18**	**7.80**	**7.5**	**7.4**	**1214**	**1237**	**1351**
S1-40-F	1.28	1.27	1.25	8.82	8.30	8.04	21.9	24.5	26.1
S1-40-T	1.25	1.25	1.26	8.66	8.14	7.89	22.7	25.6	27.9
S2-40-F	**1.31**	**1.31**	**1.29**	**7.77**	**7.39**	**7.09**	**23.5**	**26.6**	**27.4**
S2-40-5-F	**1.34**	**1.32**	**1.33**	**7.71**	**7.15**	**7.07**	**904**	**1002**	**1047**
S2-40-5-T	**1.28**	**1.26**	**1.27**	**7.80**	**7.33**	**7**	**745**	**790**	**840**

** Freshly prepared samples do not give good viscosity and density readings, since they settle fast.

Sample Naming

S2: Fernald Surrogate without $MgCO_3$ and $CaCO_3$.

S1: Fernald Surrogate with $MgCO_3$ and $CaCO_3$.

25, 35, 40: Slurry concentration in wt%.

5: Bentonite concentration in wt%.

F: Sample prepared before running experiment (fresh).

T: Sample taken from slurry tank.

5.1.2 Density

The density measurements show that the temperature does not have an important effect on the results in the experimental range, but the solids concentration does for both surrogates. The

effects are reflected in Figures 5.1.2.1 and 5.1.2.2. The relationships of the density and the total solids concentration of surrogate and bentonite have been correlated by the following equations:

Surrogate # 1:

$$\rho_e = 2225.7C_t^2 + 29.147C_t + 992.92 \quad (8.1)$$

Surrogate # 2:

$$\rho_e = 310.02C_t^2 + 599.4C_t + 971.1 \quad (8.2)$$

$40^oC \geq T \geq 4^oC$, $0.10 \geq C_b$ when $0.25 \geq C_s \geq 0.05$, and $0.05 \geq C_b$ when $C_s = 0.40$

where:

ρ_e = slurry effective density, Kg/m^3;

C_t = concentration of total solids, wt%.

C_b = Concentration of bentonite, wt%.

Note: In the equation, 0.25 means 25% solid in the slurry. The density could also be calculated with the unit of lb/ft^3 by multiplying these coefficients in the above equation by 0.0625.

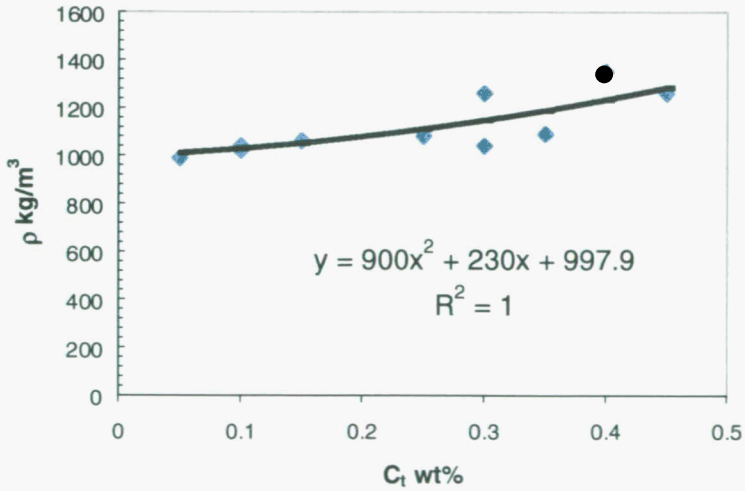

Figure 5.1.2.1. Density and solid concentration relationship of surrogate #1.

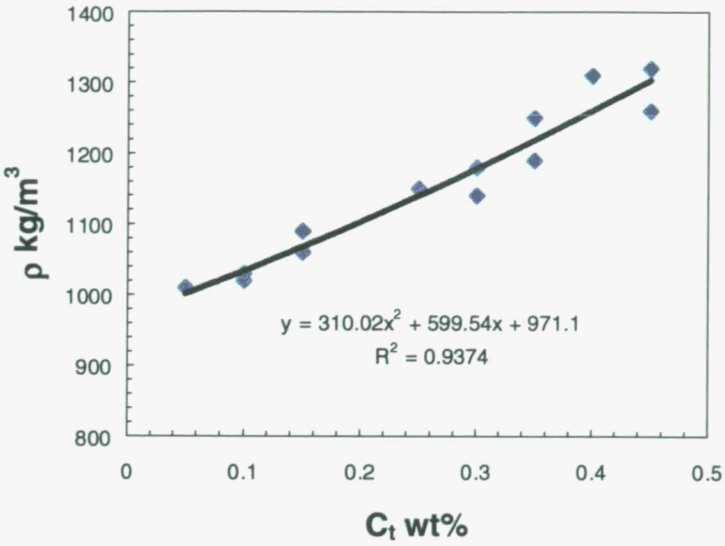

Figure 5.1.2.2. Density and solid concentration relationship of surrogate #2.

5.1.3 Viscosity and Temperature

The temperature effect on the surrogate viscosity was observed for most of the measurements in the range of 4 to 40°C. The results showed that the slurry viscosity increased as the temperature went up. The viscosity dramatically increases with the solids concentration, especially when the bentonite is presented in the slurries. The dependencies of the viscosity on the solids concentration including bentonite have been shown in Figures 5.1.3.1 through 5.1.3.3. The relationships between the viscosity and the solids concentration have been correlated by the following equations for the cases with or without bentonite.

Surrogate # 1:

$$\eta_e = 1.6348e^{7.12Cs} \tag{9.1}$$

Surrogate # 2:

$$\eta_e = 1.383e^{7..60Cs} \tag{9.2}$$

Surrogate # 2 (with 5% bentonite):

$$\eta_e = 3.2047e^{12.15Ct} \tag{9.3}$$

where:

η_e = surrogate effective viscosity, cP.

C_s = surrogate concentration, wt%.

C_t = total concentration including bentonite, wt%

Note: The viscosity is an exponential function of the solids concentration. The viscosity for surrogate 1 with bentonite was not correlated because there are only two data points.

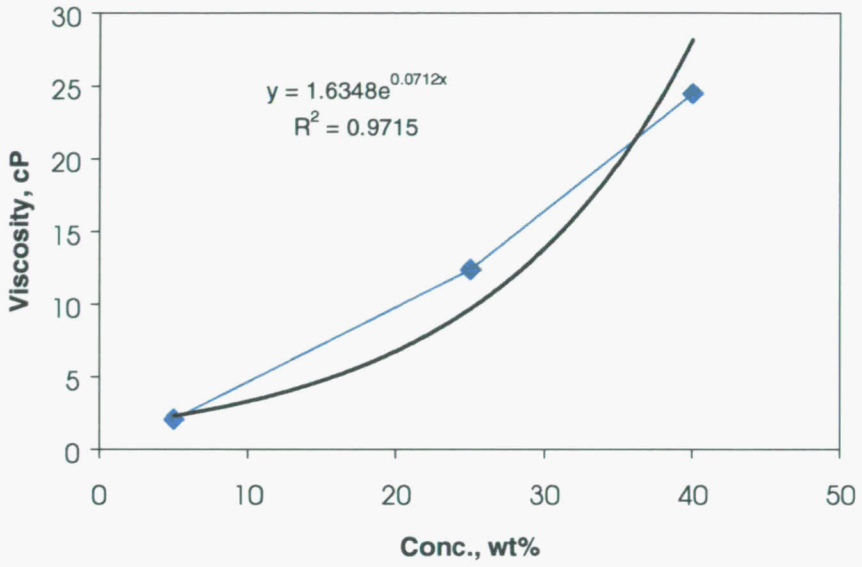

Figure 5.1.3.1. Concentration effect on fresh surrogate #1 viscosity at room temperature.

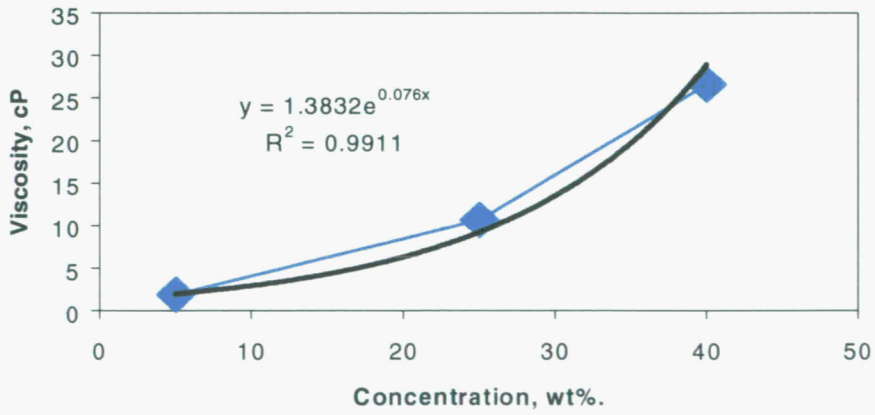

Figure 5.1.3.2. Concentration effect on fresh surrogate #2 viscosity at room temperature.

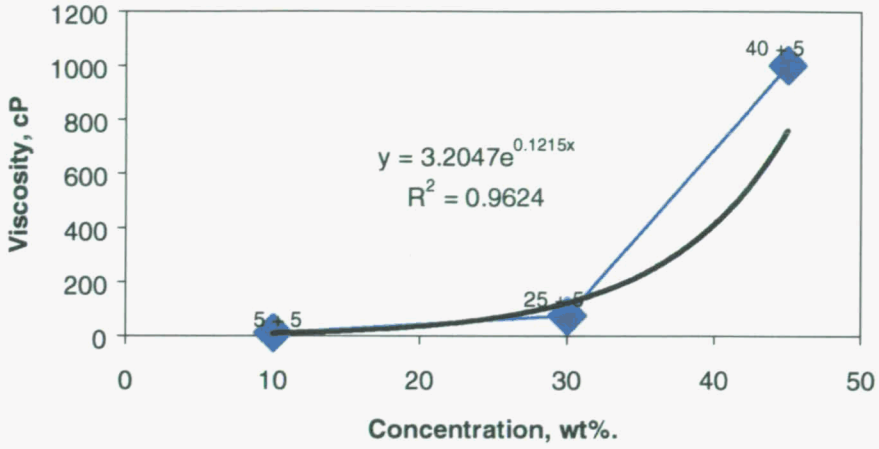

Figure 5.1.3.3. Concentration effect on fresh surrogate #2 + bentonite viscosity at room temperature.

5.1.4 Particle Size Analysis Results

The particle size analysis has been conducted for 5% and 25% surrogate slurries with and without bentonite. Both the supernate and the settled phases were analyzed. The results of the analysis are shown in Appendix A.

5.1.5 Particle Analysis Chart Sample

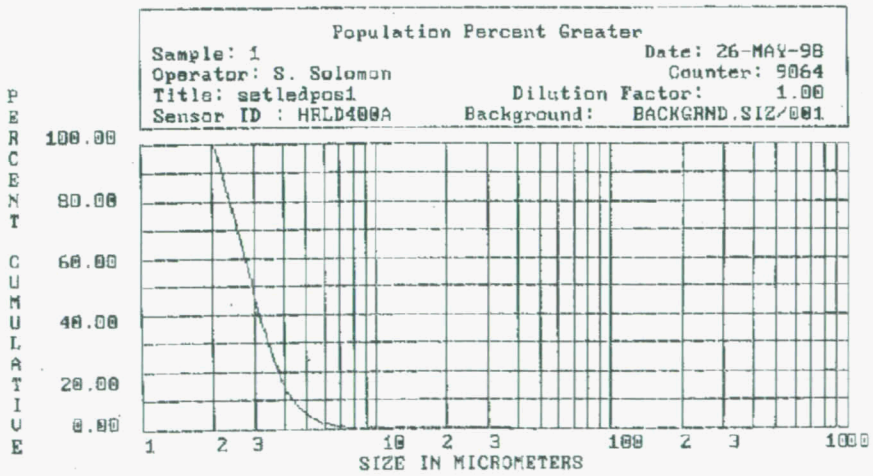

Figure 5.1.5.1. 5% unpumped surrogate without bentonite – supernatant of settled material, at 10 mm depth.

5.2 EFFECTS OF PUMPING ON PARTICLE SIZE

The effects of pumping on the particle size are summarized in Table 5.2.1 and Table 5.2.2 for supernatant and settled material, respectively. The data may suggest that the pumping process breaks down some of the particles into smaller sizes.

Table 5.2.1.
Effect of pumping on the particle size distribution of supernatant liquid of surrogate

Supernatant Liquid after Settling				
	UNPUMPED		PUMPED	
Concentration Solid + Concentration Bentonite	Particle Size Range, μm	Size of Particles with Greater than 50% Population, μm	Particle Size Range, μm	Size of Particles with Greater than 50% Population, μm
5%+0%	2 - 8	3.1	2 - 30	3.2
25%+0%	2 - 11	3.9	2 - 20	4.0
5%+5%	2 - 10	4.8	2 - 15	6.0
25%+5%	2 - 30	6.8	2 - 32	7.2

Table 5.2.2.
Effect of pumping on the particle size distribution of settled material of surrogate

Settled Material				
	UNPUMPED		PUMPED	
Concentration Solid + Concentration Bentonite	Particle Size Range, μm	Size of Particles with Greater than 50% Population, μm	Particle Size Range, μm	Size of Particles with Greater than 50% Population, μm
5%+0%	2 - 20	7.5	2 - 45	13.0
25%+0%	2 - 40	16	2 - 41	17.0

It appears that pumping does not have as great an effect on particle size as had been expected. In general, the particle size range and the particle sizes with greater than 50% population did not change much, except for the case of 5%+5% supernatant and the 5%+0% settled material where they went from 4.8μm to 6.0μm and 7.5μm to 13.0μm, respectively.

5.3 SURROGATE SLURRY PARTICLE SETTLING DATA

The surrogate slurry settling behavior has been recorded and measured using the same procedures as those used for the K-65 materials. The samples were prepared or collected in a 400ml sample bottle. The height and the diameter of the bottle are 5 and 2.75 inches. At time

equal to zero, the slurry samples were well mixed and placed on a stationary bench for settling. Then, the same procedure conducted with the hot material was followed with the surrogate. Please see section 4.0 of this report.

The measured settling distances, the ratios of the distances to the sample height, and the calculated settling velocity are shown Appendix B in Table B.3 for surrogate number 1 and in Table B.4 for surrogate number 2. In addition, the total settled distance and the actual settled distance along with settling time have been plotted in Figures C.2.1 to C.2.15 in Appendix C.

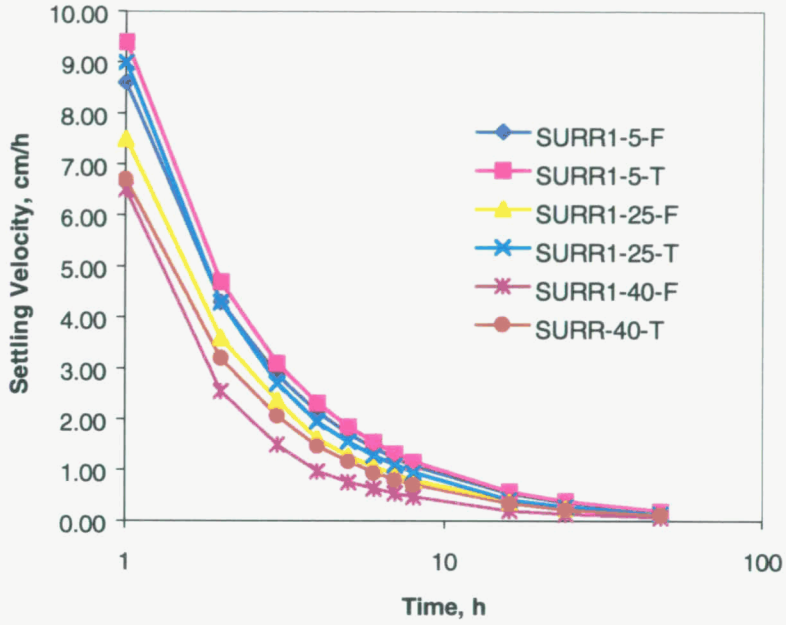

Figure 5.3.1. Settling velocity versus time for surrogate 1 slurry with and without bentonite.

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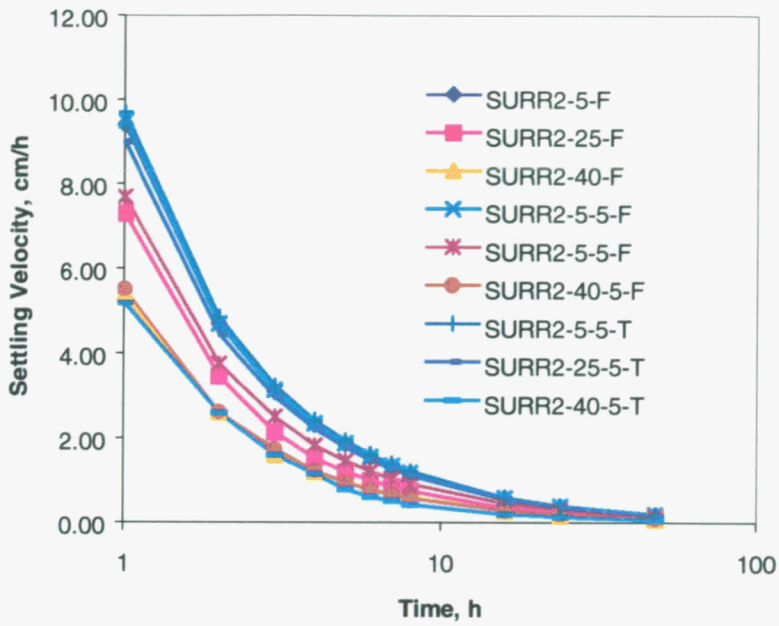

Figure 5.3.2. Settling velocity versus time for surrogate 2 slurry with and without bentonite.

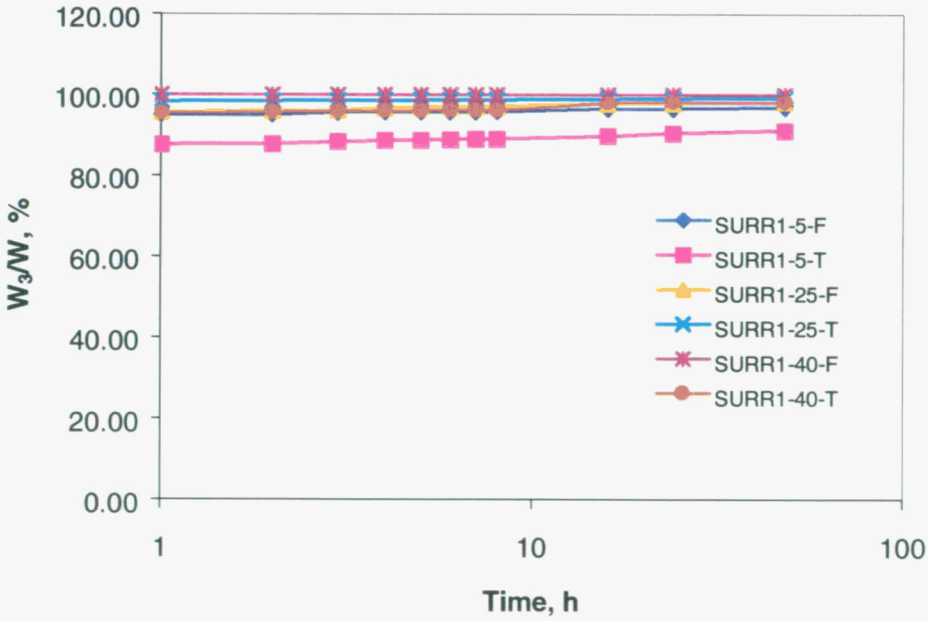

Figure 5.3.3. Weight ratio of settled solids to total solids for surrogate 1 slurry with and without bentonite.

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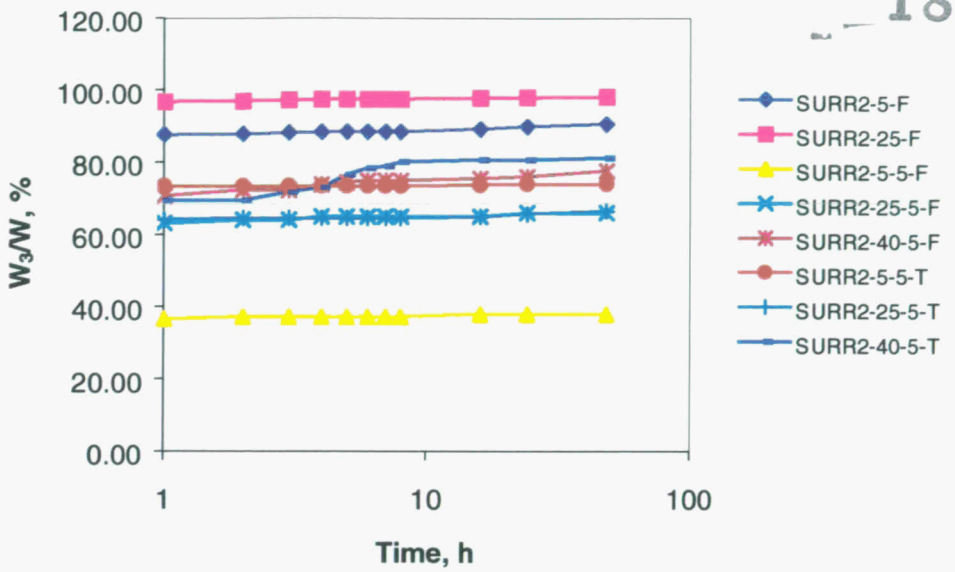

Figure 5.3.4. Weight ratio of settled solids to total solids for surrogate 2 slurry with and without bentonite.

5.4 PRESSURE DROP RESULTS AND COMPARISON

The purpose of developing surrogate is to find a substitute for silo material for testing and demonstration without involving radiation. To examine the consistency of flow resistance between silo and surrogate slurries, the pressure drop results are compared in this section.

Figure 5.4.1 and 5.4.2 show the comparison of 25% slurries of silo material and surrogate #2 without and with 5% bentonite, respectively, in the horizontal test section and at about 20°C temperature. The comparison indicates that the pressure gradient of surrogate #2 is very close to that of silo material.

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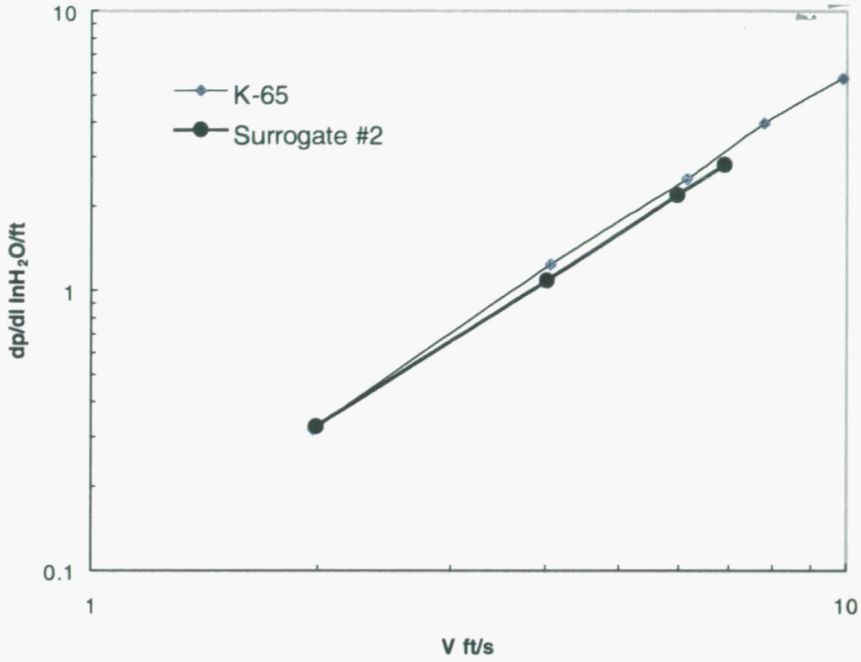

Figure 5.4.1. Comparison of pressure gradients of 25% slurries of K-65 and surrogate #2 without bentonite.

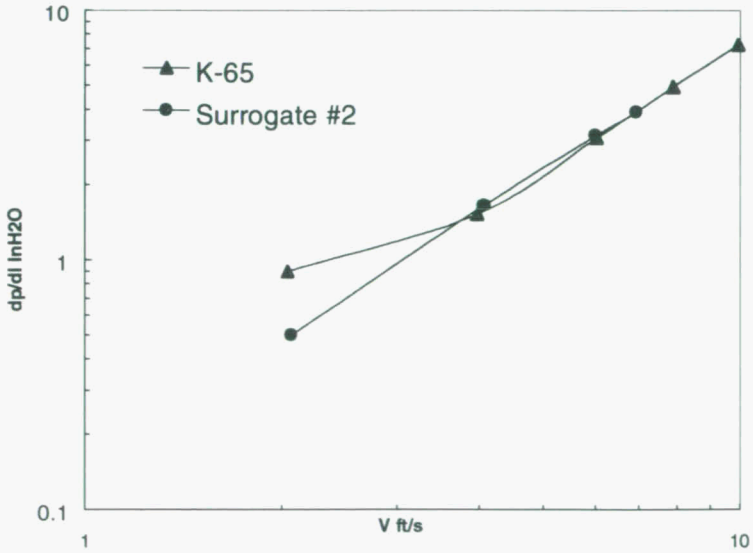

Figure 5.4.2. Comparison of pressure gradients of 25% slurries of K-65 and surrogate #2 with 5% bentonite.

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6.0 RADIATION SAFETY

6.1 RADIOACTIVE MATERIALS LICENSE

The Hemispheric Center for Environmental Technology (HCET) at Florida International University (FIU) has set up facilities to perform the investigation of the rheological properties of K-65 residue slurries from Silos 1 and 2 at the United States Department of Energy, Fernald site, Cincinnati, OH. A radioactive material license (#2846-1) was obtained from the Bureau of Radiation Control, Department of Health, State of Florida, for carrying out studies in the radiological laboratories at the Center of Engineering and Applied Sciences, Florida International University. The license covers radioactive materials and quantities needed for the rheological studies.

6.2 TRAINING

All personnel working in the Radiological Laboratory were trained in radiation safety. Some of the persons were also trained in the Department of Transportation regulations. The Radiation Safety Associates and International Union of Operating Engineers conducted these training courses.

6.3 RADIATION LABORATORY SAFETY FEATURES

The radiological laboratory at FIU-HCET is designed to handle radioactive materials in solution/slurry form or as sealed sources. The K-65 materials contain Uranium (238, 235/236, 234), Thorium (232, 230, 228), Radium-226, and their decay products. Radon-222 and Thoron-220 are gaseous decay products of Ra-226 and Ra-224, respectively, and may diffuse to the working environment, if not properly contained. Radon reaches the activity level of Radium-226 in three weeks, whereas thoron attains equilibrium with Ra-224 in 10 minutes. The short-lived decay products of Radon-222 attain activity of Radon-222 in three hours. Thoron decay products reach activity level of Th-228 in three weeks. Radon, thoron, and their short-lived decay products are of concern for both internal (inhalation) and external exposure (gamma radiation). To mitigate both internal and external exposures, all operations on the radioactive slurry were carried out in the glove box. The rheology loop was installed in the glove box. The glove box was at a lower pressure than the laboratory. The air from the loop and the glove box was exhausted through activated charcoal filtration systems. The rheology loop filtration prevents the buildup of radon, thoron, and their decay products in the loop. These radioactive species were trapped in the activated charcoal filtration system of the loop. The charcoal filtration system and slurry tank were shielded with three inches of lead to minimize gamma ray exposures. The air from these systems, as well as from the laboratory, passes through high-efficiency particulate air filters (HEPA) and an activated charcoal filter before releasing to the environment. Air flowing from the laboratory, fume hood, glove box, and loop passed through once. The exhaust system was run constantly.

7.0 QUALITY ASSURANCE

An uncontrolled copy of the FIU-HCET Quality Assurance Program Manual was transmitted to Fluor Daniel Fernald (FDF) with the Project Specific Plan (PSP) prior to start of project work. Both documents were approved by FDF on February 12, 1998, per Letter No. C: PS (CA/ACO):98-0128. Provisions in the PSP identified Quality Assurance/Quality Control requirements specified in the FDF Statement of Work to assure the quality and reliability of the rheology project data collected and analyzed.

Project records and weekly teleconference minutes with FDF describe how these requirements have been integrated and implemented. Calculations used in determining slurry density, settling times, physical property measurements, viscosity, pressure drops, and flow rates were measured using calibrated instruments. Calibration records performed at FIU-HCET are a part of project records. Repeat testing was done on a random basis to determine validity of data, and results were within control limits. Verification of calculation accuracy, precision, representativeness, and completeness was completed in-house with customer concurrence as documented in the weekly teleconference minutes.

This final report contains or references project documentation, including calibration records, that verifies the quality of data collected and methods of analysis. Electronic calculations were performed using FORTRAN software, and results are maintained on a Microsoft Excel database. Laboratory notebooks contain calculations used in determining ratios of bentonite to slurry and to the surrogates. Particle and chemical analyses performed in the analytical laboratory were performed using standard laboratory solutions and methods as described in this report. Documentation of the methods and results are recorded in the analytical laboratory notebook. Photocopies of laboratory notebook pages relating to this project are included in the project records.

The intent of Quality Assurance requirements specified in the FDF Statement of Work has been documented and supports the quality of technical data for its intended use as presented in this report.

8.0 ACCOMPLISHMENTS AND RECOMMENDATIONS

This project started September 1, 1997. During the course of the project, all tasks defined in the work statement and PSP have been conducted. The main accomplishments are summarized as follows:

8.1 ACCOMPLISHMENTS

1. Two hydraulic testing pipeline systems for the silo material and surrogate testing were designed and built.
2. The physical properties of the silo material slurries and surrogate slurries were measured.
3. Particle size analysis was performed for the silo material slurries and surrogate slurries.
4. The settling behaviors of silo material slurries and surrogate slurries were observed, and the settling velocity was measured for the stationary samples.
5. The pressure drop across different straight tube test sections and bends was measured. A set of correlations was regressed.

8.2 RECOMMENDATIONS

From the results and discussion, the following points are recommended:

6. Surrogate #2 can be used as a substitute for K-65 silo material for testing and demonstration under the operating conditions used in this study.
7. When pumping the K-65 silo material slurry, the pipeline should be run in power-law range to avoid plugging. For one-inch pipeline, the power-law range can be presented as

$$C_b = 0, \quad 0.25 \geq C_k \geq 0.05, \quad 10 \geq u \geq 2; \quad \text{and} \quad 0.40 \geq C_k > 0.25, \quad 10 \geq u \geq 4$$

$$C_b = 0.05, \quad C_k = 0.05, \quad 10 \geq u \geq 2; \quad \text{and} \quad C_k = 0.25, \quad 10 \geq u \geq 4$$

8. The regressed pressure gradient or friction factor correlations can be used to predict the flow resistance in the power-law range. The following pressure gradient correlation is recommended for prediction of pressure drop in straight section of the pipeline,

$$\frac{dp}{dl} = (0.07945 + 0.2736C_k^{1.389} + 0.1347C_b^{0.4148})u^{1.65} / d^{1.35}$$

which can only be used in the power-law range. If used for larger diameter pipeline calculations, the correlation runs high risks of underestimation.

9. The minimum transporting velocity ranges from 0.5-1.5 ft/s depending on the concentration. However, the optimal transporting is in the upper range of power-law range. Based on the 1-inch tube testing and settling tests, the ideal slurry condition for pipeline transportation is 25% K-65 silo material and 5% bentonite in the velocity range from 4 ft/s to 8 ft/s.
10. For K-65 material, the particle size analysis indicates that the particles in supernatant are in the range of 2-15 μm without bentonite and 2-10 μm with 5% bentonite. The particles in top

of the settled phase can be as large as 25 μm for lower concentration and 40 μm for higher concentration. Therefore, the bentonite did help the K-65 settling. This was supported by the observation in the settling tests. For surrogate slurry, similar particle size distribution was found.

11. The settling behavior of the slurry has been defined with three settling layers: clear supernate, cloud suspension, and settled phase. The interfaces between these layers have been detected by a hydrometer, and the settling distances have been measured using a rule. To improve the accuracy of the measurement in future work, a density gradient meter is recommended to detect the location of the interfaces.
12. To verify the validation of the correlations for a larger diameter pipeline, large-scale testing is needed. The pressure drop across the valve, enlargement section, and contraction section can provide more data that are useful for pipeline design.
13. Some further analysis is needed to identify the composition of the particles and solid concentration in supernatant, especially for the slurry with bentonite. This kind of information can clarify the function of bentonite in the settling and transporting processes. The interaction between bentonite and K-65 material can be studied chemically to explain the settling phenomena.
14. The study of phase separation or plugging behaviors in complex loop components such as reducers, the pump chamber, and valves may be needed to identify the most probable location of plugging in the pipeline system.

9.0 REFERENCES

1. M.A. Ebadian, Rheology Testing of Fernald Waste Residual Slurry for the Fernald Environmental Management Project—Project Specific Plan, Hemispheric Center for Environmental Technology, September 1997.
2. Robert L. Mott, *Applied Fluid Mechanics*, 4th Edition, Macmillan Publishing Company, 1994.
3. M. A. Ebadian, Lessons Learned from Pump Selection for Slurry Transportation in Pipeline, Hemispheric Center for Environmental Technology, 1998.

APPENDIX A

APPENDIX A

PARTICLE SIZE ANALYSIS RESULTS

A-1. K-65 SAMPLES PARTICLE SIZE ANALYSIS RESULTS

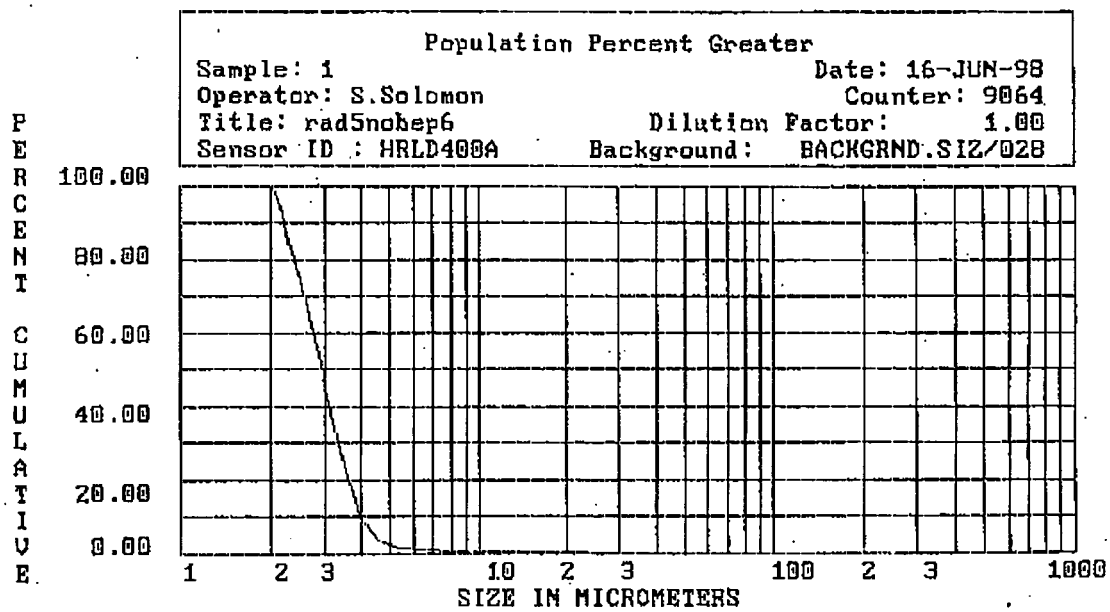

Figure A.1.1. Unpumped K-65 Slurry Without Bentonite Supernatant of Settled Material, at 10 mm Depth, Undiluted.

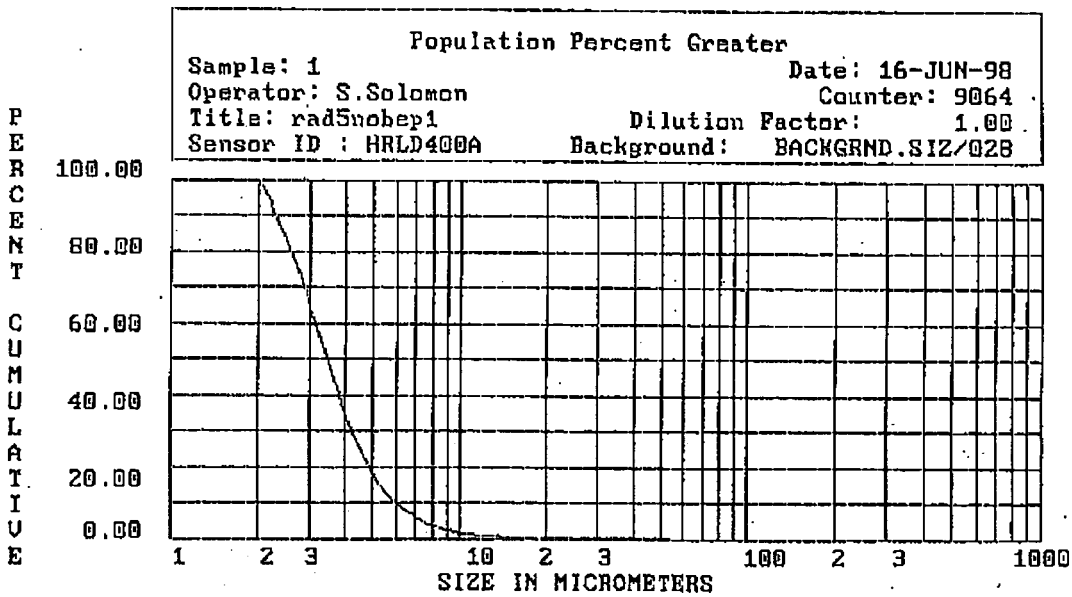

Figure A.1.2. 5% Unpumped K-65 Slurry Without Bentonite Supernatant of Settled Material, at 60 mm Depth, Undiluted.

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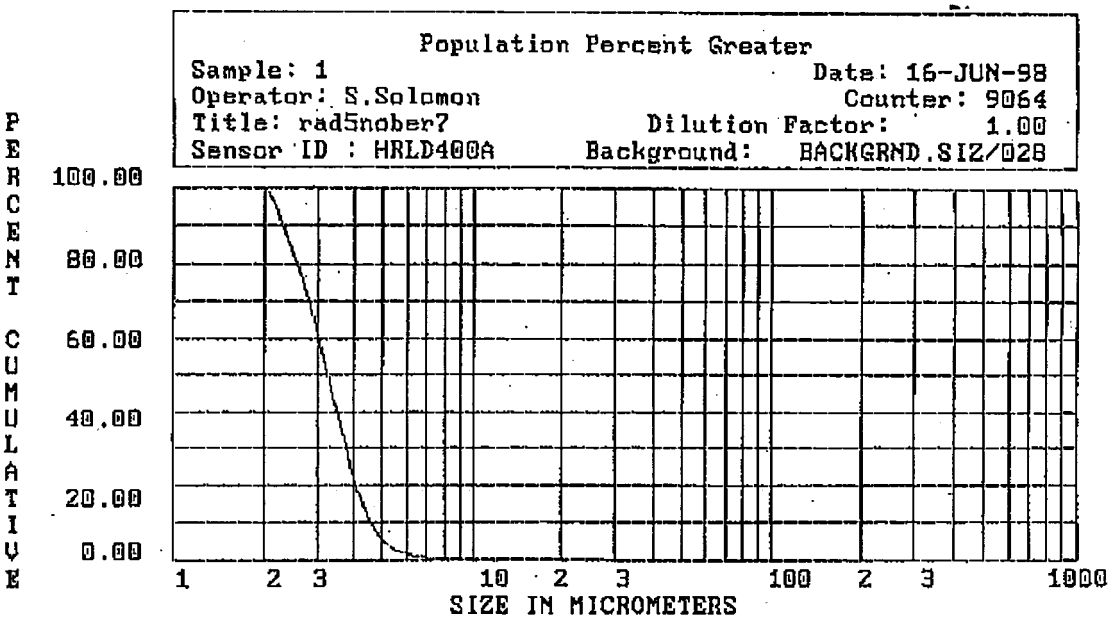

Figure A.1.3. 5% Unpumped K-65 Slurry Without Bentonite—Sample at Top of Solid Settled Material, Undiluted.

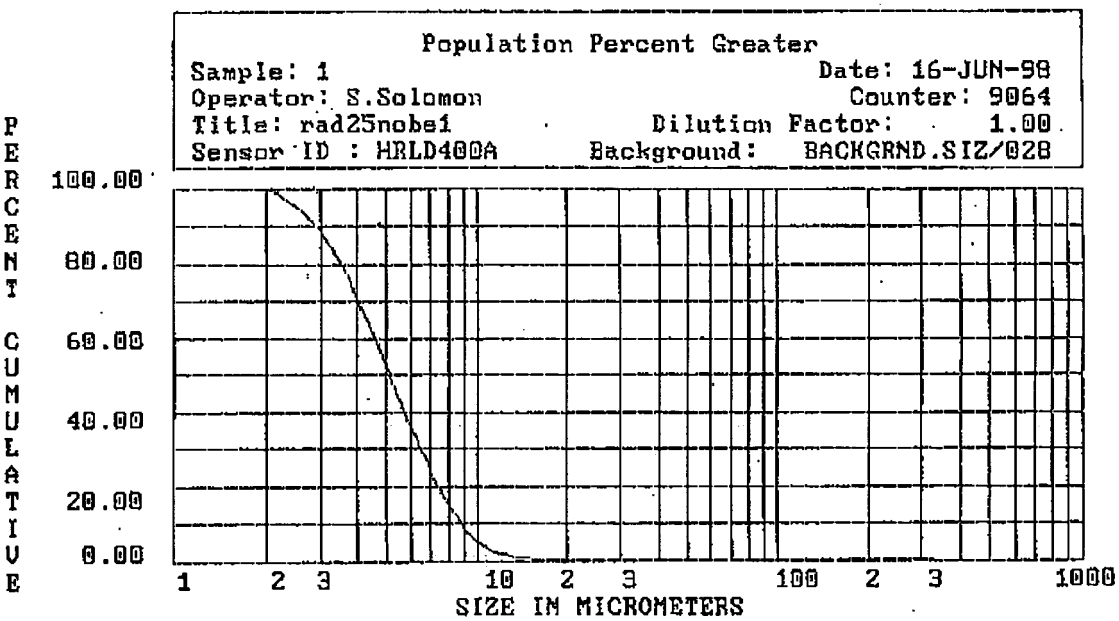

Figure A.1.4. 25% Unpumped K-65 Slurry Without Bentonite—Supernatant of Settled Material, at 10 mm Depth, Undiluted.

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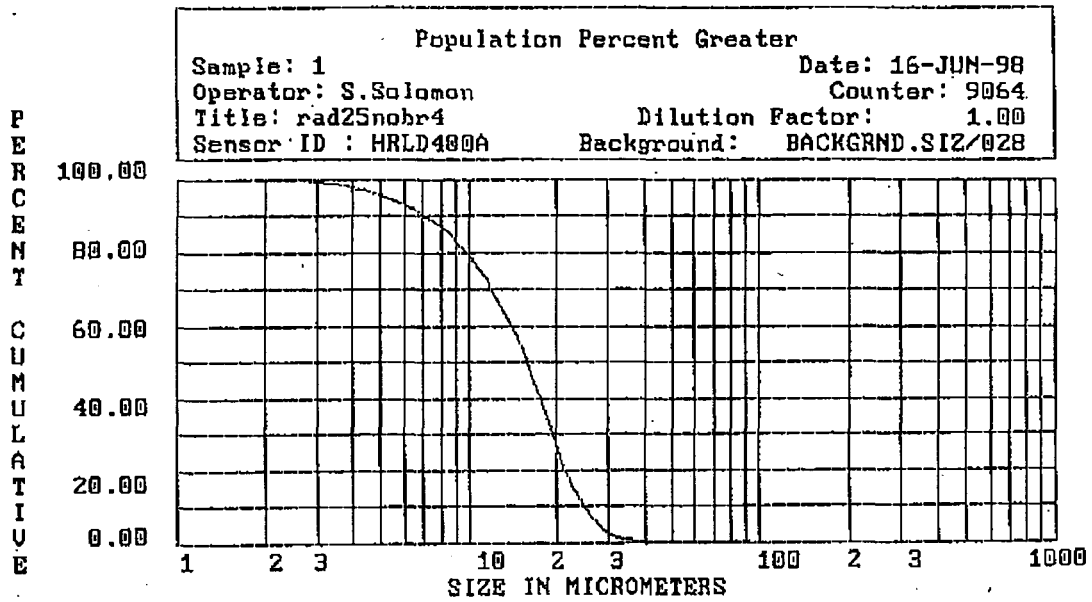

Figure A.1.5. 25% Unpumped K-65 Slurry Without Bentonite—Sample at Top of Solid Settled Material, Undiluted.

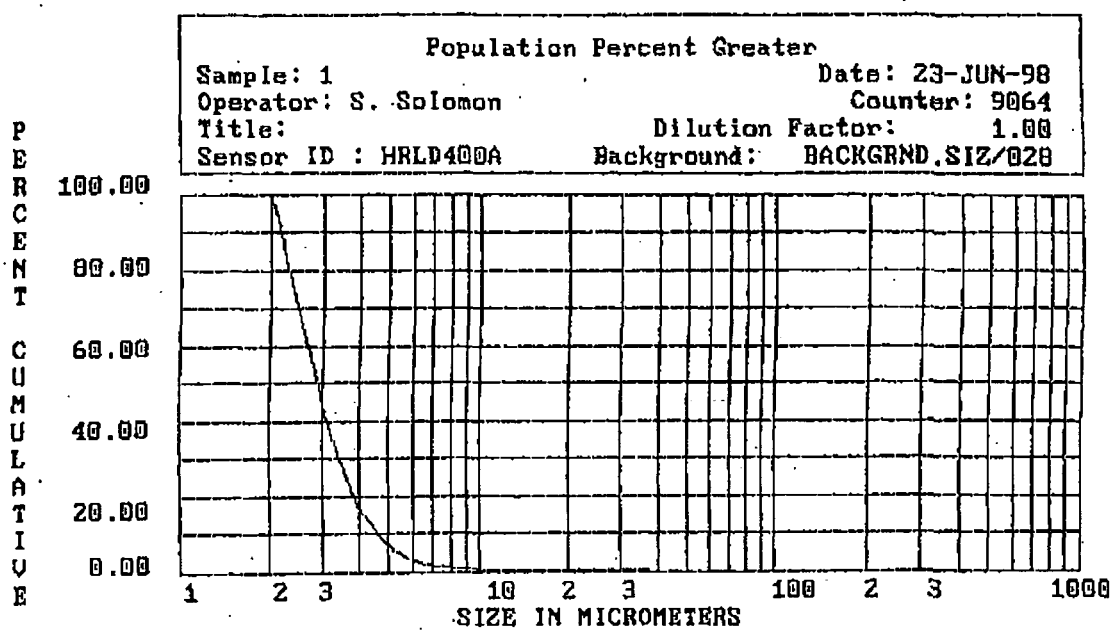

Figure A.1.6. 5% Pumped K-65 With 5% Bentonite—Supernatant of Settled Sample, at 10 mm Depth, Undiluted.

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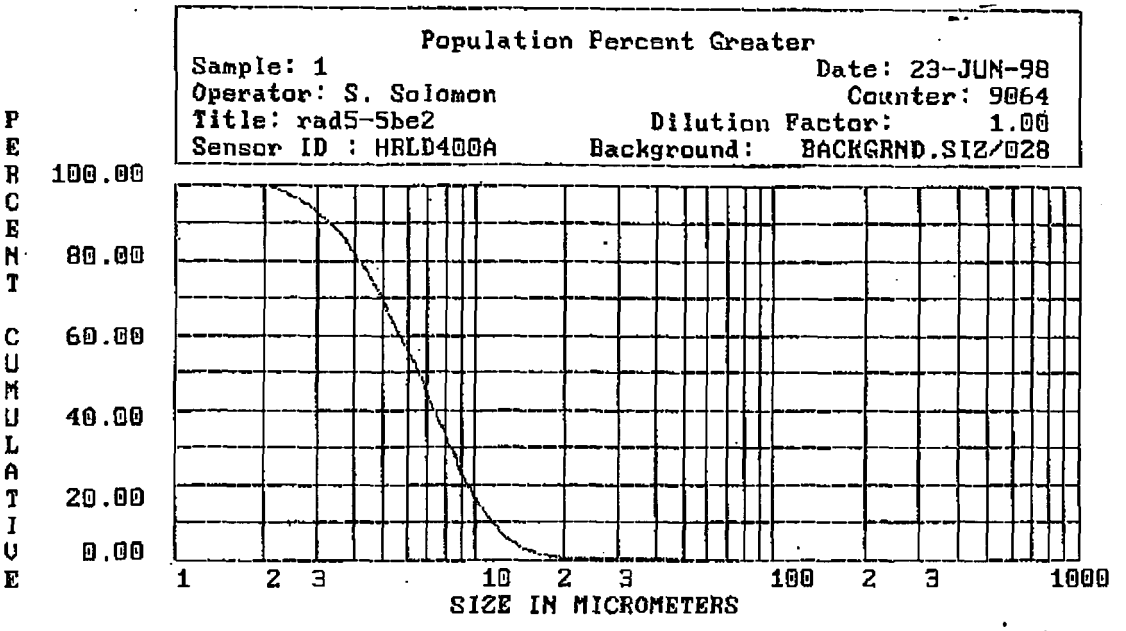

Figure A.1.7. 5% Pumped K-65 With 5% Bentonite—Settled Sample, at Top of Residue, Undiluted.

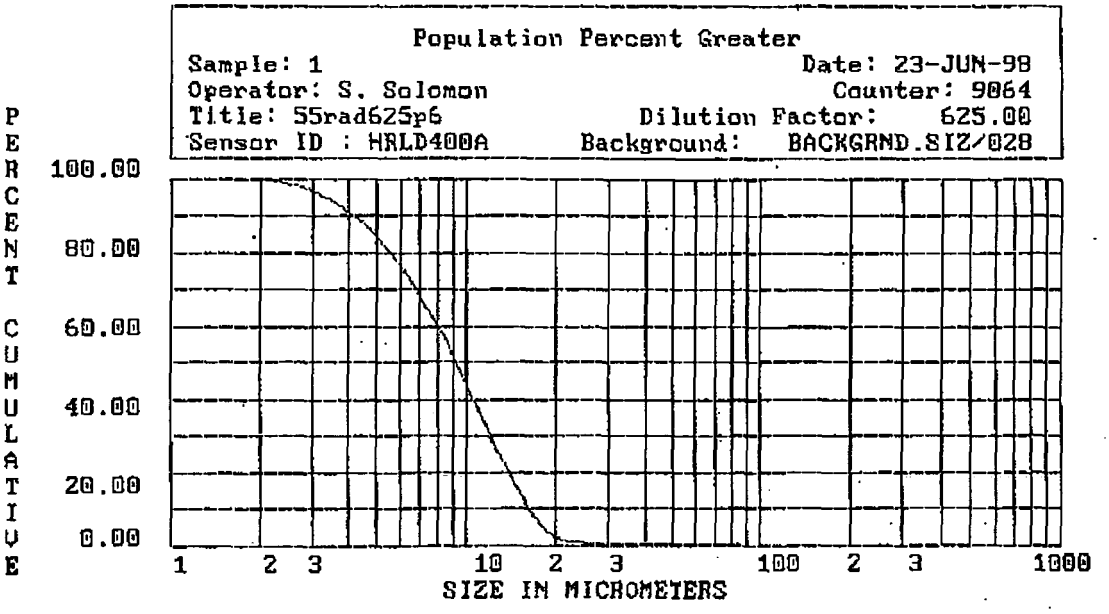

Figure A.1.8. 5% Pumped K-65 With 5% Bentonite—Settled Sample, at Full Depth, Diluted 1:625.

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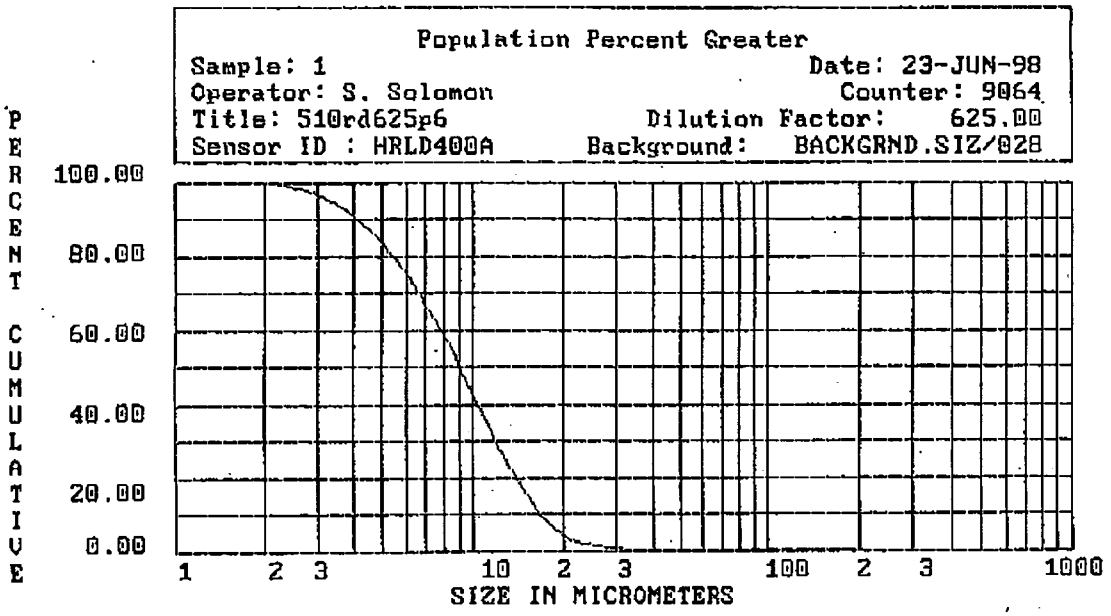

Figure A.1.9. 5% Pumped K-65 With 5% Bentonite—Settled Sample, at Full Depth, Diluted 1:625.

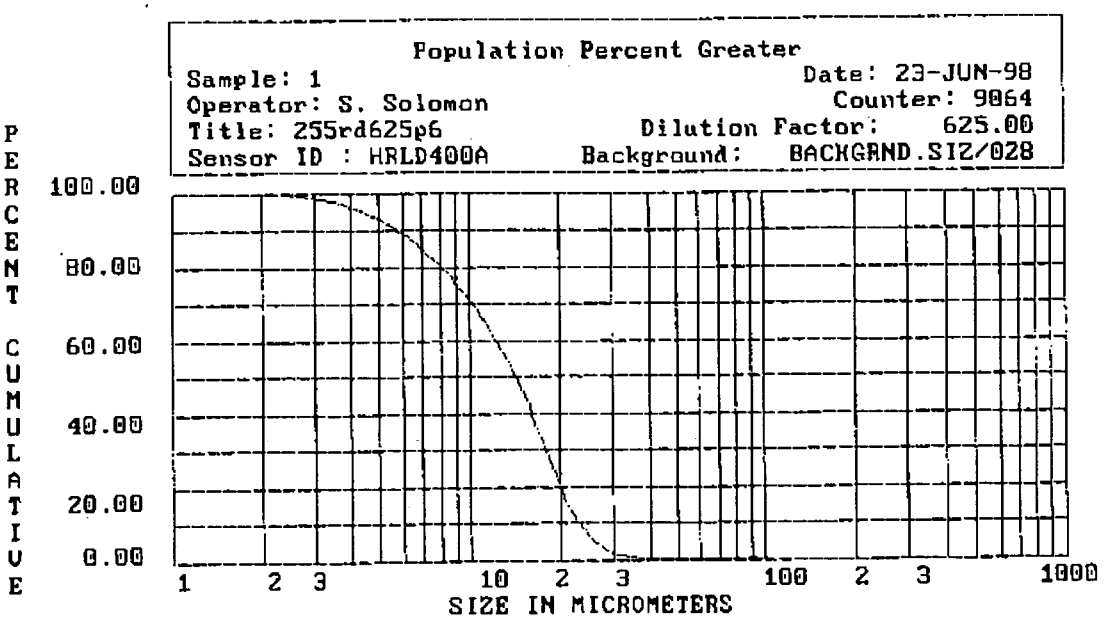

Figure A.1.10. 25% Pumped K-65 With 5% Bentonite—Settled Sample, at Full Depth, Diluted 1:625.

1811

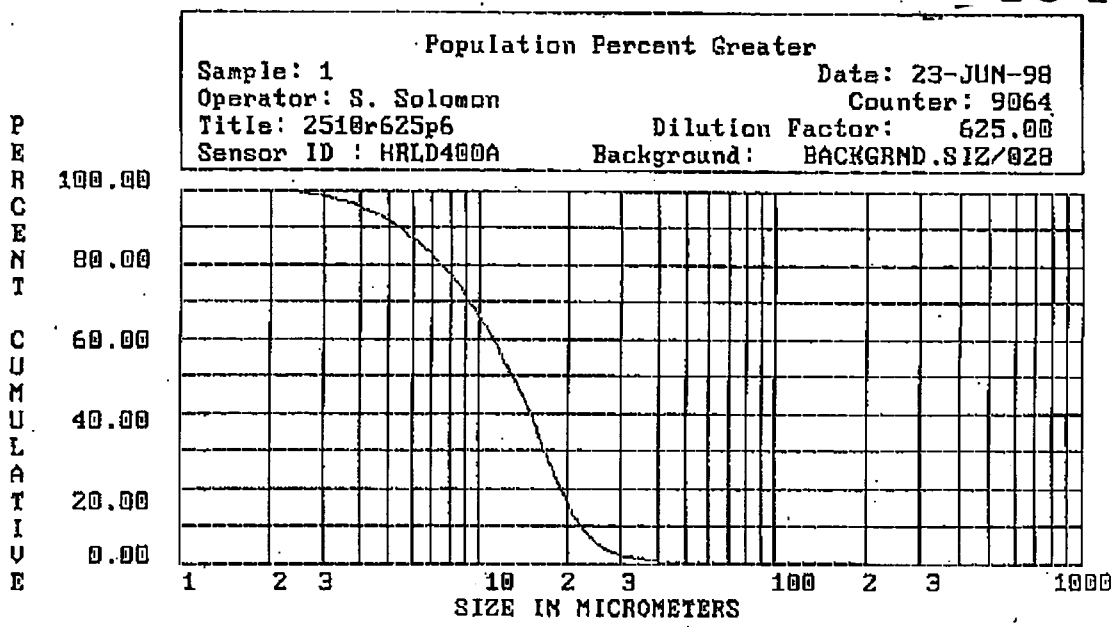

Figure A.1.11. 25% Pumped K-65 With 10% Bentonite—Settled Sample, at Full Depth, Diluted 1:625.

A-2. SURROGATE SAMPLES PARTICLE SIZE ANALYSIS RESULTS

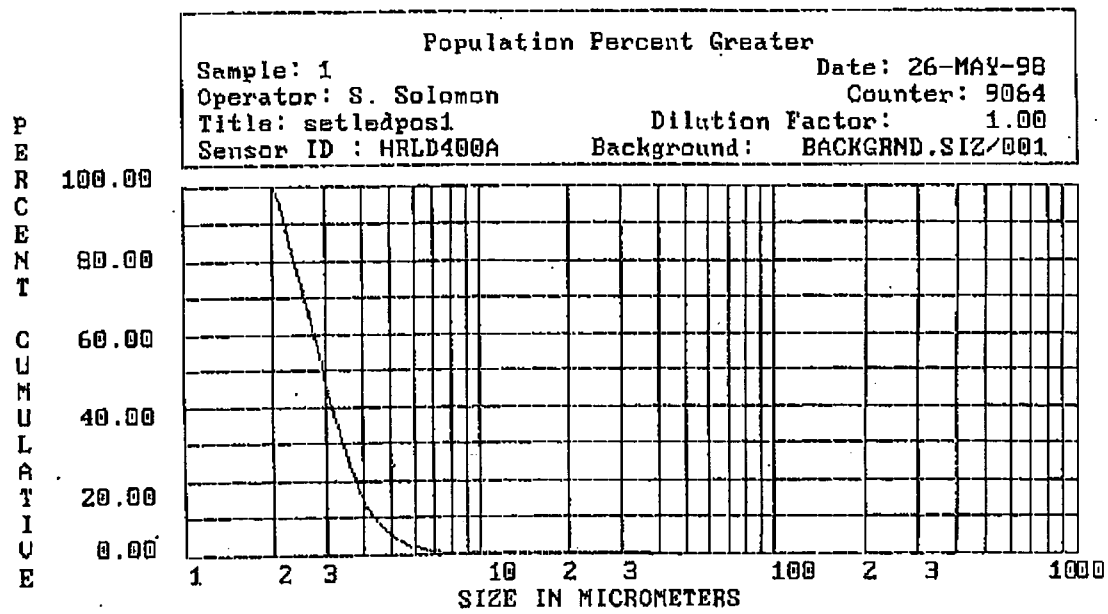

Figure A.2.1. 5% Unpumped Surrogate Without Bentonite-Supernatant of Settled Material, at 10 mm Depth.

000064

1811

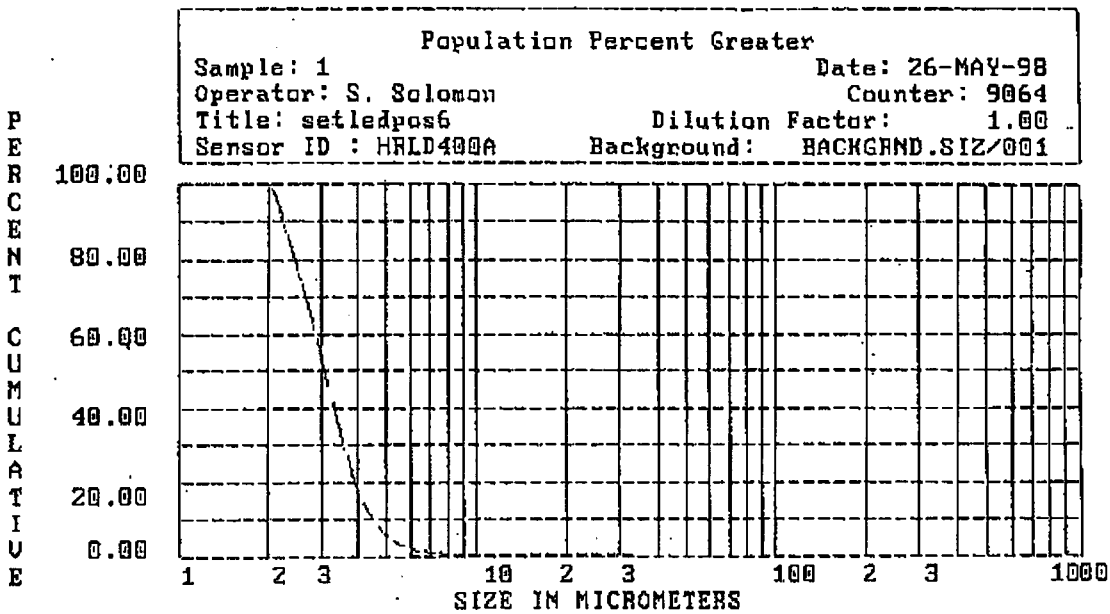

Figure A.2.2. 5% Unpumped Surrogate-Supernatant of Settled Material, at 60 mm Depth.

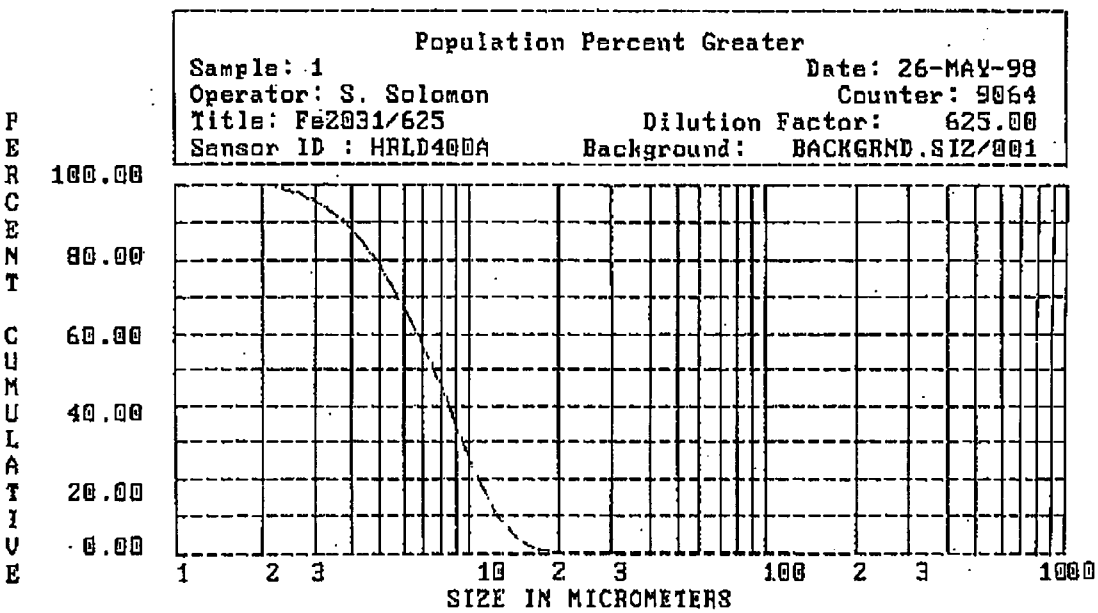

Figure A.2.3. 5% Unpumped Surrogate-Supernatant of Diluted Red Settled Layer, 1:625 Dilution 30 mm Depth.

000065

1811

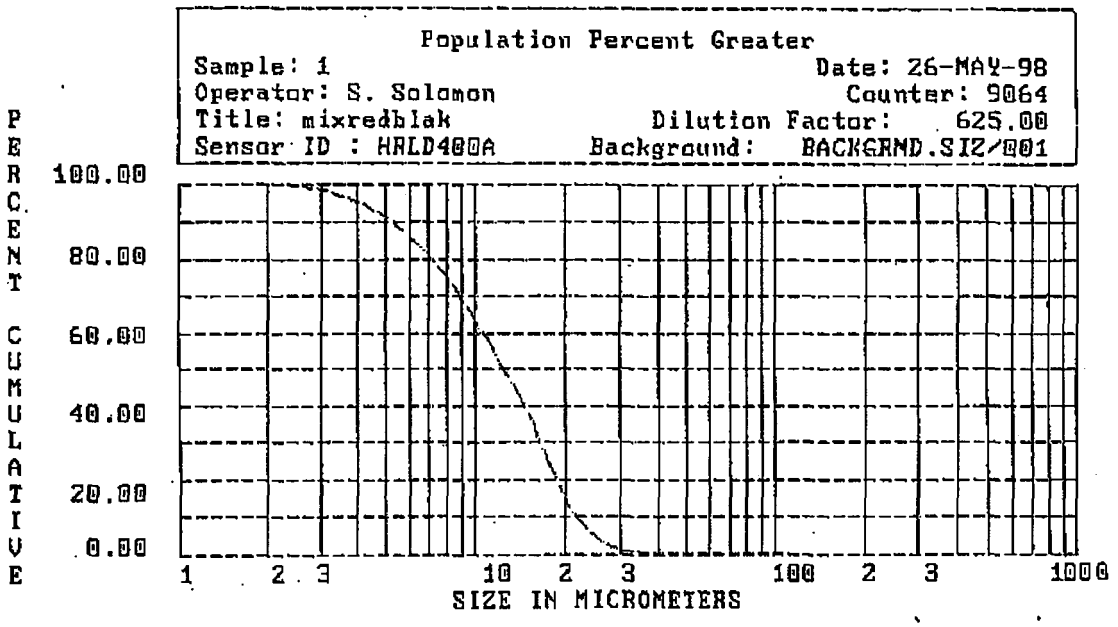

Figure A.2.4. 5% Unpumped Surrogate-Supernatant of Diluted Black Settled Layer, 1:625 Dilution.

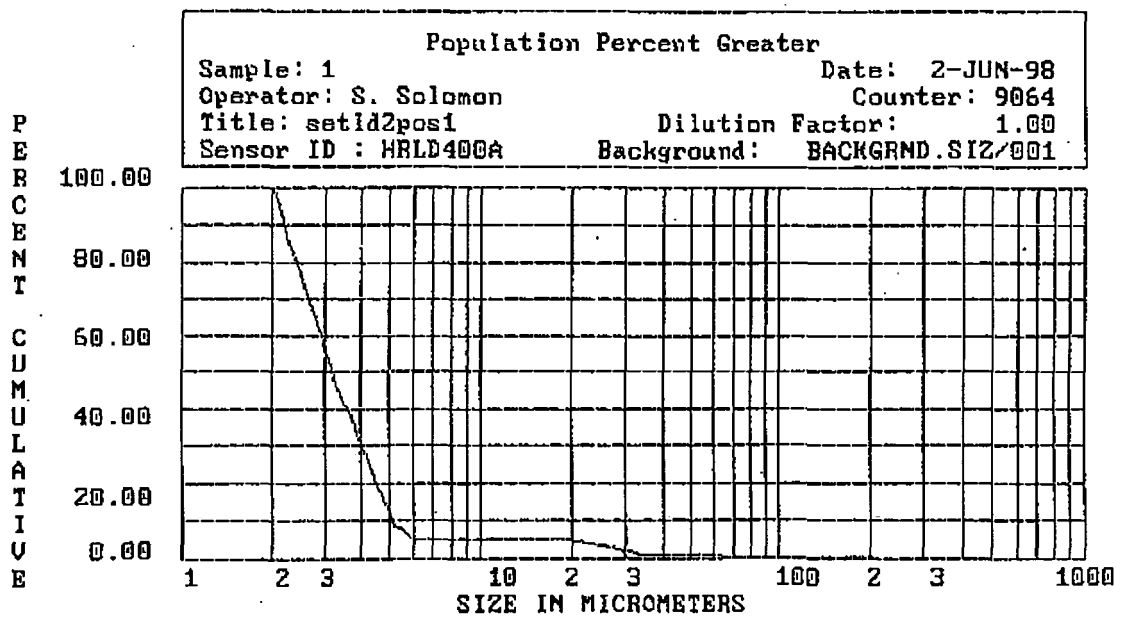

Figure A.2.5. 5% Pumped Surrogate-Supernatant of Settled Material, at 10 mm Depth.

000066

1811

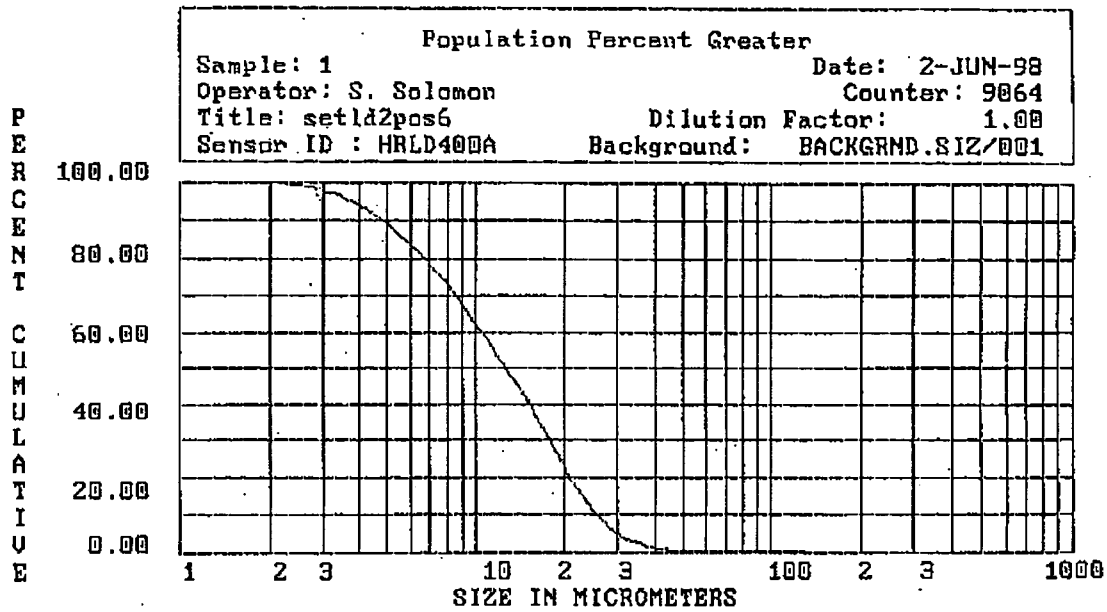

Figure A.2.6. 5% Pumped Surrogate-Sample at Top of Red Settled Material, Undiluted.

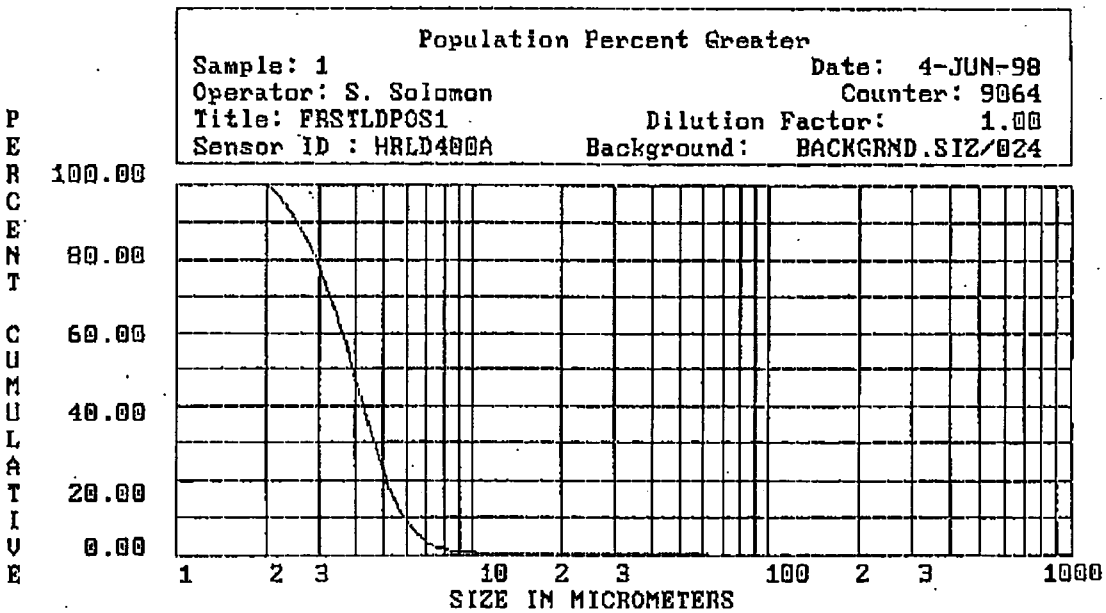

Figure A.2.7. 25% Unpumped Surrogate Without Bentonite-Supernatant of Settled Material, at 10 mm Depth.

000067

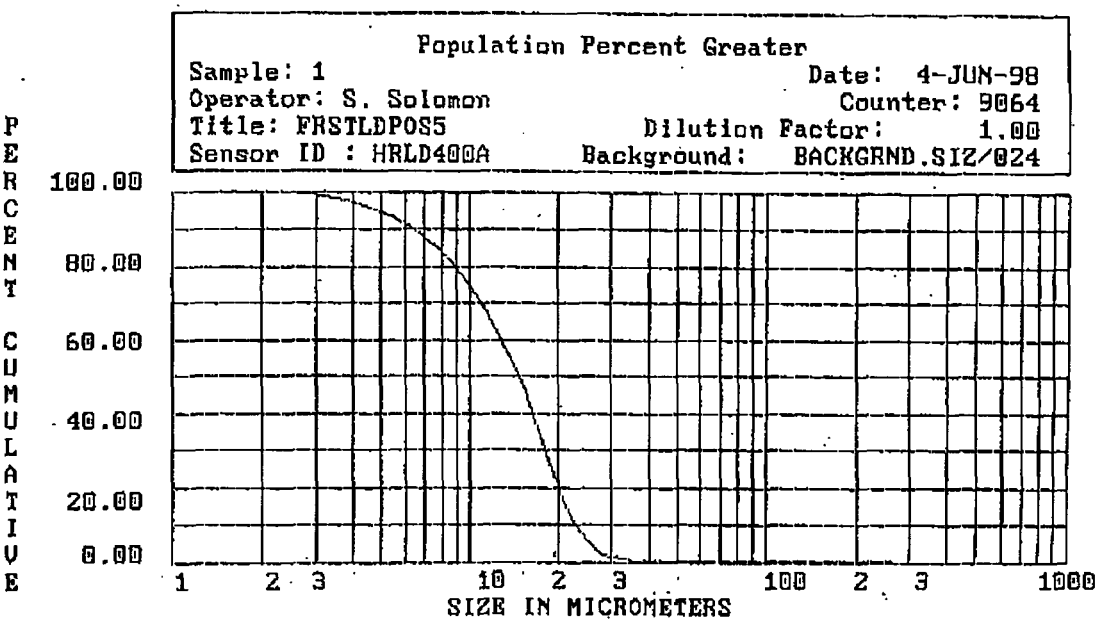

Figure A.2.8. 25% Unpumped Surrogate-Sample at Top of Red Settled Material, Undiluted.

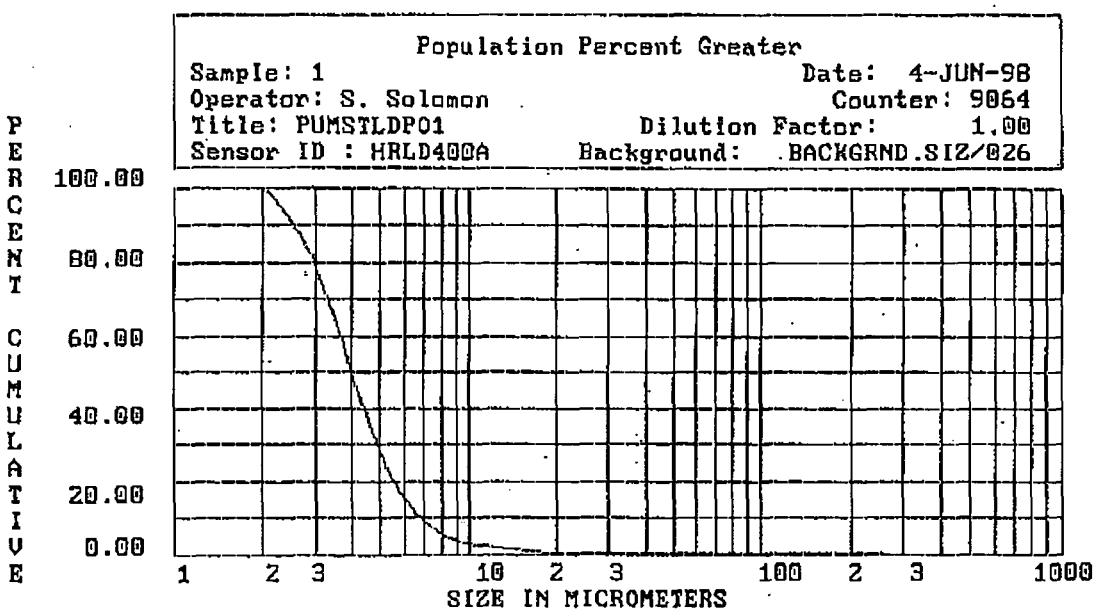

Figure A.2.9. 25% Pumped Surrogate Without Bentonite-Supernatant of Settled Material, at 10 mm Depth.

1811

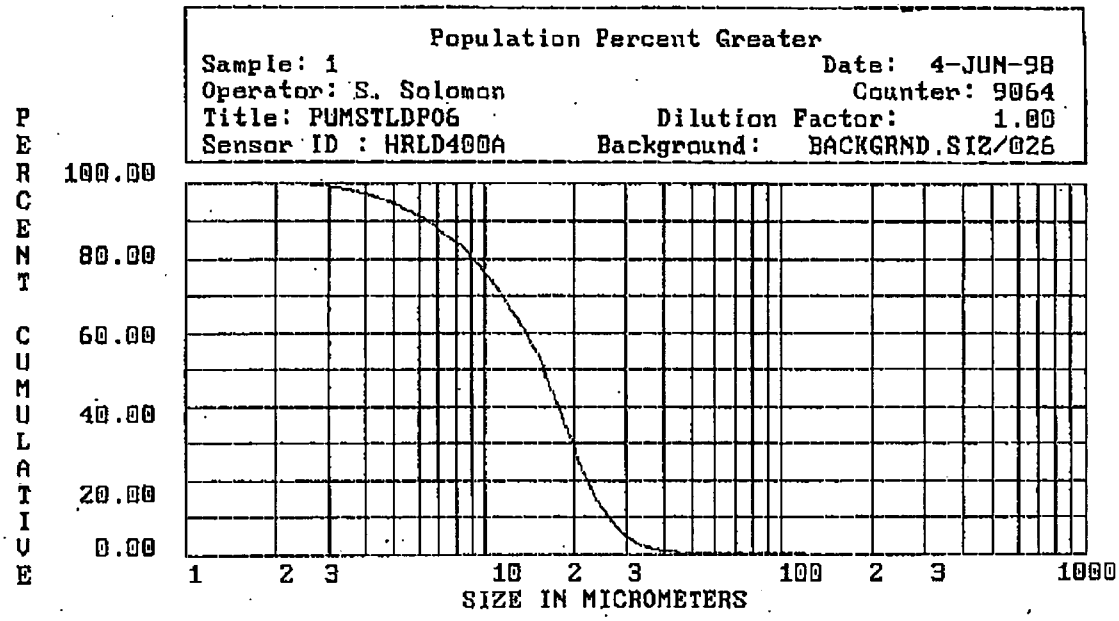

Figure A.2.10. 25% Pumped Surrogate-Sample at Top of Red Settled Material, Undiluted.

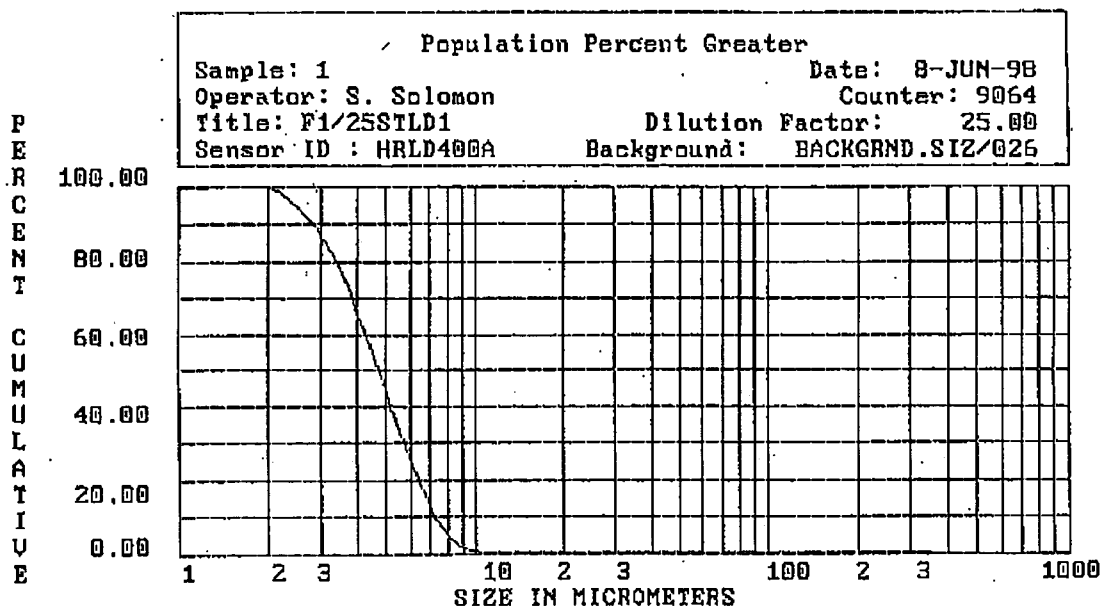

Figure A.2.11. 5% Unpumped Surrogate with 5% Bentonite-Supernatant of Settled Material, at 10 mm Depth, Diluted 1:25.

000069

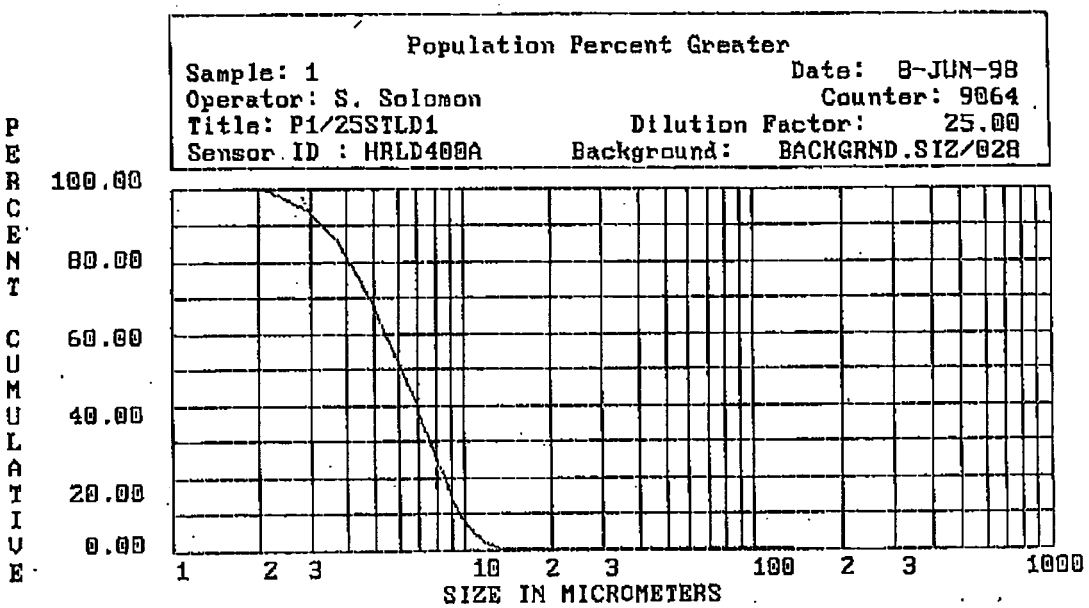

Figure A.2.12. 5% Pumped Surrogate With 5% Bentonite-Supernatant of Settled Material, at 10 mm Depth, Diluted 1:25.

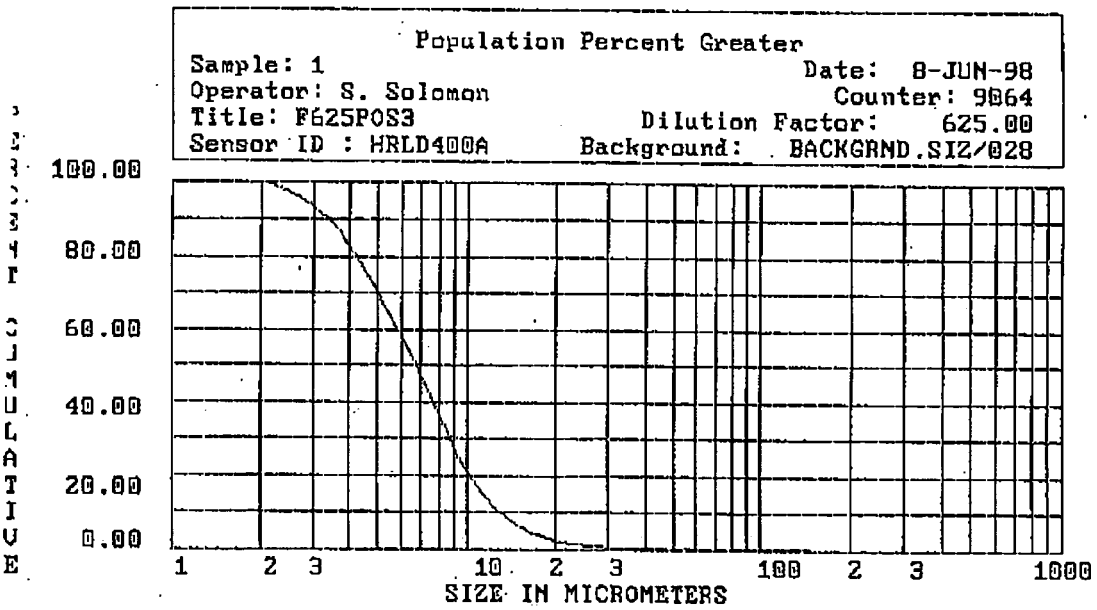

Figure A.2.13. 25% Unpumped Surrogate With 5% Bentonite-Supernatant of Settled Material, at 10 mm Depth, Diluted 1:625.

1811

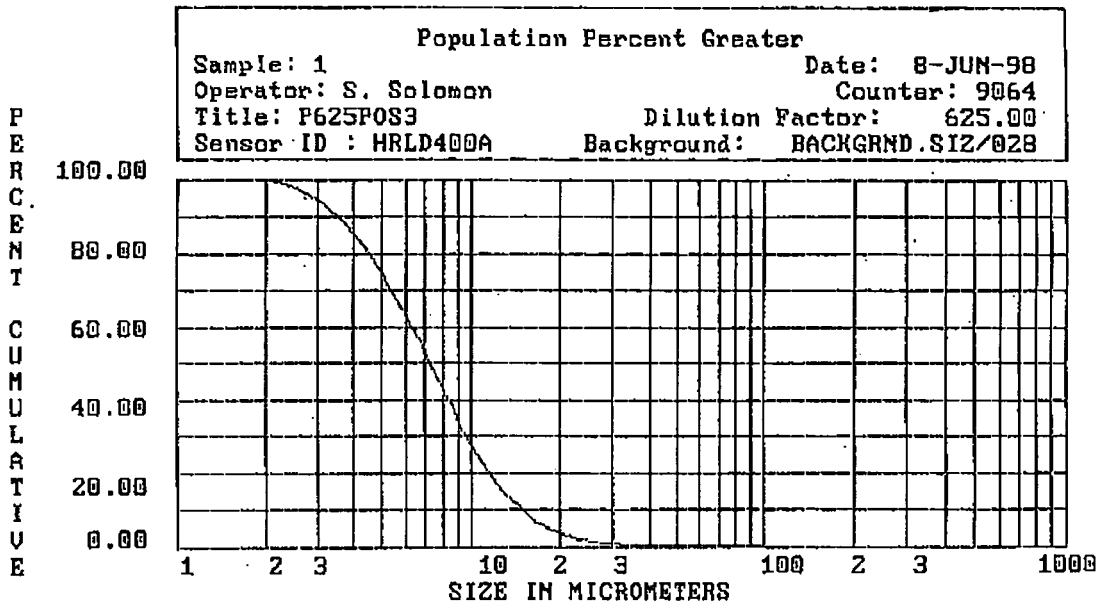

Figure A.2.14. 25% Pumped Surrogate With 5% Bentonite-Supernatant of Settled Material, at 10 mm Depth, Diluted 1:625.

000071

APPENDIX B

APPENDIX B

SETTLING VELOCITY AND WEIGHT RATIO TABLES

Table B-1. Settling Distances and Settling Velocities for K-65 Samples

Sample	Time, h	*H_1, cm	*H_2, cm	*H_3, cm	*H, cm	H_1/H	H_2/H	H_3/H	+Settling Velocity, cm/h	Settling Velocity, cm/min
K65-5-F	0				9.30				0.00	0.000
	1	0.00	8.50	0.80	9.30	0.00	0.91	0.09	8.50	0.142
	2	0.00	8.50	0.80	9.30	0.00	0.91	0.09	4.25	0.071
	3	8.40	0.00	0.90	9.30	0.90	0.00	0.10	2.80	0.047
	4	8.40	0.00	0.90	9.30	0.90	0.00	0.10	2.10	0.035
	5	8.40	0.00	0.90	9.30	0.90	0.00	0.10	1.68	0.028
	6	8.40	0.00	0.90	9.30	0.90	0.00	0.10	1.40	0.023
	7	8.40	0.00	0.90	9.30	0.90	0.00	0.10	1.20	0.020
	8	8.40	0.00	0.90	9.30	0.90	0.00	0.10	1.05	0.018
	16	8.40	0.00	0.90	9.30	0.90	0.00	0.10	0.53	0.009
	24	8.40	0.00	0.90	9.30	0.90	0.00	0.10	0.35	0.006
	32	8.40	0.00	0.90	9.30	0.90	0.00	0.10	0.26	0.004
	48	8.40	0.00	0.90	9.30	0.90	0.00	0.10	0.18	0.003
K65-5-T	0	0	0	0	9.10				0.00	0.000
	1	0.70	8.00	0.40	9.10	0.08	0.88	0.04	8.70	0.145
	2	1.00	7.60	0.50	9.10	0.11	0.84	0.05	4.30	0.072
	3	1.00	7.50	0.60	9.10	0.11	0.82	0.07	2.83	0.047
	4	1.30	7.20	0.60	9.10	0.14	0.79	0.07	2.13	0.035
	5	1.50	7.00	0.60	9.10	0.16	0.77	0.07	1.70	0.028
	6	1.80	6.70	0.60	9.10	0.20	0.74	0.07	1.42	0.024
	7	2.00	6.50	0.60	9.10	0.22	0.71	0.07	1.21	0.020
	8	2.00	6.50	0.60	9.10	0.22	0.71	0.07	1.06	0.018
	16	2.50	6.00	0.60	9.10	0.27	0.66	0.07	0.53	0.009
	24	3.50	5.00	0.60	9.10	0.38	0.55	0.07	0.35	0.006
	32	4.00	4.50	0.60	9.10	0.44	0.49	0.07	0.27	0.004
	48	5.00	3.50	0.60	9.10	0.55	0.38	0.07	0.18	0.003
K65-5-5-T	0	0	0	0	10.40				0.00	0.000
	1	0.40	9.90	0.10	10.40	0.04	0.95	0.01	10.30	0.172
	2	0.60	9.60	0.20	10.40	0.06	0.92	0.02	5.10	0.085
	3	0.60	9.60	0.20	10.40	0.06	0.92	0.02	3.40	0.057
	4	0.80	9.40	0.20	10.40	0.08	0.90	0.02	2.55	0.043
	5	0.80	9.40	0.20	10.40	0.08	0.90	0.02	2.04	0.034
	6	0.80	9.30	0.30	10.40	0.08	0.89	0.03	1.68	0.028
	7	0.80	9.30	0.30	10.40	0.08	0.89	0.03	1.44	0.024
	8	0.90	9.20	0.30	10.40	0.09	0.88	0.03	1.26	0.021
	16	1.50	8.40	0.50	10.40	0.14	0.81	0.05	0.62	0.010
	24	2.00	7.70	0.70	10.40	0.19	0.74	0.07	0.40	0.007
	48	2.80	6.00	1.60	10.40	0.27	0.58	0.15	0.18	0.003
K65-25-F	0	0	0	0	8.00				0.00	0.000
	1	3.00	0.00	5.00	8.00	0.38	0.00	0.63	3.00	0.050
	2	3.50	0.00	4.50	8.00	0.44	0.00	0.56	1.75	0.029
	3	3.50	0.00	4.50	8.00	0.44	0.00	0.56	1.17	0.019
	4	3.50	0.00	4.50	8.00	0.44	0.00	0.56	0.88	0.015
	5	4.00	0.00	4.00	8.00	0.50	0.00	0.50	0.80	0.013
	6	4.10	0.00	3.90	8.00	0.51	0.00	0.49	0.68	0.011
	7	4.10	0.00	3.90	8.00	0.51	0.00	0.49	0.59	0.010
	8	4.30	0.00	3.70	8.00	0.54	0.00	0.46	0.54	0.009
	16	4.30	0.00	3.70	8.00	0.54	0.00	0.46	0.27	0.004
	24	4.30	0.00	3.70	8.00	0.54	0.00	0.46	0.18	0.003
	32	4.30	0.00	3.70	8.00	0.54	0.00	0.46	0.13	0.002
	48	4.30	0.00	3.70	8.00	0.54	0.00	0.46	0.09	0.001

Table B-1. Settling Distances and Settling Velocities for K-65 Samples (continued)

Sample	Time, h	*H_1, cm	*H_2, cm	*H_3, cm	*H, cm	H_1/H	H_2/H	H_3/H	+Settling Velocity, cm/h	Settling Velocity, cm/min
K65-25-T	0	0	0	0	7.00				0.00	0.000
	1	2.00	0.00	5.00	7.00	0.29	0.00	0.71	2.00	0.033
	2	2.40	0.00	4.60	7.00	0.34	0.00	0.66	1.20	0.020
	3	2.60	0.00	4.40	7.00	0.37	0.00	0.63	0.87	0.014
	4	2.80	0.00	4.20	7.00	0.40	0.00	0.60	0.70	0.012
	5	3.00	0.00	4.00	7.00	0.43	0.00	0.57	0.60	0.010
	6	3.00	0.00	4.00	7.00	0.43	0.00	0.57	0.50	0.008
	7	3.20	0.00	3.80	7.00	0.46	0.00	0.54	0.46	0.008
	8	3.40	0.00	3.60	7.00	0.49	0.00	0.51	0.43	0.007
	16	3.60	0.00	3.40	7.00	0.51	0.00	0.49	0.23	0.004
	24	3.60	0.00	3.40	7.00	0.51	0.00	0.49	0.15	0.003
	32	3.70	0.00	3.30	7.00	0.53	0.00	0.47	0.12	0.002
	48	3.70	0.00	3.30	7.00	0.53	0.00	0.47	0.08	0.001
K65-25-5-T	0	0	0	0	7.80				0.00	0.000
	1	0.00	7.60	0.20	7.80	0.00	0.97	0.03	7.60	0.127
	2	0.00	7.30	0.50	7.80	0.00	0.94	0.06	3.65	0.061
	3	0.00	6.70	1.10	7.80	0.00	0.86	0.14	2.23	0.037
	4	0.00	6.40	1.20	7.60	0.00	0.84	0.16	1.60	0.027
	5	0.00	5.50	2.30	7.80	0.00	0.71	0.29	1.10	0.018
	6	0.00	4.80	3.00	7.80	0.00	0.62	0.38	0.80	0.013
	7	0.00	4.80	3.00	7.80	0.00	0.62	0.38	0.69	0.011
	8	0.00	4.60	3.20	7.80	0.00	0.59	0.41	0.58	0.010
	16	0.10	4.40	3.30	7.80	0.01	0.56	0.42	0.28	0.005
	24	0.20	4.10	3.50	7.80	0.03	0.53	0.45	0.18	0.003
	48	0.40	3.40	4.00	7.80	0.05	0.44	0.51	0.08	0.001
K65-35-T	0	0	0	0	9.50				0.00	0.000
	1	0.20	0.00	9.30	9.50	0.02	0.00	0.98	0.20	0.003
	2	0.60	0.00	8.90	9.50	0.06	0.00	0.94	0.30	0.005
	3	0.80	0.00	8.70	9.50	0.08	0.00	0.92	0.27	0.004
	4	1.80	0.00	7.70	9.50	0.19	0.00	0.81	0.45	0.008
	5	1.80	0.00	7.70	9.50	0.19	0.00	0.81	0.36	0.006
	6	1.90	0.00	7.60	9.50	0.20	0.00	0.80	0.32	0.005
	7	1.90	0.00	7.60	9.50	0.20	0.00	0.80	0.27	0.005
	8	2.00	0.00	7.50	9.50	0.21	0.00	0.79	0.25	0.004
	16	3.40	0.00	6.10	9.50	0.36	0.00	0.64	0.21	0.004
	24	3.50	0.00	6.00	9.50	0.37	0.00	0.63	0.15	0.002
	32	3.70	0.00	5.80	9.50	0.39	0.00	0.61	0.12	0.002
	48	3.80	0.00	5.70	9.50	0.40	0.00	0.60	0.08	0.001
K65-40-F	0	0	0	0	9.50				0.00	0.000
	1	2.00	0.00	7.50	9.50	0.21	0.00	0.79	2.00	0.033
	2	2.70	0.00	6.80	9.50	0.28	0.00	0.72	1.35	0.023

Table B-1. Settling Distances and Settling Velocities for K-65 Samples (continued)

Sample	Time, h	*H_1, cm	*H_2, cm	*H_3, cm	*H, cm	H_1/H	H_2/H	H_3/H	+Settling Velocity, cm/h	Settling Velocity, cm/min
	3	2.90	0.00	6.60	9.50	0.31	0.00	0.69	0.97	0.016
	4	3.40	0.00	6.10	9.50	0.36	0.00	0.64	0.85	0.014
	5	3.50	0.00	6.00	9.50	0.37	0.00	0.63	0.70	0.012
	6	3.50	0.00	6.00	9.50	0.37	0.00	0.63	0.58	0.010
	7	3.70	0.00	5.80	9.50	0.39	0.00	0.61	0.53	0.009
	8	3.80	0.00	5.70	9.50	0.40	0.00	0.60	0.48	0.008
	16	4.00	0.00	5.50	9.50	0.42	0.00	0.58	0.25	0.004
	24	4.00	0.00	5.50	9.50	0.42	0.00	0.58	0.17	0.003
	32	4.00	0.00	5.50	9.50	0.42	0.00	0.58	0.13	0.002
	48	4.00	0.00	5.50	9.50	0.42	0.00	0.58	0.08	0.001
K65-40-T	**0**	**0**	**0**	**0**	**6.00**				**0.00**	**0.000**
	1	**0.50**	**0.00**	**5.50**	**6.00**	**0.08**	**0.00**	**0.92**	**0.50**	**0.008**
	2	**0.60**	**0.00**	**5.40**	**6.00**	**0.10**	**0.00**	**0.90**	**0.30**	**0.005**
	3	**0.70**	**0.00**	**5.30**	**6.00**	**0.12**	**0.00**	**0.88**	**0.23**	**0.004**
	4	**0.80**	**0.00**	**5.20**	**6.00**	**0.13**	**0.00**	**0.87**	**0.20**	**0.003**
	5	**0.80**	**0.00**	**5.20**	**6.00**	**0.13**	**0.00**	**0.87**	**0.16**	**0.003**
	6	**0.90**	**0.00**	**5.10**	**6.00**	**0.15**	**0.00**	**0.85**	**0.15**	**0.003**
	7	**0.90**	**0.00**	**5.10**	**6.00**	**0.15**	**0.00**	**0.85**	**0.13**	**0.002**
	8	**1.00**	**0.00**	**5.00**	**6.00**	**0.17**	**0.00**	**0.83**	**0.13**	**0.002**
	16	**1.30**	**0.00**	**4.70**	**6.00**	**0.22**	**0.00**	**0.78**	**0.08**	**0.001**
	24	**1.30**	**0.00**	**4.70**	**6.00**	**0.22**	**0.00**	**0.78**	**0.05**	**0.001**
	32	**1.30**	**0.00**	**4.70**	**6.00**	**0.22**	**0.00**	**0.78**	**0.04**	**0.001**
	48	**1.30**	**0.00**	**4.70**	**6.00**	**0.22**	**0.00**	**0.78**	**0.03**	**0.0005**

* Please see Sample Bottle Diagram for H_1, H_2, H_3, H', and H identification.

+ Settling velocity was calculated using the following equation: H'/Time = (H1+ H2)/Time

NOTE: The following samples showed no settling at all times: K65-5-10-T, K65-25-10-T, K65-40-5-T

Sample Naming:

K65- : Fernald K-65.

K65-5- : First number means wt%. of K65 used.

K65-5-5- : Second number means wt%. of bentonite added.

K65-5-5-T: T means sample taken from slurry tank.

K65-5-5-F: F means sample freshly prepared.

Table B-2. Weight Ratio of Settled Solids to Total Solids in K-65 Samples

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Sample	Time, h	*W_3/W, %
K65-5-F	0	0.00
	1	87.00
	2	87.00
	3	100.00
	4	100.00
	5	100.00
	6	100.00
K65-5-F	7	100.00
	8	100.00
	16	100.00
	24	100.00
	32	100.00
	48	100.00
K65-5-T	0	0.00
	1	87.81
	2	88.42
	3	88.58
	4	89.03
	5	89.34
	6	89.79
	7	90.10
	8	90.10
	16	90.86
	24	92.38
	32	93.15
	48	94.67
K65-5-5-T	0	0.00
	1	45.43
	2	47.19
	3	47.19
	4	48.34
	5	48.34
	6	48.91
	7	48.91
	8	49.49
	16	53.51
	24	57.52
	48	66.71
K65-25-F	0	0.00
	1	100.00
	2	100.00
	3	100.00
	4	100.00
	5	100.00
	6	100.00
	7	100.00
	8	100.00
	16	100.00
	24	100.00
	32	100.00
	48	100.00

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Table B-2. Weight Ratio of Settled Solids to Total Solids in K-65 Samples (continued)

Sample	Time, h	*W_3/W, %
K65-25-T	0	0.00
	1	100.00
	2	100.00
	3	100.00
	4	100.00
	5	100.00
	6	100.00
	7	100.00
	8	100.00
	16	100.00
	24	100.00
	32	100.00
	48	100.00
K65-25-5-T	0	0.00
	1	67.52
	2	68.51
	3	71.19
	4	71.86
	5	76.21
	6	79.23
	7	79.23
	8	80.23
	16	81.24
	24	82.24
	48	85.26
K65-35-T	0	0.00
	1	100.00
	2	100.00
	3	100.00
	4	100.00
	5	100.00
	6	100.00
	7	100.00
	8	100.00
	16	100.00
	24	100.00
	32	100.00
	48	100.00
K65-40-F	0	0.00
	1	100.00
	2	100.00
	3	100.00
	4	100.00
	5	100.00
	6	100.00
	7	100.00
	8	100.00
	16	100.00
	24	100.00
	32	100.00
	48	100.00

Table B-2. Weight Ratio of Settled Solids to Total Solids in K-65 Samples (continued)

Sample	Time, h	*W_3/W, %
K65-40-T	0	0.00
	1	100.00
	2	100.00
	3	100.00
	4	100.00
	5	100.00
	6	100.00
	7	100.00
	8	100.00
	16	100.00
	24	100.00
	32	100.00
	48	100.00

* Weight Ratio of Settled Solids to Total Solids

Table B-3. Fernald Surrogate #1 Settling Distances and Settling Velocities

Sample	Time, h	*H_1, cm	*H_2, cm	*H_3, cm	*H, cm	H_1/H	H_2/H	H_3/H	+Settling Velocity, cm/h	Settling Velocity, cm/min
SURR1-5-F	0				9.40				0.00	0.00
	1	0.60	8.00	0.80	9.40	0.06	0.85	0.09	8.60	0.14
	2	0.60	8.00	0.80	9.40	0.06	0.85	0.09	4.30	0.07
	3	1.50	7.10	0.80	9.40	0.16	0.76	0.09	2.87	0.05
	4	1.70	6.90	0.80	9.40	0.18	0.73	0.09	2.15	0.04
	5	1.80	6.80	0.80	9.40	0.19	0.72	0.09	1.72	0.03
	6	1.80	6.80	0.80	9.40	0.19	0.72	0.09	1.43	0.02
	7	1.80	6.80	0.80	9.40	0.19	0.72	0.09	1.23	0.02
	8	1.90	6.70	0.80	9.40	0.20	0.71	0.09	1.08	0.02
	16	3.00	5.60	0.80	9.40	0.32	0.60	0.09	0.54	0.01
	24	3.00	5.60	0.80	9.40	0.32	0.60	0.09	0.36	0.01
	48	3.50	5.10	0.80	9.40	0.37	0.54	0.09	0.18	0.003
SURR1-5-T	**0**				**10.00**				**0.00**	**0.00**
	1	**0.60**	**8.80**	**0.60**	**10.00**	**0.06**	**0.88**	**0.06**	**9.40**	**0.16**
	2	**0.70**	**8.70**	**0.60**	**10.00**	**0.07**	**0.87**	**0.06**	**4.70**	**0.08**
	3	**1.00**	**8.30**	**0.70**	**10.00**	**0.10**	**0.83**	**0.07**	**3.10**	**0.05**
	4	**1.20**	**8.10**	**0.70**	**10.00**	**0.12**	**0.81**	**0.07**	**2.33**	**0.04**
	5	**1.30**	**8.00**	**0.70**	**10.00**	**0.13**	**0.80**	**0.07**	**1.86**	**0.03**
	6	**1.40**	**7.90**	**0.70**	**10.00**	**0.14**	**0.79**	**0.07**	**1.55**	**0.03**
	7	**1.50**	**7.80**	**0.70**	**10.00**	**0.15**	**0.78**	**0.07**	**1.33**	**0.02**
	8	**1.50**	**7.80**	**0.70**	**10.00**	**0.15**	**0.78**	**0.07**	**1.16**	**0.02**
	16	**2.00**	**7.30**	**0.70**	**10.00**	**0.20**	**0.73**	**0.07**	**0.58**	**0.01**
	24	**2.50**	**6.80**	**0.70**	**10.00**	**0.25**	**0.68**	**0.07**	**0.39**	**0.01**
	48	**3.00**	**6.30**	**0.70**	**10.00**	**0.30**	**0.63**	**0.07**	**0.19**	**0.003**
SURR1-25-F	0				9.60				0.00	0.00
	1	0.40	7.10	2.10	9.60	0.04	0.74	0.22	7.50	0.13
	2	0.70	6.50	2.40	9.60	0.07	0.68	0.25	3.60	0.06
	3	0.80	6.30	2.50	9.60	0.08	0.66	0.26	2.37	0.04
	4	1.00	5.50	3.10	9.60	0.10	0.57	0.32	1.63	0.03

Table B-3. Fernald Surrogate #1 Settling Distances and Settling Velocities (continued)

Sample	Time, h	*H_1, cm	*H_2, cm	*H_3, cm	*H, cm	H_1/H	H_2/H	H_3/H	+Settling Velocity, cm/h	Settling Velocity, cm/min
SURRI-25-F	5	1.30	5.10	3.20	9.60	0.14	0.53	0.33	1.28	0.02
	6	1.50	4.90	3.20	9.60	0.16	0.51	0.33	1.07	0.02
	7	1.50	4.90	3.20	9.60	0.16	0.51	0.33	0.91	0.02
	8	1.70	4.70	3.20	9.60	0.18	0.49	0.33	0.80	0.01
	16	2.50	3.60	3.50	9.60	0.26	0.38	0.36	0.38	0.01
	24	2.70	3.30	3.60	9.60	0.28	0.34	0.38	0.25	0.004
	48	3.10	3.00	3.60	9.70	0.32	0.31	0.37	0.13	0.002
SURR1-25-T	**0**				**9.60**				**0.00**	**0.00**
	1	**0.50**	**8.10**	**1.00**	**9.60**	**0.05**	**0.84**	**0.10**	**8.60**	**0.14**
	2	**0.50**	**8.50**	**0.60**	**9.60**	**0.05**	**0.89**	**0.06**	**4.50**	**0.08**
	3	**0.90**	**7.20**	**1.50**	**9.60**	**0.09**	**0.75**	**0.16**	**2.70**	**0.05**
	4	**1.00**	**6.80**	**1.80**	**9.60**	**0.10**	**0.71**	**0.19**	**1.95**	**0.03**
	5	**1.00**	**6.80**	**1.80**	**9.60**	**0.10**	**0.71**	**0.19**	**1.56**	**0.03**
	6	**1.20**	**6.50**	**1.90**	**9.60**	**0.13**	**0.68**	**0.20**	**1.28**	**0.02**
	7	**1.20**	**6.50**	**1.90**	**9.60**	**0.13**	**0.68**	**0.20**	**1.10**	**0.02**
	8	**1.30**	**6.30**	**2.00**	**9.60**	**0.14**	**0.66**	**0.21**	**0.95**	**0.02**
	16	**1.50**	**5.10**	**3.00**	**9.60**	**0.16**	**0.53**	**0.31**	**0.41**	**0.01**
	24	**2.00**	**4.60**	**3.00**	**9.60**	**0.21**	**0.48**	**0.31**	**0.28**	**0.005**
	48	**2.50**	**4.10**	**3.00**	**9.60**	**0.26**	**0.43**	**0.31**	**0.14**	**0.002**
SURR1-40-F	0				9.00				0.00	0.00
	1	0.70	5.80	2.50	9.00	0.08	0.64	0.28	6.50	0.11
	2	0.70	4.40	3.90	9.00	0.08	0.49	0.43	2.55	0.04
	3	0.80	3.70	4.50	9.00	0.09	0.41	0.50	1.50	0.03
	4	0.90	3.00	5.10	9.00	0.10	0.33	0.57	0.98	0.02
	5	1.00	2.80	5.20	9.00	0.11	0.31	0.58	0.76	0.01
	6	1.20	2.60	5.20	9.00	0.13	0.29	0.58	0.63	0.01
	7	1.20	2.60	5.20	9.00	0.13	0.29	0.58	0.54	0.01
	8	1.30	2.50	5.20	9.00	0.14	0.28	0.58	0.48	0.01
	16	3.20	0.00	5.80	9.00	0.36	0.00	0.64	0.20	0.003
	24	3.20	0.00	5.80	9.00	0.36	0.00	0.64	0.13	0.002
	48	3.20	0.00	5.80	9.00	0.36	0.00	0.64	0.07	0.001
SURR1-40-T	**0**				**9.00**				**0.00**	**0.00**
	1	**0.00**	**6.70**	**2.30**	**9.00**	**0.00**	**0.74**	**0.26**	**6.70**	**0.11**
	2	**0.20**	**6.20**	**2.60**	**9.00**	**0.02**	**0.69**	**0.29**	**3.20**	**0.05**
	3	**0.20**	**6.00**	**2.80**	**9.00**	**0.02**	**0.67**	**0.31**	**2.07**	**0.03**
	4	**0.20**	**5.70**	**3.10**	**9.00**	**0.02**	**0.63**	**0.34**	**1.48**	**0.02**
	5	**0.20**	**5.70**	**3.10**	**9.00**	**0.02**	**0.63**	**0.34**	**1.18**	**0.02**
	6	**0.20**	**5.50**	**3.30**	**9.00**	**0.02**	**0.61**	**0.37**	**0.95**	**0.02**
	7	**0.20**	**5.50**	**3.30**	**9.00**	**0.02**	**0.61**	**0.37**	**0.81**	**0.01**
	8	**0.20**	**5.50**	**3.30**	**9.00**	**0.02**	**0.61**	**0.37**	**0.71**	**0.01**
	16	**2.60**	**2.90**	**3.50**	**9.00**	**0.29**	**0.32**	**0.39**	**0.34**	**0.01**
	24	**2.60**	**2.70**	**3.70**	**9.00**	**0.29**	**0.30**	**0.41**	**0.22**	**0.004**
	48	**2.60**	**2.70**	**3.70**	**9.00**	**0.29**	**0.30**	**0.41**	**0.11**	**0.002**

* Please see Sample Bottle Diagram for **H_1, H_2, H_3, H', and H** identification in Section 3.3.
\+ Settling velocity was calculated using the following equation: **H'/Time = (H1+ H2)/Time**

Sample Naming:

SURR1 :	Fernald Surrogate with $MgCO_3$ and $CaCO_3$.
SURR1-5- :	First number means wt%. of solid mix used.
SURR1-5-T:	T means sample taken from slurry tank.
SURR1-5-F:	F means sample freshly prepared.

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Table B-4. Fernald Surrogate #2 Settling Distances and Settling Velocities

Sample	Time, h	*H_1, cm	*H_2, cm	*H_3, cm	*H, cm	H_1/H	H_2/H	H_3/H	+Settling Velocity, cm/h	Settling Velocity, cm/min
SURR2-5-F	0				10.10				0.00	0.00
	1	0.50	8.90	0.70	10.10	0.05	0.88	0.07	9.40	0.16
	2	0.60	8.80	0.70	10.10	0.06	0.87	0.07	4.70	0.08
	3	0.80	8.50	0.80	10.10	0.08	0.84	0.08	3.10	0.05
	4	0.90	8.40	0.80	10.10	0.09	0.83	0.08	2.33	0.04
	5	1.00	8.30	0.80	10.10	0.10	0.82	0.08	1.86	0.03
	6	1.00	8.30	0.80	10.10	0.10	0.82	0.08	1.55	0.03
	7	1.00	8.30	0.80	10.10	0.10	0.82	0.08	1.33	0.02
	8	1.00	8.30	0.80	10.10	0.10	0.82	0.08	1.16	0.02
	16	1.50	7.80	0.80	10.10	0.15	0.77	0.08	0.58	0.01
	24	2.00	7.30	0.80	10.10	0.20	0.72	0.08	0.39	0.01
	48	2.50	6.80	0.80	10.10	0.25	0.67	0.08	0.19	0.003
SURR2-25-F	0				8.70				0.00	0.00
	1	0.30	7.00	1.40	8.70	0.03	0.80	0.16	7.30	0.12
	2	0.30	6.60	1.80	8.70	0.03	0.76	0.21	3.45	0.06
	3	0.40	6.00	2.30	8.70	0.05	0.69	0.26	2.13	0.04
	4	0.50	5.60	2.60	8.70	0.06	0.64	0.30	1.53	0.03
	5	0.60	5.40	2.70	8.70	0.07	0.62	0.31	1.20	0.02
	6	0.70	5.30	2.70	8.70	0.08	0.61	0.31	1.00	0.02
	7	0.70	5.30	2.70	8.70	0.08	0.61	0.31	0.86	0.01
	8	0.70	5.30	2.70	8.70	0.08	0.61	0.31	0.75	0.01
	16	0.90	4.80	3.00	8.70	0.10	0.55	0.34	0.36	0.01
	24	1.00	4.50	3.20	8.70	0.11	0.52	0.37	0.23	0.004
	48	1.50	4.00	3.20	8.70	0.17	0.46	0.37	0.11	0.002
SURR2-40-F	0				9.50				0.00	0.00
	1	0.2	5.20	4.10	9.50	0.02	0.55	0.43	5.40	0.09
	2	0.3	4.90	4.30	9.50	0.03	0.52	0.45	2.60	0.04
	3	0.4	4.40	4.70	9.50	0.04	0.46	0.49	1.60	0.03
	4	0.4	4.40	4.70	9.50	0.04	0.46	0.49	1.20	0.02
	5	0.5	4.30	4.70	9.50	0.05	0.45	0.49	0.96	0.02
	6	0.6	4.20	4.70	9.50	0.06	0.44	0.49	0.80	0.01
	7	0.6	4.20	4.70	9.50	0.06	0.44	0.49	0.69	0.01
	8	0.6	4.20	4.70	9.50	0.06	0.44	0.49	0.60	0.01
	16	0.7	3.90	4.90	9.50	0.07	0.41	0.52	0.29	0.00
	24	0.8	3.30	5.40	9.50	0.08	0.35	0.57	0.17	0.003
	48	0.9	3.20	5.40	9.50	0.09	0.34	0.57	0.09	0.001
SURR2-5-5-F	0				9.60				0.00	0.00
	1	0	9.50	0.10	9.60	0.00	0.99	0.01	9.50	0.16
	2	0	9.40	0.20	9.60	0.00	0.98	0.02	4.70	0.08
	3	0	9.40	0.20	9.60	0.00	0.98	0.02	3.13	0.05
	4	0	9.40	0.20	9.60	0.00	0.98	0.02	2.35	0.04
	5	0	9.40	0.20	9.60	0.00	0.98	0.02	1.88	0.03
	6	0	9.40	0.20	9.60	0.00	0.98	0.02	1.57	0.03
	7	0	9.40	0.20	9.60	0.00	0.98	0.02	1.34	0.02
	8	0	9.40	0.20	9.60	0.00	0.98	0.02	1.18	0.02
	16	0	9.30	0.30	9.60	0.00	0.97	0.03	0.58	0.01
	24	0	9.30	0.30	9.60	0.00	0.97	0.03	0.39	0.01
	48	0	9.30	0.30	9.60	0.00	0.97	0.03	0.19	0.003

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Table B-4. Fernald Surrogate #2 Settling Distances and Settling Velocities (continued)

Sample	Time, h	*H_1, cm	*H_2, cm	*H_3, cm	*H, cm	H_1/H	H_2/H	H_3/H	+Settling Velocity, cm/h	Settling Velocity, cm/min
SURR2-25-5-F	0				8.50				0.00	0.00
	1	0	7.70	0.80	8.50	0.00	0.91	0.09	7.70	0.13
	2	0	7.50	1.00	8.50	0.00	0.88	0.12	3.75	0.06
	3	0	7.50	1.00	8.50	0.00	0.88	0.12	2.50	0.04
	4	0	7.30	1.20	8.50	0.00	0.86	0.14	1.83	0.03
	5	0	7.30	1.20	8.50	0.00	0.86	0.14	1.46	0.02
	6	0	7.30	1.20	8.50	0.00	0.86	0.14	1.22	0.02
	7	0	7.30	1.20	8.50	0.00	0.86	0.14	1.04	0.02
	8	0	7.30	1.20	8.50	0.00	0.86	0.14	0.91	0.02
	16	0	7.30	1.20	8.50	0.00	0.86	0.14	0.46	0.01
	24	0	7.10	1.40	8.50	0.00	0.84	0.16	0.30	0.005
	48	0	7.10	1.40	8.50	0.00	0.84	0.16	0.15	0.002
SURR2-40-5-F	**0**				**7.00**				**0.00**	**0.00**
	1	**0**	**5.50**	**1.50**	**7.00**	**0.00**	**0.79**	**0.21**	**5.50**	**0.09**
	2	**0**	**5.20**	**1.80**	**7.00**	**0.00**	**0.74**	**0.26**	**2.60**	**0.04**
	3	**0**	**5.20**	**1.80**	**7.00**	**0.00**	**0.74**	**0.26**	**1.73**	**0.03**
	4	**0**	**4.90**	**2.10**	**7.00**	**0.00**	**0.70**	**0.30**	**1.23**	**0.02**
	5	**0**	**4.80**	**2.20**	**7.00**	**0.00**	**0.69**	**0.31**	**0.96**	**0.02**
	6	**0**	**4.70**	**2.30**	**7.00**	**0.00**	**0.67**	**0.33**	**0.78**	**0.01**
	7	**0**	**4.70**	**2.30**	**7.00**	**0.00**	**0.67**	**0.33**	**0.67**	**0.01**
	8	**0**	**4.70**	**2.30**	**7.00**	**0.00**	**0.67**	**0.33**	**0.59**	**0.01**
	16	**0**	**4.60**	**2.40**	**7.00**	**0.00**	**0.66**	**0.34**	**0.29**	**0.005**
	24	**0**	**4.50**	**2.50**	**7.00**	**0.00**	**0.64**	**0.36**	**0.19**	**0.003**
	48	**0**	**4.20**	**2.80**	**7.00**	**0.00**	**0.60**	**0.40**	**0.09**	**0.001**
SURR2-5-5-T	0				9.80				0.00	0.00
	1	0.00	9.70	0.10	9.80	0.00	0.99	0.01	9.70	0.16
	2	0.00	9.70	0.10	9.80	0.00	0.99	0.01	4.85	0.08
	3	0.00	9.70	0.10	9.80	0.00	0.99	0.01	3.23	0.05
	4	0.00	9.70	0.10	9.80	0.00	0.99	0.01	2.43	0.04
	5	0.00	9.70	0.10	9.80	0.00	0.99	0.01	1.94	0.03
	6	0.00	9.70	0.10	9.80	0.00	0.99	0.01	1.62	0.03
	7	0.00	9.70	0.10	9.80	0.00	0.99	0.01	1.39	0.02
	8	0.00	9.70	0.10	9.80	0.00	0.99	0.01	1.21	0.02
	16	0.00	9.60	0.20	9.80	0.00	0.98	0.02	0.60	0.01
	24	0.00	9.50	0.30	9.80	0.00	0.97	0.03	0.40	0.01
	48	0.00	9.50	0.30	9.80	0.00	0.97	0.03	0.20	0.003
SURR2-25-5-T	**0**				**9.80**				**0.00**	**0.00**
	1	**0.00**	**9.00**	**0.80**	**9.80**	**0.00**	**0.92**	**0.08**	**9.00**	**0.15**
	2	**0.00**	**8.90**	**0.90**	**9.80**	**0.00**	**0.91**	**0.09**	**4.45**	**0.07**
	3	**0.00**	**8.90**	**0.90**	**9.80**	**0.00**	**0.91**	**0.09**	**2.97**	**0.05**
	4	**0.00**	**8.90**	**0.90**	**9.80**	**0.00**	**0.91**	**0.09**	**2.23**	**0.04**
	5	**0.00**	**8.90**	**0.90**	**9.80**	**0.00**	**0.91**	**0.09**	**1.78**	**0.03**
	6	**0.00**	**8.90**	**0.90**	**9.80**	**0.00**	**0.91**	**0.09**	**1.48**	**0.02**
	7	**0.00**	**8.90**	**0.90**	**9.80**	**0.00**	**0.91**	**0.09**	**1.27**	**0.02**
	8	**0.00**	**8.90**	**0.90**	**9.80**	**0.00**	**0.91**	**0.09**	**1.11**	**0.02**
	16	**0.00**	**8.80**	**1.00**	**9.80**	**0.00**	**0.90**	**0.10**	**0.55**	**0.01**
	24	**0.00**	**8.60**	**1.20**	**9.80**	**0.00**	**0.88**	**0.12**	**0.36**	**0.01**
	48	**0.00**	**8.40**	**1.40**	**9.80**	**0.00**	**0.86**	**0.14**	**0.18**	**0.003**

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Table B-4. Fernald Surrogate #2 Settling Distances and Settling Velocities (continued)

Sample	Time, h	*H_1, cm	*H_2, cm	*H_3, cm	*H, cm	H_1/H	H_2/H	H_3/H	+Settling Velocity, cm/h	Settling Velocity, cm/min
SURR2-40-5-T	0				9.00				0.00	0.00
	1	0.00	5.20	3.80	9.00	0.00	0.58	0.42	5.20	0.09
	2	0.00	5.20	3.80	9.00	0.00	0.58	0.42	2.60	0.04
	3	0.00	4.80	4.20	9.00	0.00	0.53	0.47	1.60	0.03
	4	0.00	4.60	4.40	9.00	0.00	0.51	0.49	1.15	0.02
	5	0.00	4.00	5.00	9.00	0.00	0.44	0.56	0.80	0.01
	6	0.00	3.70	5.30	9.00	0.00	0.41	0.59	0.62	0.01
	7	0.00	3.60	5.40	9.00	0.00	0.40	0.60	0.51	0.01
	8	0.00	3.40	5.60	9.00	0.00	0.38	0.62	0.43	0.01
	16	0.00	3.30	5.70	9.00	0.00	0.37	0.63	0.21	0.003
	24	0.00	3.30	5.70	9.00	0.00	0.37	0.63	0.14	0.002
	48	0.00	3.20	5.80	9.00	0.00	0.36	0.64	0.07	0.001

* Please see Sample Bottle Diagram for **H_1, H_2, H_3, H', and H** identification in Section 3.3.

\+ Settling velocity was calculated using the following equation: **H'/Time = (H1+ H2)/Time**

NOTE: The following samples showed no settling at all times: **SURR2-5-10-T, SURR2-25-10-T.**

Sample Naming:

SURR2 : Fernald Surrogate without $MgCO_3$ and $CaCO_3$.

SURR2-5- : First number means wt%. of solid mix used.

SURR2-5-T : T means sample taken from slurry tank.

SURR2-5-F : F means sample freshly prepared.

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Table B-5. Weight Ratio of Settled Solids to Total Solids in Surrogates 1811

Sample	Time, h	*W_3/W, %
SURR1-5-F	0	0.00
	1	95.04
	2	95.04
	3	95.60
	4	95.72
	5	95.79
	6	95.79
	7	95.79
	8	95.85
	16	96.53
	24	96.53
	48	96.84
SURR1-5-T	0	0.00
	1	87.68
	2	87.82
	3	88.38
	4	88.66
	5	88.80
	6	88.94
	7	89.08
	8	89.08
	16	89.78
	24	90.48
	48	91.18
SURR1-25-F	0	0.00
	1	99.49
	2	99.51
	3	99.53
	4	99.60
	5	99.62
	6	99.63
	7	99.63
	8	99.64
	16	99.73
	24	99.75
	48	99.78
SURR1-25-T	0	0.00
	1	98.35
	2	98.43
	3	98.60
	4	98.68
	5	98.68
	6	98.74
	7	98.74
	8	98.78
	16	99.01
	24	99.11
	48	99.21

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Table B-5. Weight Ratio of Settled Solids to Total Solids in Surrogates (continued)

Sample	Time, h	*W_3/W, %
SURR1-40-F	0	0.00
	1	100.00
	2	100.00
	3	100.00
	4	100.00
	5	100.00
	6	100.00
	7	100.00
	8	100.00
	16	100.00
	24	100.00
	48	100.00
SURR1-40-T	0	0.00
	1	95.49
	2	95.83
	3	95.96
	4	96.16
	5	96.16
	6	96.30
	7	96.30
	8	96.30
	16	98.05
	24	98.18
	48	98.18
SURR2-5-F	0	0.00
	1	87.66
	2	87.80
	3	88.22
	4	88.36
	5	88.50
	6	88.50
	7	88.50
	8	88.50
	16	89.19
	24	89.88
	48	90.57
SURR2-25-F	0	0.00
	1	96.78
	2	96.97
	3	97.24
	4	97.43
	5	97.52
	6	97.56
	7	97.56
	8	97.56
	16	97.79
	24	97.93
	48	98.16

Table B-5. Weight Ratio of Settled Solids to Total Solids in Surrogates (continued)

Sample	Time, h	*W_3/W, %
SURR2-40-F	0	0.00
	1	99.58
	2	99.61
	3	99.65
	4	99.65
	5	99.65
	6	99.66
	7	99.66
	8	99.66
	16	99.69
	24	99.73
	48	99.74
SURR2-5-5-F	0	0.00
	1	36.55
	2	37.22
	3	37.22
	4	37.22
	5	37.22
	6	37.22
	7	37.22
	8	37.22
	16	37.89
	24	37.89
	48	37.89
SURR2-25-5-F	0	0.00
	1	63.11
	2	64.07
	3	64.07
	4	65.03
	5	65.03
	6	65.03
	7	65.03
	8	65.03
	16	65.03
	24	65.98
	48	65.98
SURR2-40-5-F	0	0.00
	1	70.71
	2	72.31
	3	72.31
	4	73.91
	5	74.44
	6	74.97
	7	74.97
	8	74.97
	16	75.50
	24	76.04
	48	77.63
SURR2-5-5-T	0	0.00
	1	43.54
	2	43.54
	3	43.54

Table B-5. Weight Ratio of Settled Solids to Total Solids in Surrogates (continued)

Sample	Time, h	*W_3/W, %
SURR2-5-5-T	4	43.54
	5	43.54
	6	43.54
	7	43.54
	8	43.54
	16	43.61
	24	44.12
	48	44.12
SURR2-25-5-T	**0**	**0.00**
	1	**69.18**
	2	**69.51**
	3	**69.51**
	4	**69.51**
	5	**69.51**
	6	**69.51**
	7	**69.51**
	8	**69.51**
	16	**69.85**
	24	**70.52**
	48	**71.19**
SURR2-40-5-T	0	0.00
	1	69.54
	2	69.54
	3	71.88
	4	73.05
	5	76.57
	6	78.32
	7	78.91
	8	80.08
	16	80.67
	24	80.67
	48	81.25

* Weight Ratio of Settled Solids to Total Solids

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APPENDIX C

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APPENDIX C

INCREMENTAL AND TOTAL SETTLING DISTANCES

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C-1. K-65 SAMPLES INCREMENTAL AND TOTAL SETTLING DISTANCES

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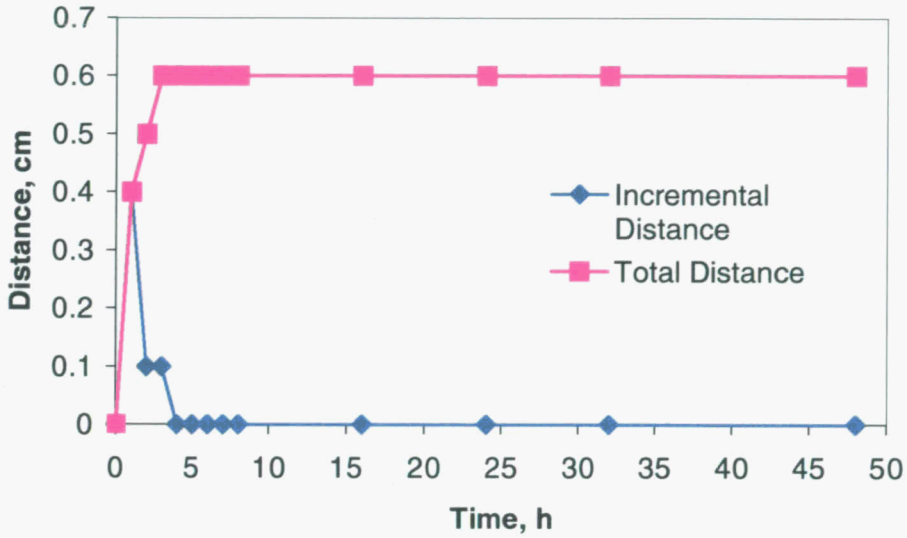

Figure C.1.1. K65-5-T Incremental and Total Settling Distances.

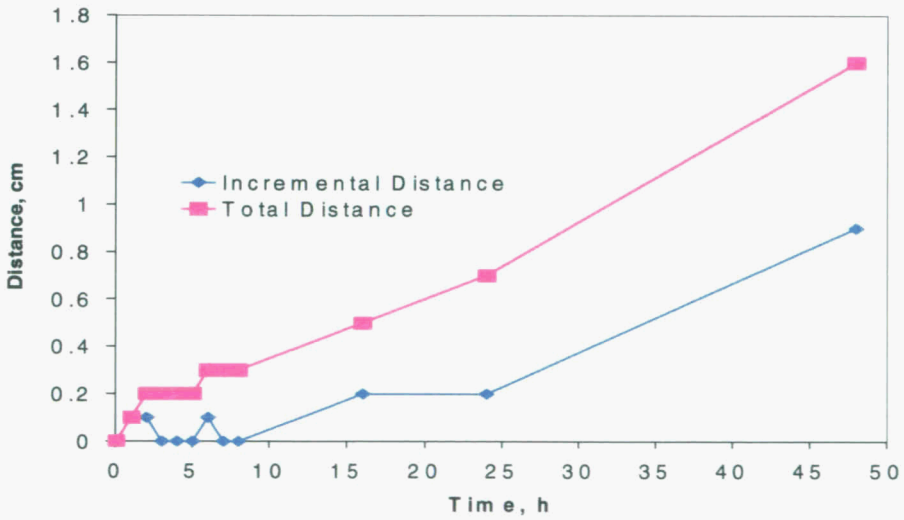

Figure C.1.2. K65-5-5-T Incremental and Total Settling Distances.

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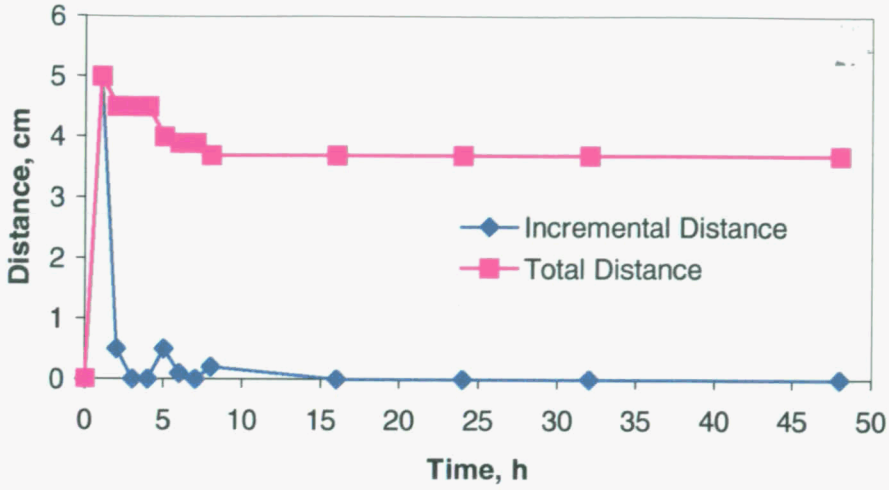

Figure C.1.3. K65-25-F Incremental and Total Settling Distances.

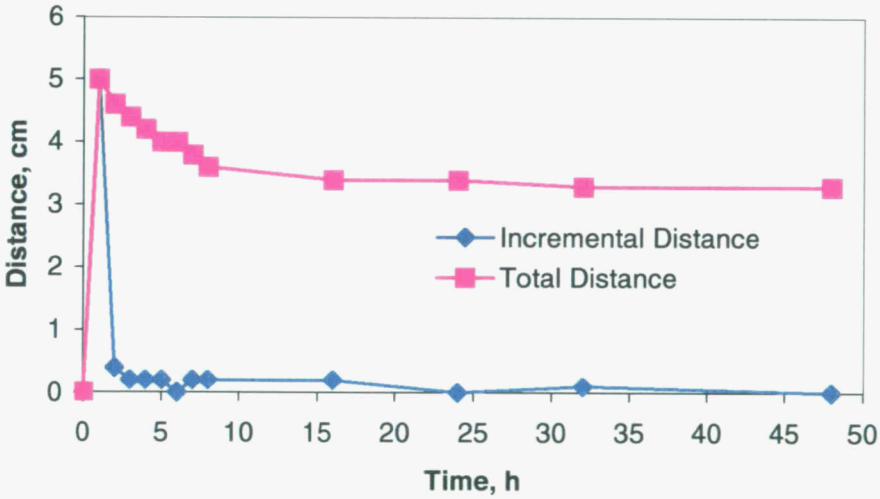

Figure C.1.4. K65-25-T Incremental and Total Settling Distances.

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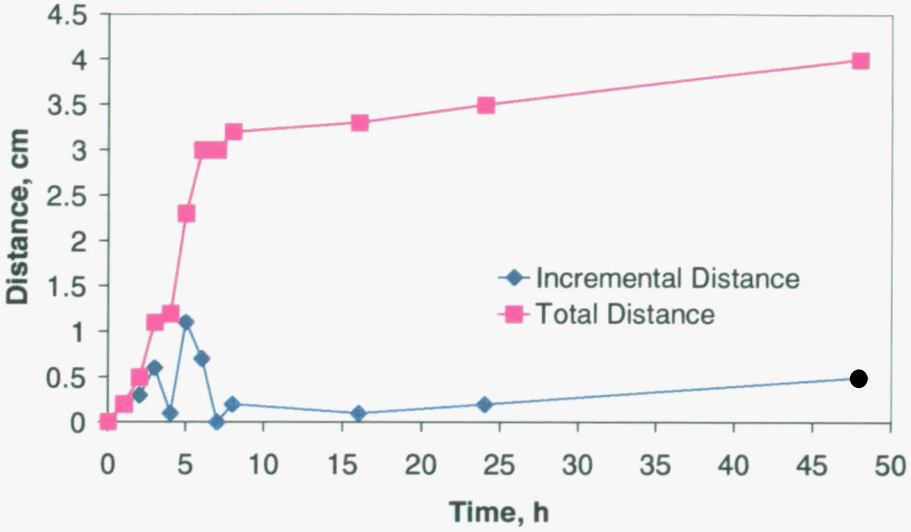

Figure C.1.5. K65-25-5-T Incremental and Total Settling Distances.

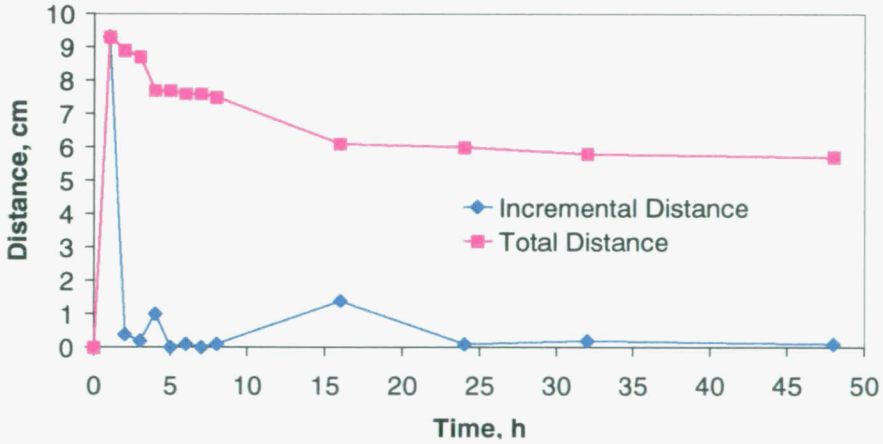

Figure C.1.6. K65-35-T Incremental and Total Settling Distances.

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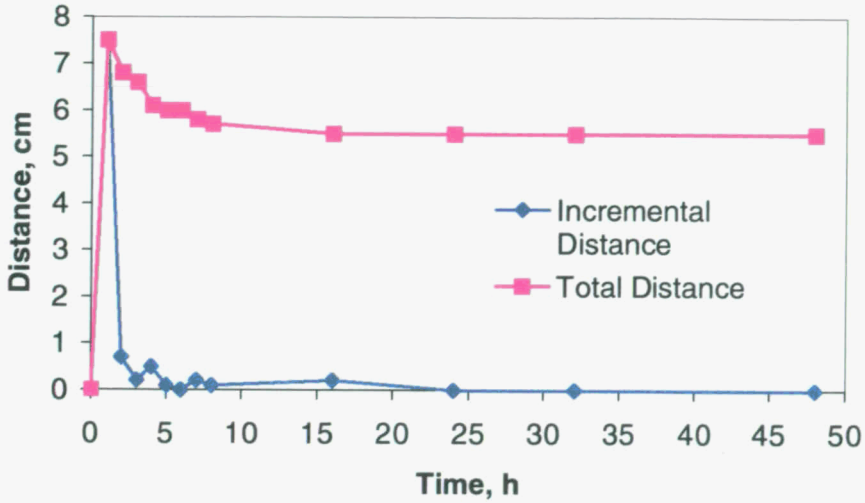

Figure C.1.7. K65-40-F Incremental and Total Settling Distances.

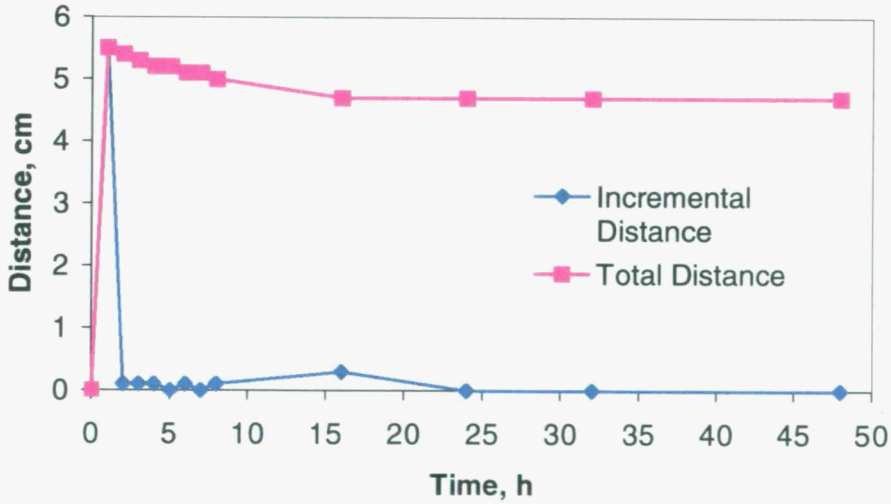

Figure C.1.8. K65-40-T Incremental and Total Settling Distances.

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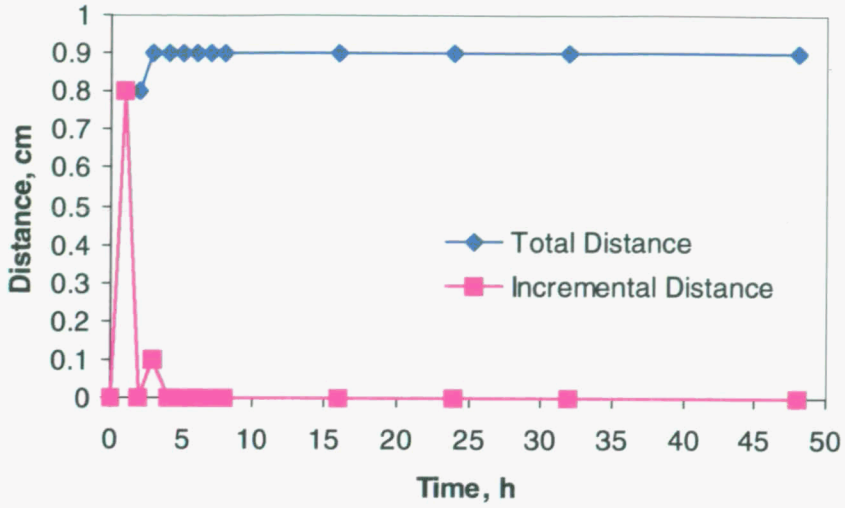

Figure C.1.9. K65-5-F Incremental and Total Settling Distances.

C-2. SURROGATES INCREMENTAL AND TOTAL SETTLING DISTANCES.

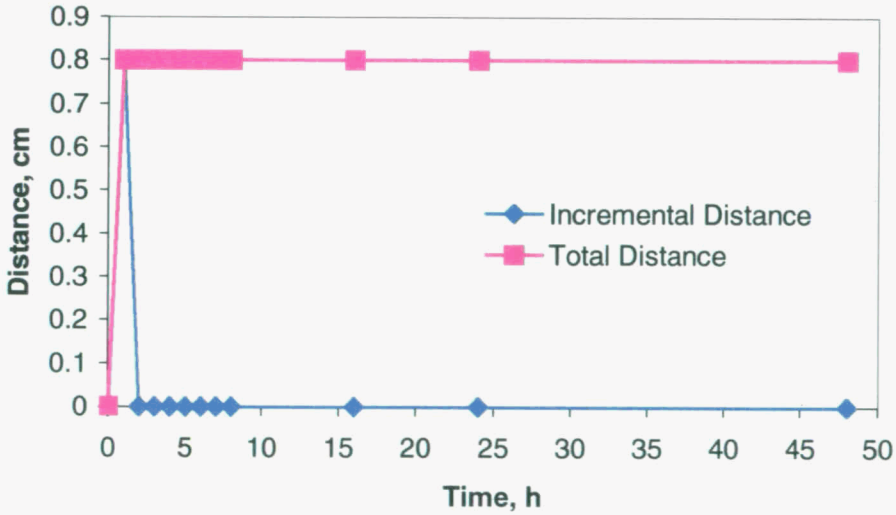

Figure C.2.1. Surr1-5-F Incremental and Total Settling Distances.

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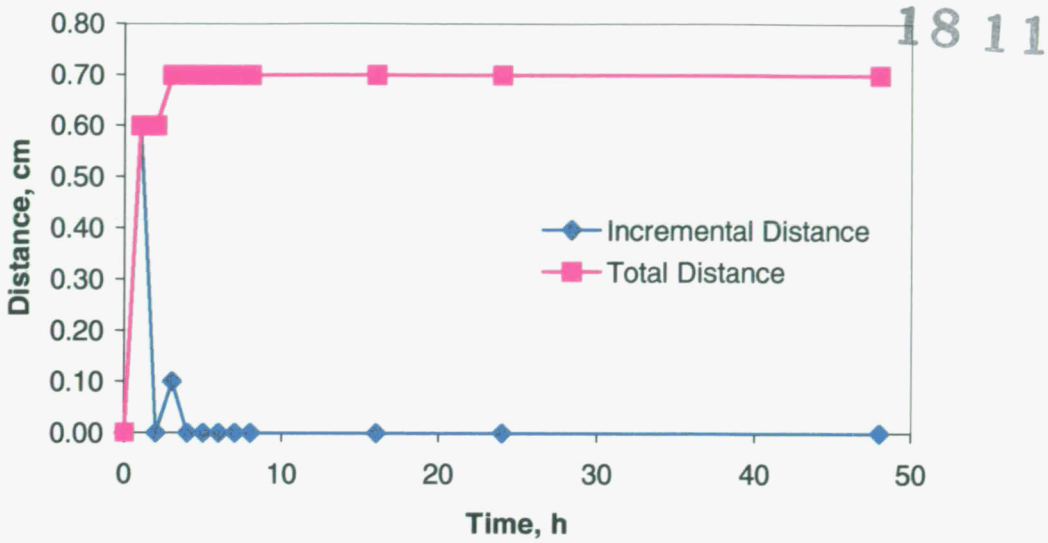

Figure C.2.2. Surr1-5-T Incremental and Total Settling Distances.

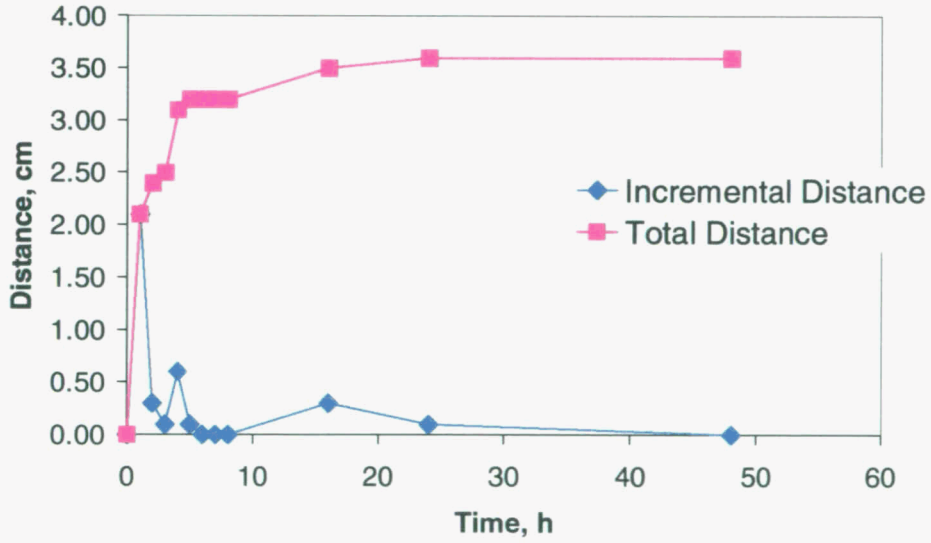

Figure C.2.3. Surr1-25-F Incremental and Total Settling Distances.

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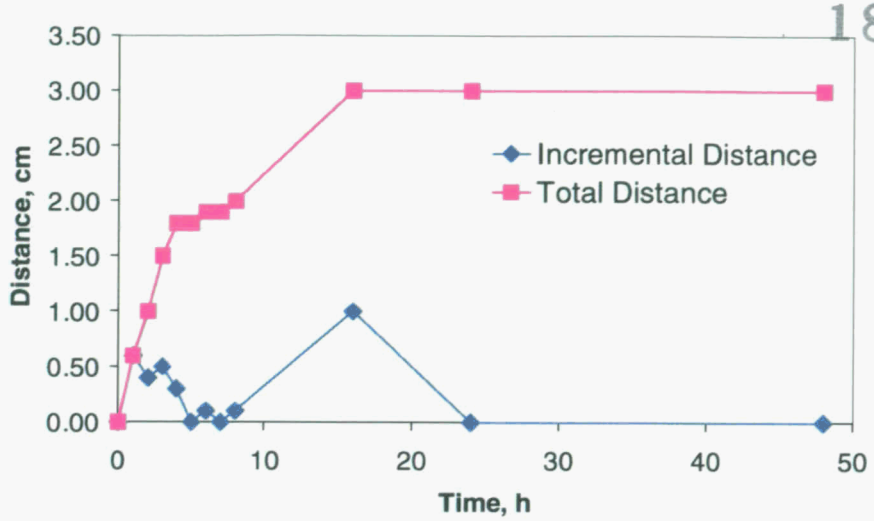

Figure C.2.4. Surr1-25-T Incremental and Total Settling Distances.

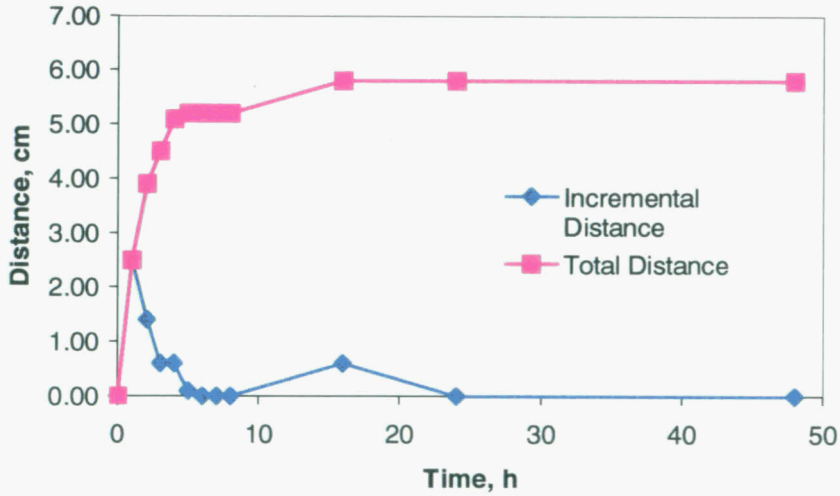

Figure C.2.5. Surr1-40-F Incremental and Total Settling Distances.

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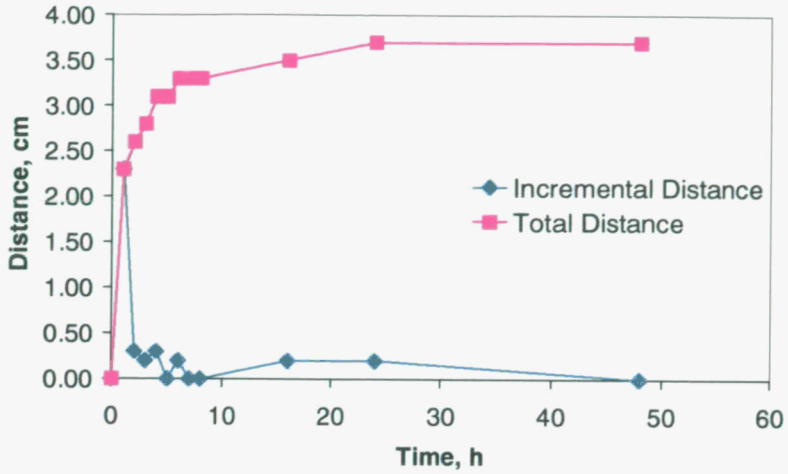

Figure C.2.6. Surr1-40-T Incremental and Total Settling Distances.

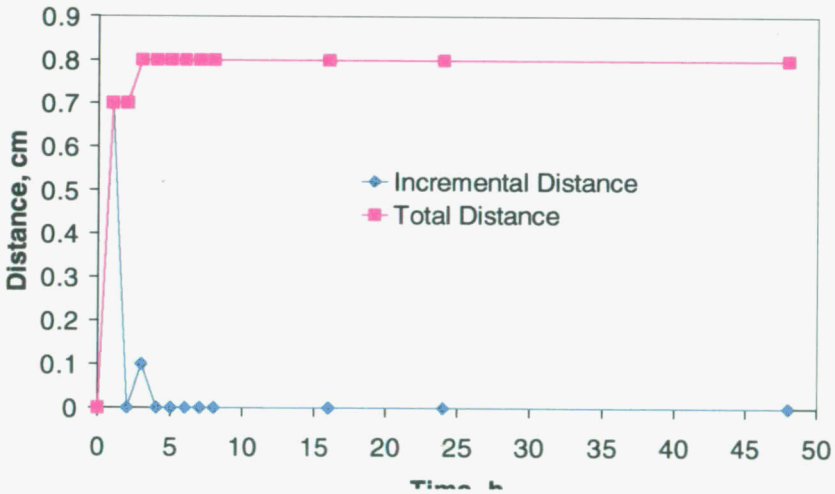

Figure C.2.7. Surr2-5-F Incremental and Total Settling Distances.

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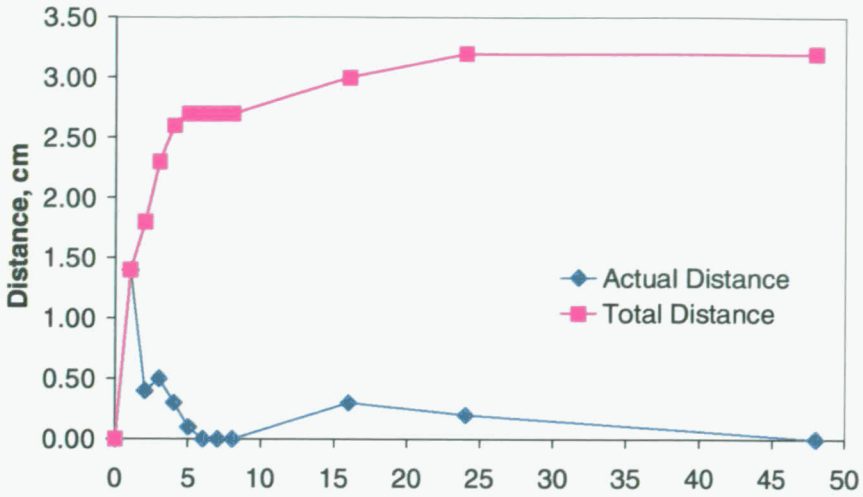

Figure C.2.8. Surr2-25-F Incremental and Total Settling Distances.

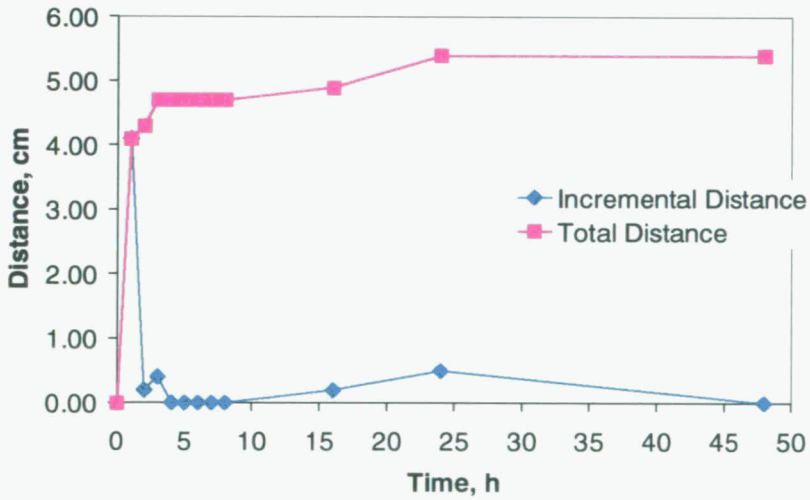

Figure C.2.9. Surr2-40-F Incremental and Total Settling Distances.

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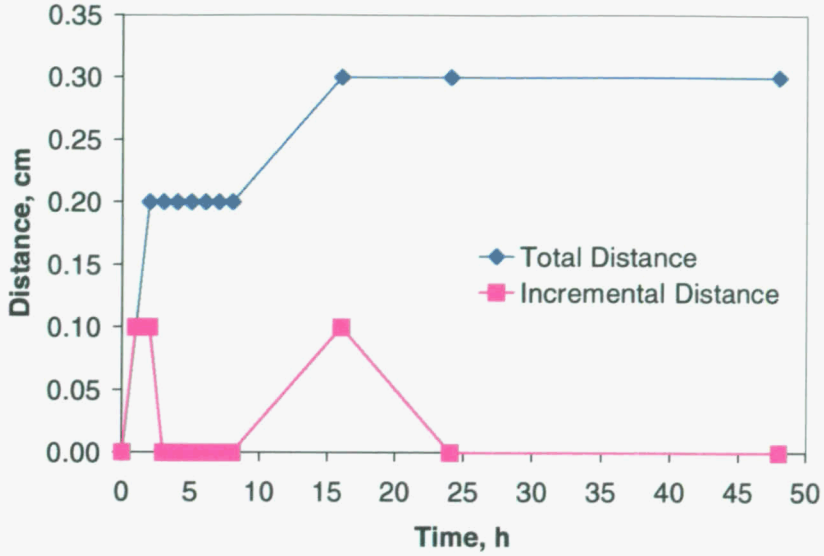

Figure C.2.10. Surr2-5-5-F Incremental and Total Settling Distances.

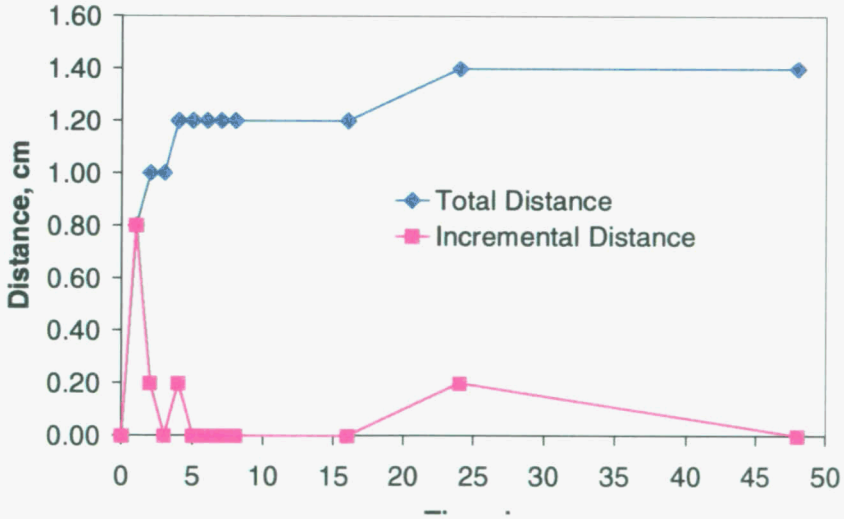

Figure C.2.11. Surr2-25-5-F Incremental and Total Settling Distances.

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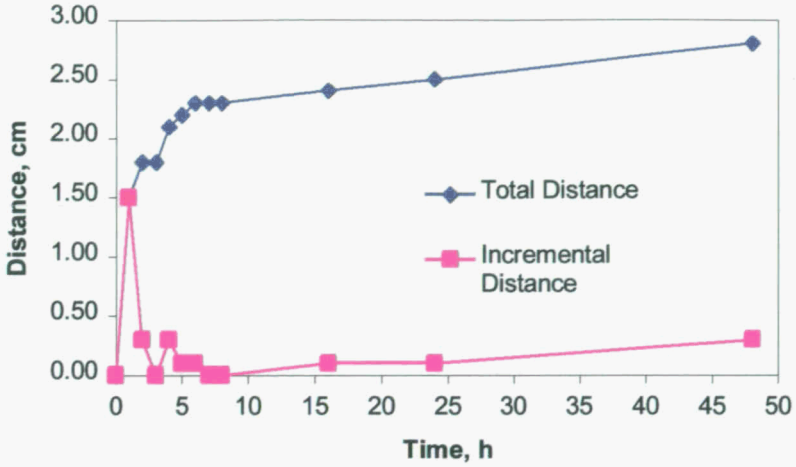

Figure C.2.12. Surr2-40-5-F Incremental and Total Settling Distances.

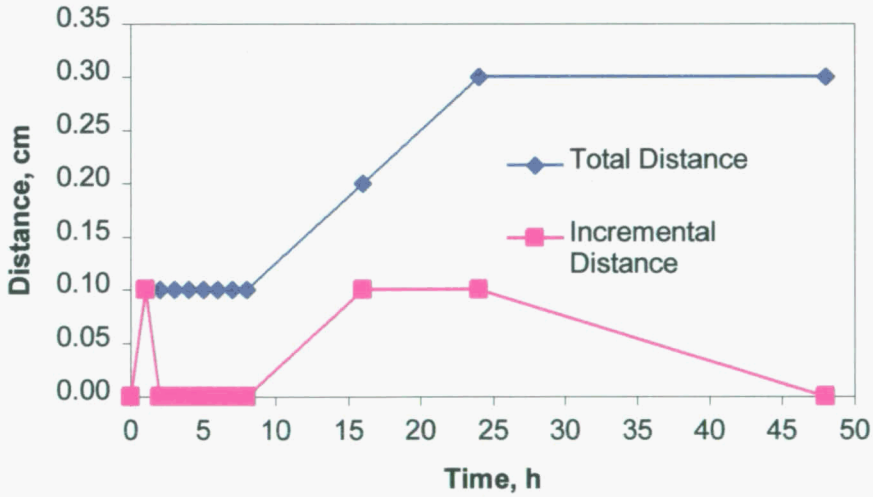

Figure C.2.13. Surr2-5-5-T Incremental and Total Settling Distances.

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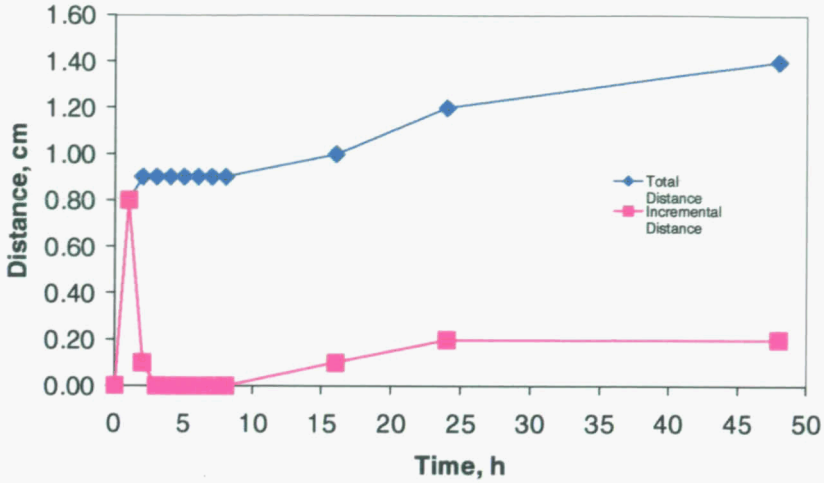

Figure C.2.14. Surr2-25-5-T Incremental and Total Settling Distances.

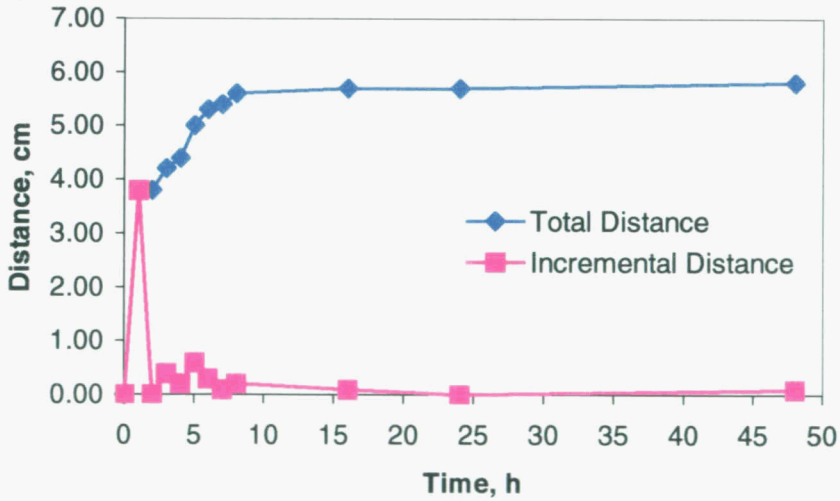

Figure C.2.15. Surr2-40-5-T Incremental and Total Settling Distances.

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