FINAL REPORT

8102

Rheology Testing of Fernald K-65 Waste Residue Slurry

Fluor Daniel Fernald
Fernald Environmental Management Project

M.A. Ebadian, Ph.D. and [illegible]

Hemispheric Center for
Environmental Technology
Florida International University

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INFORMATION ONLY

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DISCLAIMER

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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

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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

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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 INTRODUCTION

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This project was conducted according to the Project Specific Plan (PSP) prepared by the Hemispheric Center for Environmental Technology at Florida International University (FIU-HCET) and approved by Fluor Daniel Fernald (FDF).

Fluor Daniel Fernald (FDF) is a former production site of the Department of Energy (DOE) that extracted uranium from uranium ores and concentrates and produced metallic uranium for the DOE defense program. During its operating period, thousands of cubic meters of residue material, designated as K-65 materials, were accumulated and stored at this site. The K-65 materials are classified as by-products. After site production activities were ended, a bentonite clay layer was added over the residues to reduce the emission of radon. The FDF is considering characterizing this material and pumping it to a treatment facility. Therefore, the rheological and hydraulic properties of these waste slurries are important in the development of mixing and transfer systems.

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

In accordance with the PSP, the following tasks have been accomplished:

- Two loops for pressure drop testing were established.
- A physical surrogate formula for K-65 materials was developed.
- Physical properties of K-65 materials and surrogate slurries, including density, pH, and viscosity, have been measured at different temperature levels and percentages of bentonite contents. The characterization of hot material and surrogate slurries was performed to acquire data on particle size distribution and settling behaviors.
- Pressure drops in different loop components were measured for K-65 materials and surrogate slurries.

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2.0 EXPERIMENTAL METHODS, SYSTEM, AND INSTRUMENTATION

2.1 PHYSICAL PROPERTY MEASUREMENT

Temperature Control

Property measurements were taken at three temperatures (4°C, 25°C, and 40°C) to cover the possible actual operating temperature range. To reach the high temperature of 40°C, an isothermal water bath was used. A heater around the bath wall controls the bath temperature to a maximum of 100°C. A sample bottle is then immersed in the bath and heated to a previously set temperature. The bath temperature can be directly read on the attached equipment panel, but the bath temperature is not the same as the temperature inside the sample bottle. Therefore, to take a temperature reading for the sample, a thermometer had to be inserted into the sample to about the middle of the sample bottle while the bottle was submerged in the bath. Samples were well mixed prior to each temperature measurement. To reach the low temperature of 4°C, the isothermal bath was filled with ice water. After an initial cooling time with occasional stirring, the samples were cooled to the desired temperature.

Viscosity Measurement

A rheometer Model RI-1-L (Serial No: 6292) from Rheology International Shannon Ltd. was used to measure slurry viscosity. This viscometer rotates a sensing element in a fluid and measures the torque necessary to overcome the viscous resistance to the induced movement. This is done by driving the element, called a spindle, through a beryllium copper spring via a pivot point assembly. This torque is then converted into viscosity units and displayed on the viscometer panel. The manufacturer has calibrated the viscometer using viscosity standards traceable to the National Institute of Standards & Technology (NIST). These calibration results are listed in Table 2.1.1.

Table 2.1.1
Viscometer Calibration by Manufacturer (NIST)Viscosity at 25°C; 103 cP; Spindle No:L1

Speed (RPM)	% Torque	Viscosity (cP)
10	16.18	98
20	33.84	101
30	50.87	102
50	85.56	102.6

The viscometer was also calibrated at the FIU-HCET with different viscosities using viscosity standards provided by Cambridge Applied Systems, Inc., and the Cannon Instrument Company. The calibration data for spindles No. 1, 2, 3, and 4 are shown in Table 2.1.2.

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Table 2.1.2
Viscometer Calibration by FIU-HCET (Temperature 25°C)

Spindle No.	Speed (RPM)	Standard	% Torque	Measured Viscosity (cP)
1	100	Q3E	10.3	4.0
1	100	Q6E	18.5	8.4
1	100	Q20	37	18.5
1	100	K60	66	33.2
2	100	Q6E	3.84	7.8
3	100	S-200	41.68	404
4	100	S-200	12.31	404
4	100	S-2000	67.15	5817

Density Measurement

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. This method worked well for homogenous liquid samples such as those taken from the slurry tank after several hours of mixing and running through the loop. The first method of weighing, measuring volume, and calculating density was used for all samples of the surrogates.

pH-meter

A Corning pH-meter (electrode type) was used for sample pH analysis. Before one set of samples was measured, the pH-meter was calibrated using standard solutions in pH range 4 to 10. Once the samples were conditioned to the desired temperature, the pH electrode was introduced directly into the sample bottle. The pH of the solution was displayed on the instrument panel; the temperature of the solution was also displayed.

2.2 PARTICLE SIZE ANALYSIS

Particle Counter—Principle of Operation

To evaluate the size and distribution of particles in K-65 materials from Fernald Silos 1 and 2, determinations were carried out using a HIAC/ROYCO Model 9703 particle counter, manufactured by the HIAC/ROYCO division of Pacific Scientific in Silver Springs, Maryland. The instrument was fitted with an HRD-400 laser sensor capable of determining particles in the 2μm to 400μm size range.

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The particle counter functions by drawing a suspension of particles in a liquid fluid through an opening upon which a laser beam is impinged. As particles pass the beam, the laser is blocked to an extent corresponding to the size of the particle. The amount of light passing the particle is sensed by a detector and translated by the counter into the size of the particle doing the blocking. As each particle passes the laser, it is both sized and counted. Thus, the particle counter produces an indication of the number of particles of each size that are present in a sample.

The instrument can also be fitted with sensors that cover specific particle size ranges. The liquid suspension is drawn through an immersed probe and into the sensor by an automated syringe; therefore, the volume of liquid drawn can be varied by the instrumental controls. Typically, for this work 3ml were used. The depth of the probe can also be controlled by the instrument. The sample positions indicate strictly the point at which the sample was taken and do not necessarily reflect the overall particle distribution of the liquid above or below that point. It is possible that a portion of the 3-ml sample derives from above or below the position taken; however, the relatively low flow rate at which the sample is drawn into the instrument should minimize any disturbance of the liquid around the probe tip. The sample can be stirred magnetically during the determination.

The software associated with the particle counter is capable of presenting the data in several formats. The raw data is produced in tabular form based on the size of the particle, the number of counts of each size, the cumulative size, and the cumulative number of counts. The particle size range of the instrument, 2-400μm, can be divided into as many channels as desired by the operator. In this case 128 channels were selected, which provide 128 separate particle size ranges to be determined. Since the particle sizes are spaced logarithmically, they are not divided equally. Therefore, the cumulative size represents the sum of all size differentials beginning with the lower end of the particle range, i.e., 2.00μm. The cumulative count is the sum of all counts for all sizes measured.

In addition, the particle counter software can present the collected data graphically. Because of the large volume of tabular results and for convenience of interpretation, graphical results are being included in this report. The tabular results, however, are available for examination.

By using various descriptions, the software can report the data in tabular reports organized by population distribution, volume distribution, surface distribution, particle concentration, population summary, volume summary, and as volume-weighted data. Similar formats are also available graphically. The graphical results submitted here are those that define the percentage of particles greater than a given size. This data should provide the most meaningful information for evaluation of the surrogates and the K-65 materials.

Measurement Methods

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.

The size range choice of 2μm to 400 μm was based on information received from Fluor Daniel Fernald indicating that the K-65 materials showed a particle distribution after sieving as presented in Table 2.2.1.

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Table 2.2.1
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

To develop a systematic method for measuring particle size distribution, the non-radioactive surrogate samples were run before the radioactive ones. This was done so that any technical problems in carrying out the determination could be resolved before handling radioactive material. Initially, it was hoped that a sample could be run while being thoroughly stirred so that all particle sizes present could be measured at once. When this was tried, however, the sensor channel through which the particles passed became clogged due to the presence of either particles greater than 400µm or an agglomeration of smaller particles. Because of the clogging, the samples were allowed to settle for a prolonged period, during which time some samples separated into several layers indicative of particle sizes. These layers were typically comprised of a supernatant liquid and one or more layers of solid.

Measurement was carried out by placing 50 ml of a sample in a 25 mm × 95 mm vial. After allowing the sample to settle for one to two days, the height of the sample in the vial was marked off in 10 mm increments, and each height was given a position number. The top of the sample was designated position 0, and the subsequent position numbers increased downward. The vial was then placed on the instrument stage and the instrument probe lowered to each position. For a 3-ml sample size, counting was activated using the instrument software, and the particle size distribution at each level was recorded.

In all cases the samples were tested either after being freshly made in sample bottles or after being pumped from the slurry tank. This was done in order to determine whether there was any deterioration in particle size because of the pumping and mixing process. Certain tank samples were not available as freshly made since they had been used in the preparation of subsequent concentrations without being removed from the loop.

Fifty milliliters of each sample were received in 25 mm × 95 mm vials as described previously. Upon settling for approximately 24 hours, in addition to those samples without bentonite, only the samples containing 5% solids + 5% bentonite and 25% solids with 5% bentonite exhibited any separation of the solid from the liquid. The supernatant liquid from the sample with 5% solids and 5% bentonite was able to be evaluated for particle size distribution; however, the supernatant for the 25% solids with 5% bentonite, because of its extremely small volume, could

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not be run. Likewise, since no supernatant separated out in the remaining samples, it was not possible to run a particle size distribution directly on them.

To determine the particle size profile of those samples that did not separate, each was diluted 1:25 with water. Each of the diluted samples, in turn, was diluted a second time 1:25, producing samples with an overall dilution of 1:625 from the original. Under these conditions the samples were analyzed using the particle counter with the probe at the lowest depth into the suspension, presumably where the largest particles would be found. All samples could now be analyzed, with the exception of one containing 40% solids and 5% bentonite that continued to block the sensor channel even after dilution.

2.3 PRESSURE DROP TESTING LOOPS

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 is to verify the consistency of the rheological and 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. 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.

A diagram of the loop is shown in Figure 2.3.1. Photographs of the two systems are shown in Figures 2.3.2 and 2.3.3. 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 (77.5in), straight horizontal section (77.5in), vertical section with bend, horizontal section with bend, and flow control valves. The bend radius is 5 times the tube diameter.

Slurry was loaded and mixed in the slurry reservoir tank. A mixer was installed on top of the reservoir tank to keep the slurry mixed during testing. A rotary screw pump was used to pump the slurry through the loop. Two ball valves were installed at both sides of the pump to isolate the pump for maintenance and repair. A double tube heat exchanger was used to control the

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temperature of the slurry. The slurry flows through the inner tube and the coolant flows through the annular passage between the inner tube and outer tube. The coolant temperature was controlled by a chiller that operated in the temperature range of –10°C to 50°C. A pressure transducer measured the static pressure at the pump outlet. The slurry flowed in sequence through the upward vertical test section with bend, the downward vertical section, the horizontal test section, and the horizontal test section with bend. Then the slurry flowed back to the slurry reservoir tank. A flow meter was installed upstream from the horizontal test section to measure the slurry flow rate. One differential pressure transducer with remote diagram seal system was installed for each test section. The two legs of the differential transducer were connected to both ends of the corresponding test section. Another pressure transducer was used at the end of the loop to measure the static pressure. The slurry temperatures at both ends of the heat exchanger were measured using two E-type thermocouples. In the cooling loop between heat exchanger and chiller, two thermocouples were used to measure the temperatures of the coolant at the inlet and outlet of the heat exchanger. The coolant flow rate was measured by a turbine flow meter with an accuracy of ±0.5%. All the signals from the thermocouples, flow meters, pressure transducers, and differential pressure transducers were read by a National Instrument LabVIEW Data Acquisition system.

At the beginning of the testing, a TUTHILL HD PROCESS PUMP with rotary positive displacement, circumferential piston design, and heavy-duty construction was installed. It failed to work for the slurry flow. The details of the pump failure analysis were provided in a separate report. A screw type MOYNO 1000 series pump was selected and installed. The new pump worked well and lasted about 400 running hours with little performance reduction in the hot loop for K-65 and bentonite slurry flow. The same type of pump used in the cold loop for surrogate slurry flow experienced a significant performance decrease after running about 500 hours. The maximum pump flow rate decreased from 20 GPM to 12 GPM.

The slurry and coolant temperatures were measured by E-type thermocouples, with accuracy of ±0.5%. Two pressure transducers, the EPO-W41-250P and EPO-W41-100P, with upper limits of 100 psi and 250 psi, respectively, were used. The accuracy level is ±1% of full-scale output. The differential transducers for pressure drop measurement are ROSEMOUNT DP1151 series transducers. The mode 1199 diagram seal system was chosen for the slurry application. In each loop, two 1151DP4S transducers were used for the vertical and horizontal straight test sections, and two 1151DP5S transducers were used for vertical and horizontal straight and bend sections. The accuracy of the transducers is ±0.25% of the calibrated span (150 InH_2O). The stability was ±0.25% of URL (Upper Range Limit, 150 InH_2O for 1151DP4S and 750 for 1151DP5S) for six months. The accuracy of the mass flow meter measuring the slurry flow rate was ±0.25% of rate.

Consequently, the uncertainties of the calculated Reynolds number and friction factor are ±2.5% and ±3.8%, respectively. The main parameter uncertainties are summarized in Table 2.3.1.

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Table 2.3.1
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

2.4 LOOP TEST PROCEDURES

For each concentration, the whole test process includes loading water and solids, mixing and conditioning, controlling temperature, and collecting data. The quantity of water and solids can be determined from the total weight of slurry needed and concentration of each solid ingredient. The procedures for performing the tests are described below.

1. Load water in the amount required into reservoir tank.
2. Start pump and mixer to keep loop running and begin to run data acquisition system to monitor and record the meter readings.
3. Load the solids into the reservoir tank while the loop is running.
4. Start the chiller; set the temperature, and keep the loop running until the slurry is well mixed and the temperature is stabilized at the required level. The loop status should be monitored by the data acquisition system.
5. Set the flow rate to the required value; wait 2-5 minutes. Then change the file name in the data acquisition program and run the program to collect the data into the file. Repeat this step to run all flow rates from high to low.
6. Repeat steps 4-5 for all three temperatures.
7. Run timing or settling tests, if required.
8. After finishing all cases, add more solids to change the concentration or discharge the system for the new slurry testing.

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2.5 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 have 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 following calculations are based on the assumptions that the flows are in steady state, the flows are well developed, and there is no phase separation in the flows.

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

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

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.

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

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.

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

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

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

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

where u is the average flow velocity; d is the inner diameter of the tube; L denotes the length of the test section; ΔP is the pressure drop across the test section; ρ symbolizes the slurry density; and μ is the 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

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

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

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$$\rho = f(C_b, Cs, T)$$

$$\mu = f(C_b, Cs, T)$$

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]:

$$f = \frac{0.25}{\left[\log\left(\frac{1}{3.7(d/\varepsilon)} + \frac{5.74}{Re^{0.9}}\right)\right]^2}$$

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

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.

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3.0 K-65 MATERIAL CHARACTERIZATION AND PRESSURE DROP RESULTS

3.1 PHYSICAL PROPERTY DATA

The K-65 samples were prepared either in a bottle as fresh samples or taken from the test loop as pumped samples. All the measured properties for K-65 and bentonite slurries are listed in Table 3.1.1.

Table 3.1.1
Physical Properties of K-65 and Bentonite Slurries

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
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.

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.

The measured results indicate that the temperature effect on the K-65 slurries is not significant for the test conditions. Therefore, the general function was developed for density estimation.

$$\rho_e = 900C_t^2 + 230C_t + 997.9,$$

$$40^\circ C \geq T \geq 4^\circ C,\ 0.10 \geq C_b \text{ when } 0.25 \geq C_s \geq 0.05, \text{ and } 0.05 \geq C_b \text{ when } C_s = 0.40$$

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The correlation and the measurement data are shown in Figure 3.1.1.

ρ_e is slurry effective density with the unit of Kg/m^3; C_t is the concentration of total solids including K-65 and bentonite. 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.

The viscosity of the K-65 and bentonite slurries was correlated. The following equations are suggested.

Without bentonite:

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

With 5% bentonite:

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

Figure 3.1.2 shows the measurement data and correlations. The viscosity unit is cP. The K-65 concentration C_s takes decimal number 0.25 (25%). The viscosity is an exponential function of K-65 hot material concentration. These two correlations are for room temperature around 25°C. The dependence of the viscosity on temperature can be positive or negative for different slurry conditions. It has to be analyzed individually. The viscosities for the 10% bentonite slurries are very high, and few data are available to make a correlation.

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 for all samples.

3.2 PARTICLE SIZE ANALYSIS RESULTS

The samples of K-65 radioactive material that were tested for particle size distribution are catalogued below in Table 3.2.1. The Figure numbers refer to the specific particle size distribution curve for the sample, as it appears in the report. Although presented here first, the K-65 samples were run after the surrogate samples had been run to develop the methodology. Those concentrations not shown were not run because they couldn't flow in the instrument.

Table 3.2.1
Radioactive K-65 Samples Tested for Particle Size Distribution

Sample #	Description	Figure #	K-65 Solid Content	Bentonite Content	Pumped	Diluted
1	top of supernatant	3.2.1	5%	0	no	no
	bottom of supernatant	3.2.2	5%	0	no	no
	top of settled material	3.2.3	5%	0	no	no
2	top of supernatant	3.2.4	25%	0	no	no
	top of settled material	3.2.5	25%	0	no	no
3	top of supernatant	3.2.6	5%	5%	yes	no
	top of settled material	3.2.7	5%	5%	yes	no
	solid material	3.2.8	5%	5%	yes	yes,1:625
4	solid material	3.2.9	5%	10%	yes	yes,1:625
5	solid material	3.2.10	25%	5%	yes	yes,1:625
6	solid material	3.2.11	25%	10%	yes	yes,1:625

The curves presented 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.

Among the samples tested, only samples 1, 2, 3, and 4 showed any settling that produced enough supernatant liquid to run on the particle counter. Sample 6 also underwent some settling; however, the supernatant volume was not sufficient to be analyzed directly. In those cases where the supernatant was not adequately present, the samples were diluted with particle-free water and analyzed.

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.

Sample 1. 5% K-65 Unpumped Slurry Without Bentonite

Top of Supernatant. Figure 3.2.1 shows the results of the particle size measurement on the supernatant unpumped K-65 slurry material without bentonite. The particles measured lie in the range of 2μm to approximately 15μm. Figure 3.2.3 shows the results taken at the top of the settled solid material. This profile appears quite similar to the supernatant taken close to the top of the precipitate. The range of sizes lies between 2μm to 7μm with 50% of them greater than 3.2μm. The narrowness of this range indicates the homogeneity of the settled layer in the K-65 material. Surprisingly, there is a lack of large particles to be found in the material. An attempt to sample the settled layer at a slightly deeper point resulted in blockage of the sensor.

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Bottom of Supernatant. Only a slight variation in the particle size distribution of the supernatant with the depth of sampling was evident, as shown by Figure 3.2.2 where the supernatant was taken 60mm below that for Figure 3.2.1. In Figure 3.2.1, 50% of the particles were greater than 3.5μm, while in Figure 3.2.2, 50% were greater than 3μm. The latter curve is steeper at the lower 60mm depth (closer to the settled precipitate) indicating a narrower range of sizes.

Examination of the actual cumulative counts show that Sample 1(Table 3.2.1) taken away from the settled material had a total count of 19285 and that taken closer (Sample 2, Table 3.2.1) had 42232 total counts as might be expected. In Figure 3.2.1, tabular results indicated that only 78 counts were higher than 15μm, while in the lower sample, 18 counts were higher than 15μm, reflecting the narrower range of counts exhibited there.

Top of Settled Material, Undiluted. In contrast to the surrogate material, very little change is observed in the particle size distribution. An attempt, however, to sample at a slightly deeper point into the settled solid resulted in blockage of the sensor. The maximum particle size shown in Figure 3.2.3 was approximately 7μm in keeping with the supernatant taken near the top of the settled material shown in Figure 3.2.2. The steepness of the curve is also similar to that of Sample 2 (Table 3.2.1), indicating the narrower particle size range.

Sample 2. 25% K-65 Unpumped Slurry Without Bentonite

Supernatant Material, Undiluted. Figure 3.2.4 shows the particle size distribution of the 25% solids K-65 material without added bentonite. Although the range of particle sizes is similar to those shown for the 5% material in Figure 3.2.1, i.e., 2μm to 15μm, there seems to be more larger particles present, indicated in the bulge of the curve between 2μm to 4 μm. Here also 50% of the particles are greater than 4.6μm, compared to 50% greater than 3.5μm in the 5% solids material. This sample was homogeneous throughout the supernatant layer, as indicated by testing the supernatant at different depths.

Top of Settled Material, Undiluted. At the surface of the settled solid, the particle sizes increased as shown in Figure 3.2.5, a clear increase in particle size was evident with 50% of the particles 18μm or greater. The overall range of particle sizes also increased over that of the 5% material. It is possible that the higher solids concentration did not allow the solid to separate as much. This might have implications in the fact that the pressure drop characteristics of the 25% material were higher than the corresponding 5%. Further attempts to measure the settled material at a deeper position were unsuccessful because the sensor clogged.

Sample 3. 5% K-65 Pumped Slurry With 5% Bentonite

Supernatant Material, Undiluted. Figure 3.2.6 indicates the particle size distribution in the supernatant liquid of the previously pumped, undiluted K-65 sample with 5% solids and 5% bentonite (5%+5%). This sample showed almost identical particle characteristics as that of the 5% supernatant without bentonite, which had been taken close to the settled material, as shown in Figure 3.2.2. The steepness of the curve indicated the narrow particle size range of 2μm to 10μm. This sample was only one of a few with added bentonite that demonstrated any settling. At that, the volume of supernatant was very low. The other concentration where supernatant material was present was the 25% solids with added 5% bentonite. Here the volume was so low that it could not be determined directly.

Top of Settled Material, Undiluted. The settled material from the 5% solids K-65 with 5% added bentonite showed the results illustrated in Figure 3.2.7. The size range of 2μm to 20μm was most similar in shape to that of the 25% unpumped K-65 without added bentonite. Here the steepness was not as great as that of the 25% material, indicating the wider size range. In addition, 50% of the particles were greater than 6.5μm, compared to a corresponding value of less than 3μm in the supernatant.

Solid Material, Diluted 1:625. Figure 3.2.8 shows the particle size results after diluting 1 ml of the original sample to 625 ml. The results were taken after shaking the diluted solution and sampling as close to the bottom of the vial as possible. The results demonstrate a particle size range of 2μm to 25μm with 50% of the particles 9μm or greater. This is a much higher value than the corresponding result of 3.3μm obtained on the undiluted sample at the top of the settled residue. This value may represent a profile of the largest particles present in this sample, since no blockage of the sensor occurred.

Sample 4. 5% K-65 Pumped Slurry with 10% Bentonite

Solid Material, Diluted 1:625. Figure 3.2.9 shows the result obtained after diluting this sample 1:625 and taking a reading after shaking, close to the bottom of the vial. The profile is similar to that obtained for the 5%+5% (Figure 3.2.8) material, indicating that the chief contributing factor to the particle size may be the solid content rather than the bentonite.

Sample 5. 25% K-65 Pumped Slurry with 5% Bentonite

Solid Material, Diluted 1:625. As shown in Figure 3.2.10, similar results to those shown for the undiluted material sampled at the top of the settled residue were obtained. Thus, a particle size range of 2μm to 40μm is exhibited. That the 50% size is greater than for the 25%+5% sample in Figure 3.2.5 is consistent with the solid content contributing to the profile to a larger extent than does the bentonite.

Sample 6. 25% K-65 Pumped Slurry with 10% Bentonite

Solid Material, Diluted 1:625. Again Figure 3.2.11 shows a similar profile of the 25% solids sample with 10% bentonite to the same sample containing only 5% bentonite (Figure 3.2.10). The particle size range is 2μm to 40 with 50% of the particles greater than 13μm. Again, this is in keeping with the solid content dictating the particle size distribution to a greater extent than does the bentonite content.

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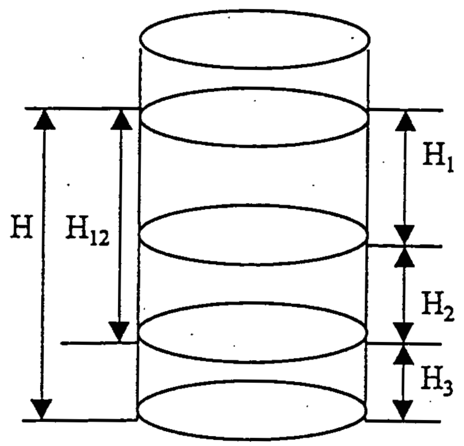
3.3 SLURRY PARTICLE SETTLING DATA

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. Figure 3.3 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 3.3. Diagram of settling distances.

The measured settling distances, the ratios of the distances to the total sample height, and the calculated settling velocities defined in the above diagram and equation are shown in Table 3.3.1. The ratio of settled solids to total solids in the K-65 samples has been estimated based on an equation described in section 4.4. Because the W_2 and ρ_2 in the equation were not able to be measured for the K-65 samples, their values for surrogate #2 under the same concentration have been used in the estimation. The estimated results are shown in Table 3.3.2. The settling distances, including the total distance over all settling time and the incremental distance over the settling periods between two recorded times, have been plotted in Figures 3.3.1 to 3.3.9.

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Table 3.3.1
Settling Distances and Settling Velocities for K-65 Samples

Sample	Time, h	*H1, cm	*H2, cm	*H3, cm	*H, cm	H1/H	H2/H	H3/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

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Table 3.3.1
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
	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
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

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Table 3.3.1
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
K65-25-5-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
	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

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Table 3.3.1
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
	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	[illegible]	[illegible]	[illegible]	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.

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Table 3.3.2
Weight Ratio of Settled Solids to Total Solids in K-65 Samples

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
	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

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Table 3.3.2
Weight Ratio of Settled Solids to Total Solids in K-65 Samples (continued)

Sample	Time, h	*W_3/W, %
	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
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

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Table 3.3.2
Weight Ratio of Settled Solids to Total Solids in K-65 Samples (continued)

Sample	Time, h	*W_3/W, %
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

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Table 3.3.2
Weight Ratio of Settled Solids to Total Solids in K-65 Samples (continued)

Sample	Time, h	*W_s/W, %
	16	100.00
	24	100.00
	32	100.00
	48	100.00
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

One interesting phenomenon was observed. After the 5% and 25% K-65 slurry with 5% bentonite was pumped in the loop and allowed to settle several hours, there was a clear liquid layer on the top. This phenomenon may suggest that there is some interaction between the K-65 and bentonite bounding certain chemical compounds in the K-65 materials after pumping, heating, and cooling processes. This point is also consistent with the viscosity and pressure drop data.

Pipeline settling tests have been done for the K-65 material slurries. In these tests, the flow was set to maximum velocity; then the pump frequency was reduced systematically until the flow rate reading reached zero. The pressure gradient variation versus flow velocity was plotted and analyzed. Figure 3.3.10 shows the pressure gradient variation in the settling test of 5% K-65 and 10% bentonite slurry.

In some settling cases, the deviation among the pressure gradients of vertical and horizontal sections increased in the low flow velocity range. It may indicate that the particle settling in the slurry (or phase separation) exists. A rough estimation of the minimum transporting velocity is in the range of 0.5-1.5 ft/s depending on the concentration. From experience and observation during the testing, a small amount of bentonite (5%) helps to suspend the particles in the slurry and reduce the minimum transporting velocity without high pressure drop increase.

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3.4 PRESSURE DROP RESULTS AND CORRELATION

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. The residue slurry composition and case sequence are shown in Table 3.4.1.

Table 3.4.1
Silo Material Slurry Compositions

Slurry	Date	Water kg	K-65 kg	Bentonite kg	K-65 %	Bentonite %
5% K-65	2/12	18.256	1.21 (0.8)	0	4.97	0
25% K-65	4/6	18.304	8.358 (0.8)	0	25.08	0
35% K-65	4/7	18.304 - 0.489 =17.815	8.358 - 0.223 + 5.954 = 14.089 (0.8)	0	35.33	0
40% K-65	4/8	17.815 - 0.49 = 17.324	14.089 - 0.389 + 6.446 =20.146 (0.8)	0	43.01	0
5%-K 5%-B	4/21	15.71	2.46 (0.40)	0.952	5.15	4.98
25%-K 5%-B	4/22	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	4/23	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%
K-65 material has 20% moisture. Dry K-65 density 2.7 kg/l, the water density 1.0 kg/l. K = K-65 material, B = BentoGrout™ material						

The surrogate slurry pressure drop and comparison to the hot material slurry data are discussed in the surrogate development section. All the hot loop pressure drop data and dimensionless results are attached in Appendix A and Appendix B, respectively. In this section, the temperature, orientation, and concentration effects on the pressure gradient are discussed. The dimensionless results are then presented, and some correlations are suggested.

Temperature Effect

In general, as the temperature increases, the pressure gradient or bend resistance decreases as shown on Figures 3.4.1-3.4.4. It is well known that the water viscosity decreases with

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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 3.4.2). 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.

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 3.4.5 without bentonite and Figure 3.4.6 with bentonite. Figure 3.4.7 and Figure 3.4.8 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 3.4.5 and Figure 3.4.6, 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 3.4.9. However, the bentonite concentration has more sensitive effect than silo material concentration.

Orientation Effect

The pipeline orientation effect on the flow resistance can be observed from Figure 3.4.10 and Figure 3.4.11. 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.

Correlation

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.

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

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The equation was correlated in the following test condition.

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

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

where, dp/dl has the unit of InH_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.

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.

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

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

The comparison between experimental data and prediction from the correlation is shown in Figure 3.4.12.

Friction factor and resistance factor

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

$$f = 144.4\,Re^{*-1.856} \qquad K = 236.85\,Re^{*-1.298} \qquad Re^* \leq 100$$

$$f = 0.0355\,Re^{*-0.0432} \qquad K = 0.8186\,Re^{*-0.124} \qquad 100 < Re^* < 2.0\text{x}10^4$$

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

$$0.05 < C_s < 0.40,\ 0.0 < C_b < 0.05$$

$$\text{and } 0.05 < Cs < 0.25,\ 0.0 < C_b < 0.10$$

The testing data points and the correlations are shown in Figures 3.4.13 and 3.4.14 for comparison.

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4.0 SURROGATE DEVELOPMENT

4.1 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 which is identical to the hot loop. Two surrogate formulations have been developed and tested in the cold loop. Table 4.1.1 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 4.1.2. 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 4.1.3.

Table 4.1.1
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 4.1.2
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

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Table 4.1.3
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 are 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 has 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.

After the pressure drop data were compared between the surrogates and the K-65 materials, the physical properties of the surrogates, such as pH, density, viscosity, particle size distribution, settled solids percentage, and settling behaviors, have also been measured and compared to those of the K-65 materials. The measurements of the settling behaviors have been described in section 3.3; that is, the settling phases have been defined as three portions of clear layer, cloudy layer, and settled layer. The comparison of the pressure drops and the physical properties of the surrogate with those of the K-65 materials indicates that surrogate #2 has the consistent pressure drops and similarity of the properties under the testing range, and it could be recommended as a good substitute for the K-65 materials.

4.2 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 4.2.1.

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Table 4.2.1
Surrogate Slurry Physical Properties

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
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**
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.

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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 4.2.1 and 4.2.2. The relationships of the density and the total solids concentration of surrogate and bentonite have been correlated by the following equations:

Surrogate # 1:

$$\rho_e = 2225.7C_t^2 + 29.147C_t + 992.92$$

Surrogate # 2:

$$\rho_e = 310.02C_t^2 + 599.4C_t + 971.1$$

$$40°C \geq T \geq 4°C,\ 0.10 \geq C_b \text{ when } 0.25 \geq C_s \geq 0.05,\ \text{ and } 0.05 \geq C_b \text{ when } C_s = 0.40$$

ρ_e is slurry effective density with the unit of Kg/m^3; C_t is the concentration of total solids including surrogate solids and bentonite. 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.

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. This is opposite to the regular fluids such as water and other homogeneous solutions whose viscosity decreases when the temperature increases. The special viscosity behavior for the surrogate slurries could be caused by the interactions of the surrogate chemicals and the bentonite. The interactions could be enhanced when the temperature is higher. The solids concentration effect on the viscosity has been observed for all samples at each temperature level. 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 4.2.3 and 4.2.5. 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:

$$\eta_e = 1.6348e^{7.12C_s}$$

Surrogate # 2:

$$\eta_e = 1.383e^{7.60C_s}$$

Surrogate # 2 (with 5% bentonite):

$$\eta_e = 3.2047e^{12.15C_t}$$

The viscosity unit is cP. The surrogate concentration C_s and the total concentration C_t including bentonite take decimal number 0.25 (25%). 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 available. These two correlations are made for room temperature around 25°C.

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4.3 PARTICLE SIZE ANALYSIS RESULTS

The samples of surrogates that were tested for particle size distribution are summarized below in Table 4.3.1.

Table 4.3.1
Surrogate Samples Tested for Particle Size Distribution

Sample	Description	Figure #	Surrogate Solid Content	Bentonite Content	Pumped	Diluted
7	top of supernatant	4.3.1	5%	0	no	no
	bottom of supernatant	4.3.2	5%	0	no	no
	Supernatant of red settled material	4.3.3	5%	0	no	yes, 1:625
	Supernatant of black settled material	4.3.4	5%	0	no	yes, 1:625
8	top of supernatant	4.3.5	5%	0	yes	no
	top of red settled material	4.3.6	5%	0	yes	no
9	top of supernatant	4.3.7	25%	0	no	no
	top of red settled material	4.3.8	25%	0	no	no
10	top of supernatant	4.3.9	25%	0	yes	no
	top of red settled material	4.3.10	25%	0	yes	no
11	top of supernatant	4.3.11	5%	5	no	yes, 1:625
	top of supernatant	4.3.12	5%	5	yes	yes, 1:625
12	top of supernatant	4.3.13	25%	5	no	yes, 1:625
	top of supernatant	4.3.14	25%	5	yes	yes, 1:625

Sample 7. 5% Surrogate Unpumped Slurry Without Bentonite

Top and Bottom of Supernatant, Undiluted. Figure 4.3.1 indicates the distribution of particles in the supernatant liquid of the surrogate, comprised of 5% solids without added bentonite. Figure 4.3.2 representing increasing depth of sampling on the supernatant illustrates that there is essentially no change on the particle size distribution throughout the supernatant portion. Thus, in this area, the particle size distribution is homogeneous.

Top of Red Layer Material, Diluted 1:625. An attempt to measure the particle sizes in the red layer which separated out below the supernatant was unsuccessful in that blockage of the sensor channel occurred. Addition of 25ml of water to this layer also resulted in blockage during attempts to measure it. Further dilution of 1ml of this suspension with 25ml of water, corresponding to an overall dilution of 1:625, followed by measurement of the supernatant was successful. These results are shown in Figure 4.3.3 taken at a depth of position 3 (approximately

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30mm below the top surface of the liquid). Clearly, there is an increased count of larger particles, with 50% of the particles larger than 7µm, as compared to 50% of the particles larger than 3µm in the original supernatant. At a deeper depth (position 6, not shown) no change in particle characteristics was observed.

Top of Black Layer Material, Diluted 1:625. Below the red layer discussed above, a thin black layer was observed. This layer was diluted 1:625 and the particle size distribution measured. Figure 4.3.4 shows the results of this measurement. Here there is a significant increase in particle size with approximately 50% of the particles being greater than 11µm. A second reading taken slightly deeper into this layer afforded an even greater particle size profile.

Sample 8. 5% Surrogate Pumped Slurry without Bentonite

Top of Supernatant, Undiluted. Figure 4.3.5 shows the results obtained upon measuring the supernatant liquid on a 5% surrogate without bentonite, which had been previously pumped in the loop. Additional measurement at other depth positions (not shown) indicated the same homogeneity experienced with the unpumped sample. Of interest is the relative increased number of particles in the 6µm to 20µm range. One would have expected a decrease because of pumping. One does observe a slight increase in smaller particles compared to the unpumped material with slightly greater than 3µm particles accounting for 50% of the population, while somewhat less than 3µm particles for the same percentage in the pumped sample.

Top of Red Settled Material, Undiluted. Figure 4.3.6 shows the particle characteristics for a sample taken just at the top of the red layer, in an undiluted mode. Here 50% of the particles are larger than 11µm corresponding to the same large size increase as was observed with the unpumped sample.

Sample 9. 25% Surrogate Unpumped Slurry without Bentonite

Top of Supernatant, Undiluted. Figure 4.3.7 shows the results of particle count testing on supernatant liquid of the 25% solids surrogate material before pumping and without bentonite. These results differ somewhat from the fresh 5% material, with 50% of the particles being greater than 4µm, compared to 50% greater than 3µm in the 5%. Homogeneity in the supernatant was again observed in this case (other depth positions not shown).

Top of Red Settled Layer, Undiluted. Figure 4.3.8 shows the results obtained upon sampling at the top of the red layer. A marked increase in particle size is indicated as expected, with it being somewhat greater than that observed in the 5% case.

Sample 10. 25% Surrogate Pumped Slurry without Bentonite

Top of Supernatant, Undiluted and Top of Red Settled Layer, Undiluted. Figure 4.3.9 shows the particle size distribution in the supernatant liquid for 25% solid surrogate that had been pumped. Very little change is observed from the unpumped material (Figure 4.3.7) or from the 5% unpumped material (Figure 4.3.1). Again homogeneity was observed at other depths throughout the supernatant layer. Sampling at the top of the red layer produced the expected increase in particle size as shown in Figure 4.3.10. Here approximately 50% of the particles were greater than 17μm. This represents very little change from the unpumped material (Figure 4.3.8).

Sample 11. 5% Surrogate Unpumped Slurry with 5% Bentonite

Top of Supernatant, Diluted 1:25. Figure 4.3.11 shows the particle size distribution of the supernatant layer of 5% unpumped surrogate. This sample needed to be diluted 1:25 in order to obtain a reading. Comparison to Figure 4.3.1 of the corresponding material without bentonite indicates a slightly increased particle size population in the sample containing the bentonite. It was not possible to obtain a measurement of the separated solid fraction, because blockage of the instrument occurred.

Sample 11. 5% Surrogate Pumped Slurry with 5% Bentonite

Top of Supernatant, Diluted 1:25. Similar measurement of the pumped material to that of the unpumped produced the results shown in Figure 4.3.12. Again 1:25 dilution of the sample was required to take the measurement. Again a slight increase in particle size is evident compared to the unpumped material (Figure 4.3.11) with 50% of the particles greater than 7μm being observed as compared to 50% greater than 5μm in the unpumped sample. This increase seems to be consistent with the previous data reported.

Sample 12. 25% Surrogate Unpumped Slurry with 5% Bentonite

Top of Supernatant, Diluted 1:625. Figure 4.3.13 shows the findings on the supernatant particle size distribution of the unpumped 25% solids surrogate with 5% bentonite added. The measurement required a 1:625 dilution in order to obtain a reading from the particle counter. This material showed a relatively high particle count with 50% of the particles greater than 7μm.

Sample 12. 25% Surrogate Pumped Slurry with 5% Bentonite

Top of Supernatant, Diluted 1:625. The corresponding pumped material at a 1:625 dilution is shown in Figure 4.3.14. In this case, very little change is observed from the unpumped surrogate (Figure 4.3.13).

Effects of Pumping on Particle Size

The effects of pumping on the particle size are summarized in Table 4.3.2 and Table 4.3.3 for supernatant and settled material, respectively. The data may suggest that the pumping process breaks down some of the particles into smaller sizes.

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Table 4.3.2
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 4.3.3
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

The data gathered for the particle count distribution of both the K-65 material and the surrogate indicate that pronounced effects are produced due to the solid concentration. Examination of Tables 4.3.2 and 4.3.3 indicates a general increase in mean particle size with increasing solids concentration. This is particularly evident in the case of the surrogate settled material in Table 4.3.3 where the particle size having greater than 50% population more than doubles in going from 5% solids to 25% solids 7.5µm to 16µm. This finding follows the increase in pressure drop measurements with increasing solids. Bentonite also increases the mean particle size with increasing concentration and likewise increases the pressure drops. It is possible that hydration effects will produce some agglomeration to account for this.

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

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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.

It appears that the particle size distribution is dependent on both the solids content and the bentonite content of the K-65 based upon the particle size profiles which give a greater than 50% population. The results are consistent with increased pressure drop observation both with increasing bentonite concentrations and with increasing solids concentration. The effect of the bentonite on the particle size characteristics may be due to agglomeration due to hydration. This may be verified by further work on particle size characteristics on bentonite itself.

4.4 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 inch. At time equal to zero, the slurry samples were well mixed and placed on a stationary bench for settling. Pictures were taken at different times until the solid phase in the slurry was totally settled. The distances defined in section 3.3 were measured at different times. The settling velocity is calculated by the same equation described in section 3.3. The measured settling distances, the ratios of the distances to the sample height, and the calculated settling velocity are shown in Table 4.4.1 for surrogate number 1 and 4.4.2 for surrogate number 2. Additionally, the total settled distance and the incremental settled distance along with settling time have been plotted in Figures 4.4.1 to 4.4.15.

Table 4.4.1
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

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Table 4.4.1
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
	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
	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

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Table 4.4.1
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
	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

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Table 4.4.1
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
	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 4.4.2
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

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Table 4.4.2
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
	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
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

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Table 4.4.2
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
	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

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Table 4.4.2
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
	48	0.00	8.40	1.40	9.80	0.00	0.86	0.14	0.18	0.003
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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The weight ratio of solids in the settled phase to the total solids in the sample could be calculated by the following equation:

$$W_3/W = (\text{Total solids} - \text{Solids in suspension}) / \text{Total solids}$$
$$= (V\rho W - V_2\rho_2 W_2) / V\rho W$$
$$= 1 - (V_2/V)(\rho_2/\rho)(W_2/W)$$
$$= 1 - (H_2/H)(\rho_2/\rho)(W_2/W)$$

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.%

H and H_2 are the sample height and the settling distance as defined in section 3.3.

The solids concentration, W_2, and the density, ρ_2, of the suspension layer were determined by sampling, drying, and weighing of 10 ml sample taken from the middle height of the suspension layer after 48 hours settling. Using the data at this point, the ratio of settled solids to the total solids in the sample can be accurately calculated. The W_2 and ρ_2 were not able to be measured during the settling because sampling from the bottle would affect the settling behavior. To estimate the ratio at each settling time point, the final ρ_2 and W_2 could be approximated for each time point. Based on this approximation, the weight ratio has been estimated at each settling time using the above equation. The estimated results are shown in Table 4.4.3.

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Table 4.4.3
Weight Ratio of Settled Solids to Total Solids in Surrogates

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

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Table 4.4.3
Weight Ratio of Settled Solids to Total Solids in Surrogates (continued)

Sample	Time, h	*W_3/W, %
	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
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

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Table 4.4.3
Weight Ratio of Settled Solids to Total Solids in Surrogates (continued)

Sample	Time, h	*W_3/W, %
	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

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Table 4.4.3
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

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Table 4.4.3
Weight Ratio of Settled Solids to Total Solids in Surrogates (continued)

Sample	Time, h	*W_3/W, %
	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
	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

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Table 4.4.3
Weight Ratio of Settled Solids to Total Solids in Surrogates (continued)

Sample	Time, h	*W_3/W, %
	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

4.5 PRESSURE DROP RESULTS AND COMPARISON

The surrogate slurry pressure drop and comparison to the hot material slurry data were discussed in the surrogate development section. The pressure gradient and bend resistance data versus velocity are listed in Appendix D, and the calculated friction factor versus Reynolds number data are listed in Appendix E.

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 4.5.1 and 4.5.2 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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5.0 RADIATION SAFETY

5.1 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.

5.2 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.

5.3 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.

The lab floor is lined with linoleum for easy decontamination. The radioactive material storage is fabricated from interlocking 3-inch-thick lead brick walls of 5ft 8in height. This area is ventilated through an activated charcoal bed to minimize release of radon and thoron into

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laboratory air. A sink is available in the radioactive materials laboratory. This sink is connected to the facility drain system, which is connected directly to the municipal drain system.

K-65 material shipped to the laboratory was contained in a 5-gallon can, which was placed in a 10-gallon drum. The 10-gallon drum was inside a 30-gallon drum, which has an O-ring to prevent radon escape from the material. The 30-gallon and 10-gallon drums were opened inside a tent to access the 5-gallon can. The tent air was exhausted through a portable activated charcoal filtration system to prevent radon release into the laboratory.

The laboratory area is declared and posted radioactive; no food or drinks are allowed in the area, and necessary radiation signs are posted.

5.4 EXPOSURE CONTROL

All personnel working in the laboratory were issued Thermoluminescent Dosimeters (TLDs), and adequate dose records were maintained. These were changed quarterly. Persons working on the rheology loop were issued extremity TLDs, which were changed monthly. The maximum whole body exposure received by any person was 10 mrem. The maximum extremity dose was 110 mrem.

Radiation surveys and wipe checks were done weekly. Surveys were performed at the end of each day when radioactive materials are used. General background in the laboratory is 60 μR/h.

Assessment of inhalation exposures was done by collecting air samples and measuring radon and radon progeny concentration. The average radon and radon progeny concentrations were nearly 2.5 pCi/L and 1 mWLM.

TLDs and Electret Ionization Chambers (EICs) were used for measuring radiation exposures outside the laboratory at the fence. TLDs were not yet processed. The EIC measurements show background radiation levels of 8-10 μR/h, which increased to 19 μR/h due to radioactive materials in the lab.

5.5 ACCESS CONTROL

The radioactive materials laboratory is housed within a security fence constructed in the Operations/Utility Building 102, Room 108 at the Center for Applied Science and Engineering, 10555 W. Flagler St., Miami, Florida 33174. The compound at W. Flagler St. is gated and under 24-hour security by contract personnel. This room is a concrete block construction building, configured as a high-bay measuring 80 ft × 40 ft × 20 ft with one, lockable garage door as an entrance. The floors are of concrete; a wire security fence with one 4 ft wide entrance is constructed as a 25 ft × 25 ft perimeter. Controlled access to the radioactive materials laboratory is provided by the following methods:

- Site security by contract personnel with backup response by FIU campus police
- Limited keyed access to Room 108, authorized project personnel only.
- Limited keyed access to radioactive materials laboratory security perimeter; authorized, supervised access for named radioactive materials laboratory users and maintenance staff only.

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- Limited keyed access to radioactive materials laboratory by named users and supervised, trained staff only.
- A telephone and monitored alarm.

5.6 RECEIPT AND STORAGE OF RADIOACTIVE MATERIALS

The radioactive materials were shipped from Fernald, OH via FedEx and received at the Radiation Laboratory situated in room number 108, building 102, of the Center for Engineering and Applied Sciences (CEAS) by the CEAS Radiation Safety Officer. There were five 30-gallon containers. Inside each 30-gallon container there was a 10-gallon container, which, in turn, contained a 5-gallon can. The radioactive material was inside the 5-gallon can. The space between the container drum and between drums was filled with vermiculites. A total of 88 pounds of K-65 material was received from FDF. The drums were surveyed and stored in the shielded radioactive storage area prior to studies.

5.7 LOADING OF RADIOACTIVE MATERIAL

1. Two persons and a health physicist were present to handle the drum. One person was suited in approved personnel protective equipment (PPE). The other wore a lab coat and hand gloves. Dust masks were used for this work. Respirators and other safety equipment were available in a cabinet for use in the unlikely event of a spill.
2. The drum was handled by the person dressed in PPE. The other person provided assistance, if needed. The health physicist measured radiation fields.
3. Using the drum hand-truck, the 30-gallon drum was moved from the radioactive material storage area and brought close to the glove box. It was placed in a small tent, and the portable activated charcoal filtration was started. The bolt of the drum was removed, and the drum top cap was opened. The accumulated radon was exhausted through the charcoal beds for two minutes. The 10-gallon drum empty was taken out, and the 30-gallon drum was moved out. The 10-gallon drum was opened to access 5-gallon can, and radon was exhausted through portable filtration system.
4. The person in lab coat opened the upper outer air-lock door of the glove box. The suited person lifted the 5-gallon can (diameter 12 inch, height 13.25 inch) by hand and placed it on a polyethylene-covered stool. The health physicist collected wipe samples from the can, measured the radiation field, and kept record of the survey. The suited person then quickly transferred the can into the upper air-lock of the glove box. All operations on the can were carried out by keeping it as far from the person's body as possible.
5. The person in a lab coat closed the upper outer air-lock door of the glove box.
6. The can was moved on rollers to the inner door of the air-lock.
7. The inner door of the air-lock was opened, the can was moved into the glove box on rollers, and the inner door of the air-lock closed.
8. The desired quantity of material was transferred to the slurry tank, and its record was maintained. Record of material used for sample preparation was also maintained.

5.8 TRANSFER OF RADIOACTIVE MATERIAL FROM GLOVE BOX

1. The 5-gallon can was weighed when it was transferred into the glove box. It was re-weighed before it was transferred out and the new weight recorded.
2. The upper-level inner air-lock door was opened.
3. By means of rollers, the 5-gallon can was moved from the glove box into the upper level of the glove box air-lock.
4. The upper-level inner air-lock door of the glove box was closed. The outer surface of the can was cleaned by wiping with tissue paper. The can was surveyed for contamination and radiation field and sealed in a polyethylene bag and tagged.
5. One person donned in PPE moved out the 5-gallon and placed it in 10-gallon tank, which in turn was placed in 30-gallon drum. This operation was performed in a ventilated tent. The 30-gallon drum was then transferred to the radioactive material storage area.

5.9 TRANSFER OF OTHER RADIOACTIVE MATERIAL FROM GLOVE BOX

The procedure for transfer of other radioactive materials was the same as that for the 5-gallon can. They were first cleaned inside the glove box, transferred from the convenient upper/lower section of glove box, surveyed and stored in the radioactive material storage area in the radiation lab.

5.10 REPACKAGING RADIOACTIVE MATERIAL AND SHIPMENT

After testing the rheological properties of silo materials, the radioactive materials as well as wastes will be shipped back to Fernald in containers and concentrations as approved by the FDF waste management representative and as per the current DOT regulations. The cans and the drum will be surveyed prior to leaving FIU-HCET, and details will be shipped along with the drum to FDF. The Bureau of Radiation Control, Department of Health for the state of Florida will be notified at least 48 hours in advance of any radioactive material shipment.

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6.0 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 made for inclusion in the project records.

6.1 CONCLUSIONS

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.

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7.0 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:

7.1 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.

7.2 RECOMMENDATIONS

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

1. 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.
2. When pumping the K-65 silo material slurry, the pipeline should be run in power-law range to avoid plugging. For 1-inch pipeline, the power-law range can be presented as

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

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

3. 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.

4. 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.
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

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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.

6. 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 ruler. 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 when 10 wt % bentonite was present in the K-65 and surrogate slurries. To improve the accuracy of the measurement in future work, a density gradient meter is recommended to detect the location of the interfaces.
7. 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.
8. 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.
9. 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.

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8.0 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.

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APPENDIX A

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LOOP CALIBRATION DATA

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Nine cases were conducted for each test loop, at three temperature levels, and with three velocities. The results are presented and evaluated in the three sections that follow.

DIMENSIONAL DATA

Following the data deduction procedures, after the averaging and zero-flow correction, the original results are summarized in Table A-1.

Table A-1.
Water flow calibration data

Case		ΔP1 in H_2O			ΔP2 in H_2O			ΔP3 in H_2O			ΔP4 in H_2O		
		Hot	Cold	D%	Hot	Cold	D%	Hot	Cold	D%	Hot	Cold	D%
Cold: 6.83°C	2 ft/s	2.70	2.92	7.44	2.10	2.10	0.00	2.21	2.14	-3.26	2.13	2.20	3.18
Hot: 6.72°C	4 ft/s	9.10	9.69	6.06	7.20	7.19	-0.08	7.19	7.02	-2.42	7.32	7.34	0.27
	8 ft/s	30.66	32.13	4.57	24.07	23.89	-0.74	23.74	23.37	-1.58	24.72	24.63	-0.37
Cold: 20°C	2 ft/s	2.43	2.93	17.06	1.88	1.93	2.59	1.95	1.91	-2.09	1.91	1.95	2.05
Hot: 23.3°C	4 ft/s	8.11	8.99	9.79	6.35	6.42	1.09	6.35	6.28	-1.11	6.49	6.59	1.52
	8 ft/s	27.7	29.6	6.42	21.69	21.71	0.09	21.49	21.22	-1.27	22.31	22.57	1.15
Cold: 45°C	2 ft/s	2.08	2.27	8.37	1.78	1.7	-4.71	1.8	1.66	-8.43	1.42	1.73	17.92
Hot: 46°C	4 ft/s	7.17	7.59	5.53	5.78	5.65	-2.30	5.77	5.49	-5.10	5.75	5.8	0.86
	8 ft/s	25.08	26.17	4.17	19.77	19.32	-2.33	19.84	18.86	-5.20	20.29	20.23	-0.30

All the data are shown in Figures A-1 to A-4 for vertical/bend, straight vertical, straight horizontal, and horizontal/bend sections, respectively.

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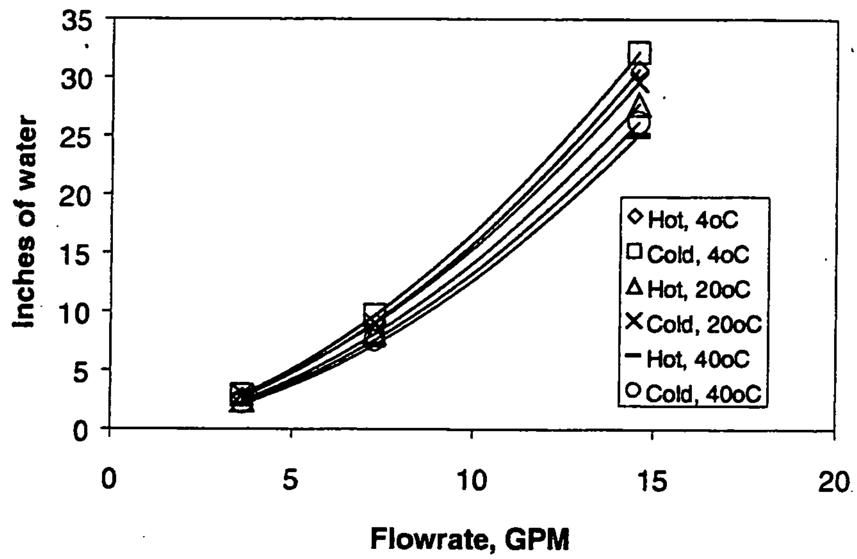

Figure A-1. Pressure drop results of vertical/bend section of calibration tests.

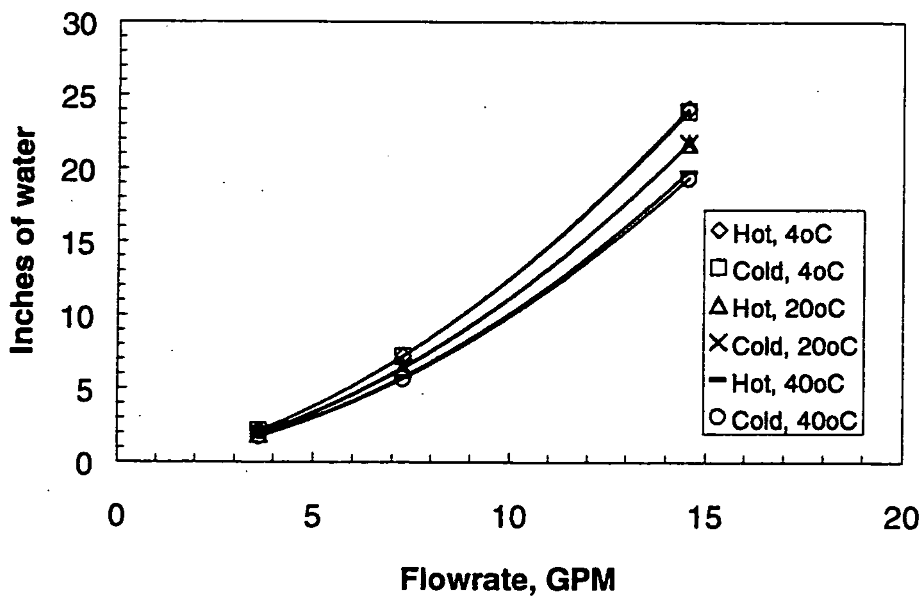

Figure A-2. Pressure drop results of vertical section of calibration tests.

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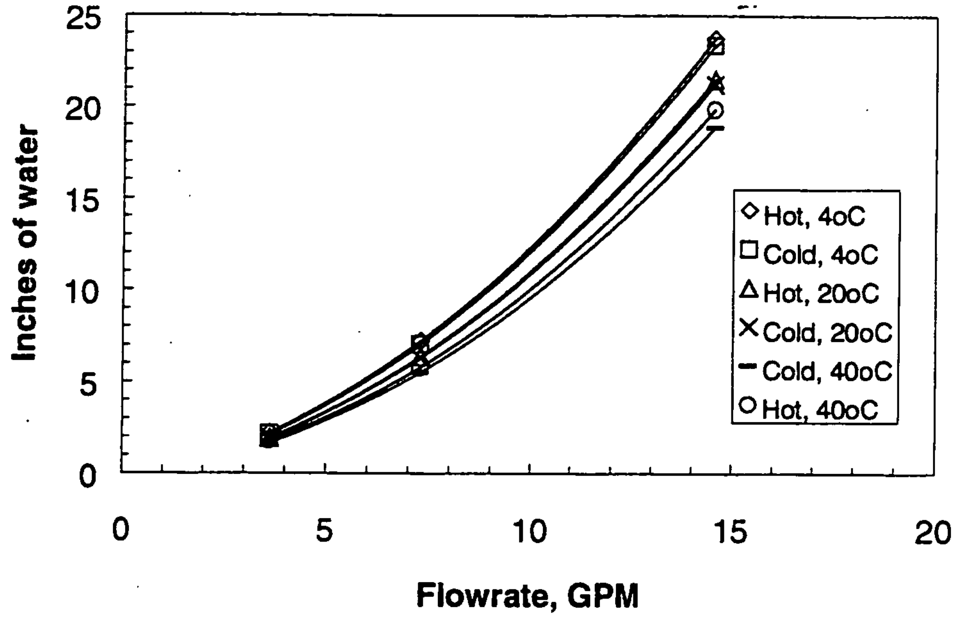

Figure A-3. Pressure drop results of horizontal section of calibration tests.

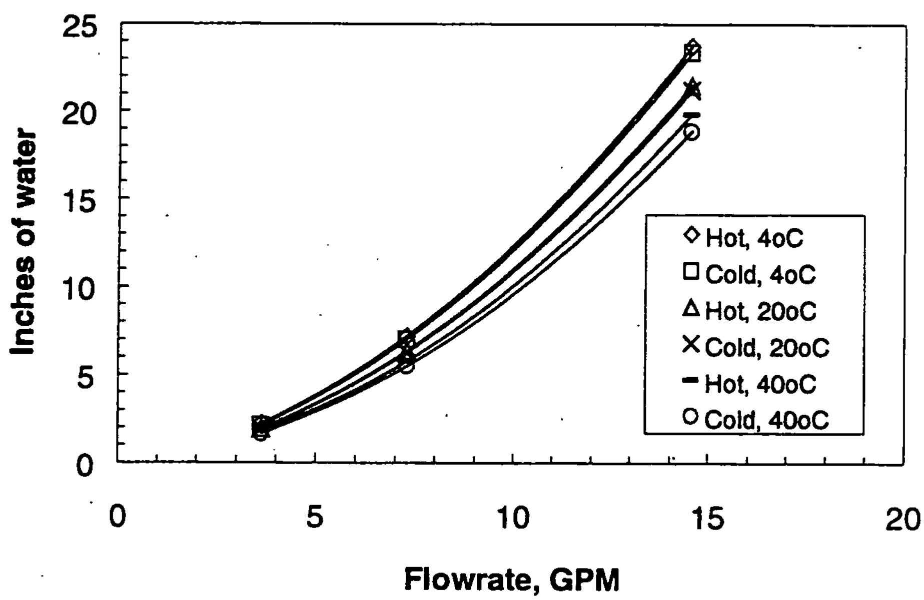

Figure A-4. Pressure drop results of horizontal/bend section of calibration tests.

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From the results, it can be seen that most of the readings for the same normal cases of the cold loop and hot loop are consistent with less than 10% deviation, except two points at the lowest flow rates. It has to be pointed out that the flow rate and temperature are not exactly the same values. So, the dimensionless presentation of the results is shown in the next section.

DIMENSIONLESS RESULTS

For further analysis of the experimental results, eliminating the temperature and flow rate effects, the friction factors and the corresponding Reynolds numbers were calculated for all the test cases. The results are shown in Table A-2a and A-2b and Figure A-5, and the correlation developed by Swamee & Jain, 1976, is presented in the figure for comparison. From Figure A-5, it can be seen that most of the experimental points are very close to the correlation line with the deviations less than 10% (except one case of the vertical/bend test section at Reynolds number of 13790).

Careful examination shows that there is a system error of the differential transmitter used in the vertical/bend test section of the cold loop. However, it is in the transmitter error limit. This system error may be reduced by carefully calibrating that transmitter. Overall, the experimental results are fairly consistent with the correlation developed by Swamee and Jain, 1976. This indicates that both the cold loop and hot loop and measurement system can conduct the slurry pressure drop tests with accuracy and consistency.

The friction factor results for the vertical/bend and horizontal/bend are on the same line of correlation. It means that the bends have little influence on the flow resistance. This is consistent with the suggestion from the textbook, which says that the curvature of the bend causes little extra loss for single-phase flow when the curvature ratio is larger than 3. (The curvature ratio in this study was 5.8 for both hot and cold loops.)

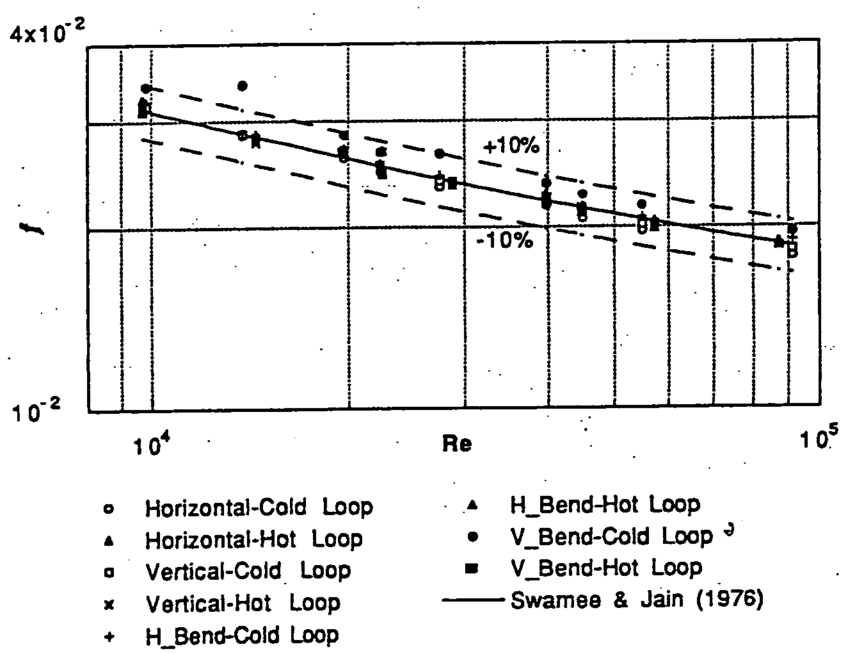

Figure A-5. Reynolds number and friction factor correlation of calibration test data.

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Table A-2a.
Friction factors and comparison with a correlation for loops without bends

Re	Horizontal-Cold Loop	D%	Horizontal-Hot Loop	D%	Vertical-Cold Loop	D%	Vertical-Hot Loop	D%	Swamee & Jain
9703			0.03253	3.8965			0.03104	-0.86234	0.03131
9820	0.03168	1.5059			0.03178	1.8263			0.03121
13790	0.02839	-0.38597			0.02856	0.21052			0.0285
14460			0.02849	1.2078			0.0276	-1.9538	0.02815
19610			0.02651	1.7268			0.02656	1.9186	0.02606
19710	0.02605	0.1153			0.02682	3.0746			0.02602
22430	0.02467	-2.142			0.02532	0.43633			0.02521
22620			0.02673	6.2401			0.0266	5.7234	0.02516
27550	0.02333	-2.7511			0.02384	-0.62526			0.02399
28770			0.02348	-1.1368			0.02349	-1.0947	0.02375
39700			0.02193	-0.54422			0.02224	0.86167	0.02205
39780	0.0217	-1.5426			0.02223	0.86206			0.02204
44730			0.02145	-0.09315			0.02151	0.18631	0.02147
44900	0.02063	-3.8228			0.02127	-0.83916			0.02145
54990	0.01966	-4.191			0.02011	-1.998			0.02052
57290			0.01984	-2.4582			0.02004	-1.4749	0.02034
87180			0.01854	-0.53648			0.01849	-0.80472	0.01864
91260	0.01781	-3.5734			0.01824	-1.2453			0.01847

Table A-2b.
Friction factors and comparison with a correlation for loops with bends

Re	H_Bend-Cold Loop	D%	H_Bend-Hot Loop	D%	V_Bend-Cold Loop	D%	V_Bend-Hot Loop	D%	Swamee & Jain
9703			0.03112	-0.60683			0.03151	0.63877	0.03131
9820	0.03219	3.14			0.03414	9.388			0.03121
13790	0.02867	0.59649			0.0343	20.351			0.0285
14460			0.02778	-1.3144			0.0282	0.17762	0.02815
19610			0.02677	2.7245			0.02651	1.7268	0.02606

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Table A-2b.
Friction factors and comparison with a correlation for loops with bends (continued)

Re	H_Bend-Cold Loop	D%	H_Bend-Hot Loop	D%	V_Bend-Cold Loop	D%	V_Bend-Hot Loop	D%	Swamee & Jain
19710	0.02698	3.6895			0.0284	9.1468			0.02602
22430	0.02546	0.99166			0.02656	5.355			0.02521
22620			0.0252	0.15898			0.02442	-2.9412	0.02516
27550	0.0243	1.2922			0.02641	10.088			0.02399
28770			0.02378	0.12631			0.02371	-0.16842	0.02375
39700			0.02264	2.6757			0.02239	1.5419	0.02205
39780	0.02267	2.8584			0.02358	6.9873			0.02204
44730			0.02123	-1.1178			0.02107	-1.8631	0.02147
44900	0.02164	0.88579			0.02258	5.2681			0.02145
54990	0.02074	1.0721			0.02168	5.653			0.02052
57290			0.02043	0.44248			0.02022	-0.58997	0.02034
87180			0.01881	0.91202			0.01853	-0.59013	0.01864
91260	0.01894	2.5447			0.01953	5.739			0.01847

CONSISTENCE OF COLD AND HOT LOOPS

From the discussion above, it can be concluded that the two loops are satisfactory and thus have a good consistency. The pressure drop data are plotted in Figure A-6 in the form of cold loop data versus hot loop data for the same nominal conditions. A good straight-line correlation with a slope of 1.0137 was obtained, and the correlation coefficient is 0.9986, very close to 1. This means that the two loops are satisfactory in performance and identical to each other. They can be used to verify the consistency of the rheological and pressure drop characteristics between the K-65 and the prepared surrogates.

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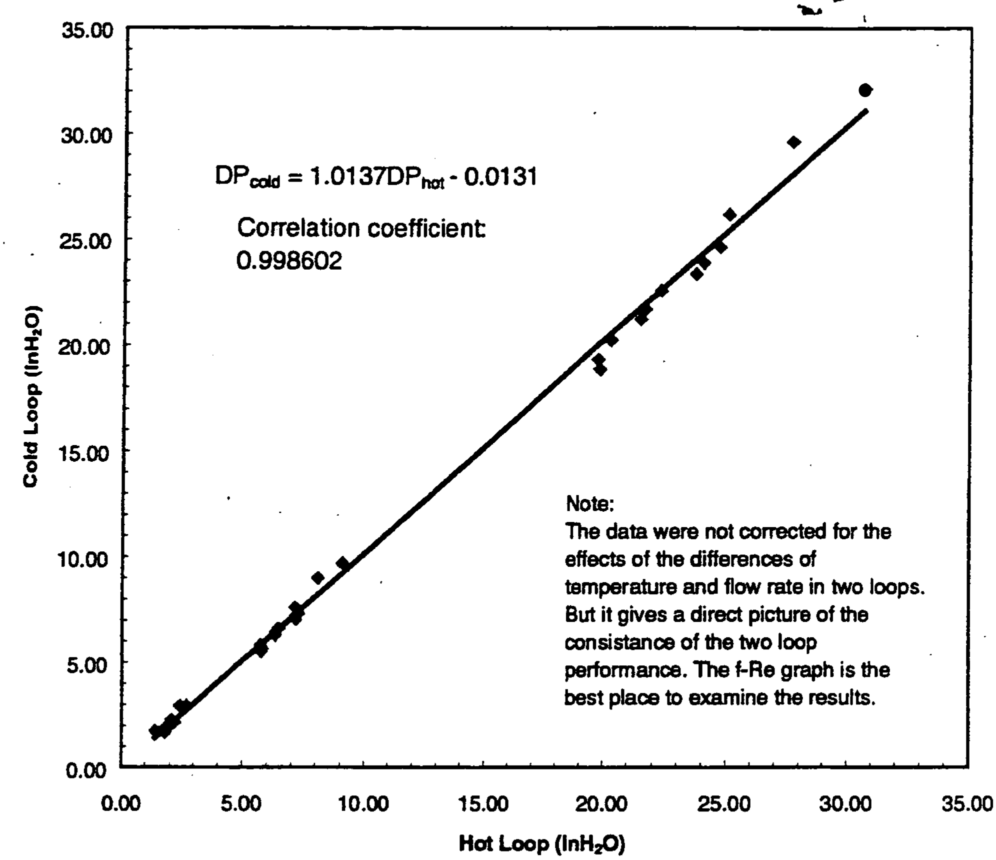

Figure A-6. Correlation between hot loop and cold loop calibration data.

TEMPERATURE DEPENDENCE

The pressure drop is temperature/viscosity dependent. The influence of the temperature on the pressure drop of water flow was analyzed. Figures A-7 – A-10 show the pressure drops across the test sections versus temperature. As the temperature increases, the viscosity of water decreases, thus the pressure drop decreases. However, all the data at different temperature levels are well correlated in the dimensionless correlations, as was seen previously.

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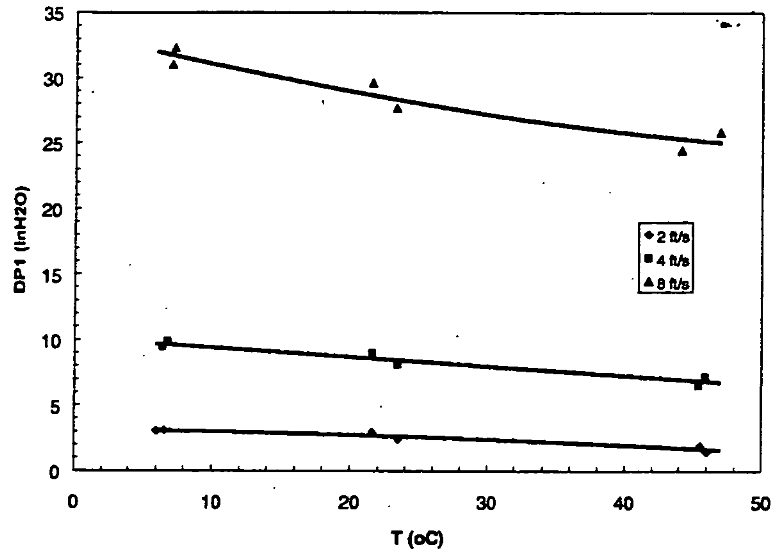

Figure A-7. Temperature effect on the pressure drop of vertical/bend sections.

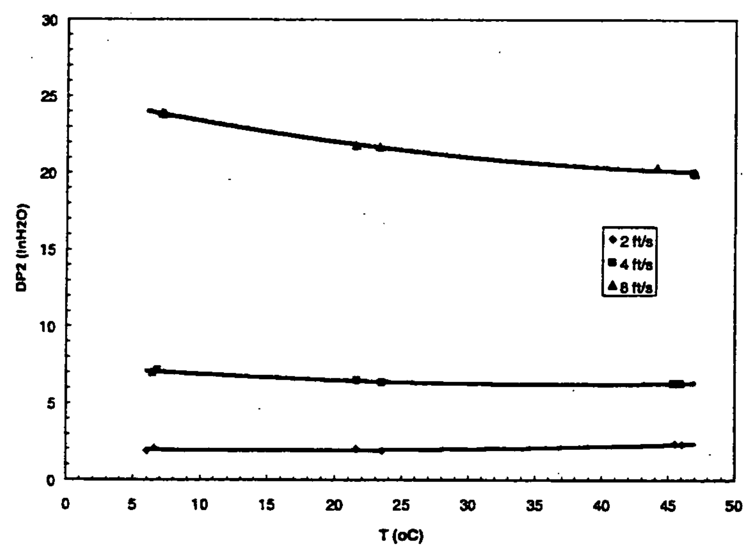

Figure A-8. Temperature effect on the pressure drop of vertical section.

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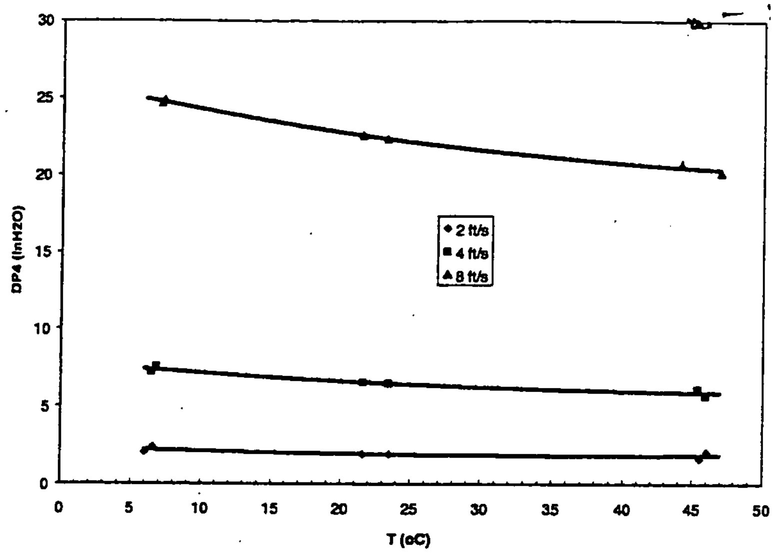

Figure A-9. Temperature effect on the pressure drop of horizontal/bend sections.

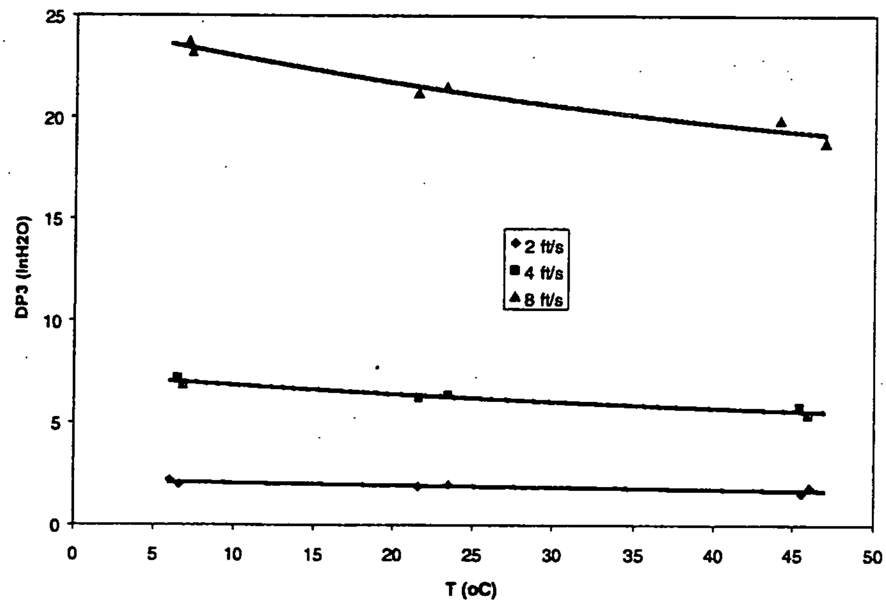

Figure A-10. Temperature effect on the pressure drop of horizontal section.

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Concluding Remarks

Based on the analysis and discussions presented, the following conclusions can be drawn:

- The performance of these two loops is satisfactory for the pressure drop measurement. The deviations from the correlation in the handbook are less than 10%.
- The two loops are consistent with each other. A good straight line correlation with a slope of 1.0137 was obtained for correlation of the cold loop data versus hot loop data, and the correlation coefficient is 0.9986, very close to 1.
- The bends in the current loop have little effect on the pressure drop in the pipelines for water flow.
- As the temperature increases, the pressure drop decreases across the test sections. This effect can be well correlated when the dimensionless variables are used.

APPENDIX B

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PRESSURE DROP LOOP TEST RAW DATA

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Table B-1
Pressure Drop Test Data of Silo Material

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
H5-0-7-0	7.4423	6.7616	7.017	-2.4094	-0.2755	1.9336	-1.6563	0.4235	1.0814	0.011	8.4179	0.161	-0.15
H5-0-7-2	6.9064	6.0817	6.3457	2.0817	3.4842	4.8273	0.535	2.4998	2.6848	3.7736	8.5418	0.9638	0.1594
H5-0-7-4	7.6354	7.2742	7.4394	10.5929	11.0358	11.8205	5.9882	7.7782	8.2023	7.4177	8.7398	2.5164	0.2666
H5-0-7-8	7.3803	6.4108	6.6334	-2.296	0.0975	35.0901	23.9006	25.4422	26.6198	14.7163	8.4166	7.8923	0.7966
H5-0-26-0	24.9472	25.0256	25.074	25.138	25.827	1.5566	-1.5002	0.451	1.1228	0.014	0.0022	-0.3314	-0.282
H5-0-26-2	27.1136	27.2251	27.2575	26.3866	26.435	4.111	0.4338	2.0355	2.694	3.6241	-0.005	0.3655	0.1471
H5-0-26-4	26.7546	26.8438	26.9004	25.9006	26.3402	10.5788	5.29	6.827	7.7286	7.5253	-0.005	1.7974	0.2275
H5-0-26-8	25.8006	25.8498	25.9212	25.3842	26.1125	30.377	20.5236	21.9006	23.367	14.5073	-0.008	6.4231	0.6254
H5-0-22-0	21.4065	21.4124	21.5179	27.7422	27.4151	1.1066	-1.0408	0.3868	1.04	0.0134	0.0037	-0.102	-0.19
H5-0-22-2	23.1124	23.1599	23.2322	27.2466	27.1107	3.7614	0.7098	2.0175	2.4778	3.6274	-0.014	0.4573	0.1076
H5-0-22-4	22.8974	22.8978	22.9702	27.402	27.2097	9.853	5.7306	6.7626	7.4121	7.4517	-0.014	1.9353	0.227
H5-0-22-8	22.3031	22.2773	22.3512	27.5305	27.2911	29.6602	21.116	21.8684	23.1417	14.5174	-0.015	6.5915	0.5703
H5-0-42-0	41.3948	43.6466	42.2318	50.3881	48.9011	1.1141	-1.0178	0.2672	1.0952	0.011	1.8599	-0.6586	-0.414
H5-0-42-2	41.7073	42.2834	42.2049	45.3465	43.8821	3.56	0.7236	1.8752	2.6066	3.6985	-0.002	-0.2011	-0.101
H5-0-42-4	42.2774	42.9304	42.8444	47.2719	44.9629	8.9799	4.876	5.9586	6.8188	7.2486	-0.002	1.0162	-0.006
H5-0-42-8	41.7683	42.7824	42.6882	49.3472	46.9418	27.7215	19.467	20.3432	21.6303	14.4876	4.6297	5.5557	0.2787
H25-0-40-2	36.16	37.49	37.91	28.63	29.80	12.05	-5.63	2.37	2.58	3.70	0.96	0.32	0.14
H25-0-40-4	36.18	37.65	38.05	28.55	29.79	19.46	-1.60	6.79	7.49	7.19	0.00	2.06	0.21
H25-0-40-8	32.53	36.74	37.15	28.40	29.70	40.36	17.83	24.21	25.23	14.34	0.00	8.61	0.61
H25-0-20-2	20.84	19.21	19.14	21.84	18.40	12.59	-5.64	2.06	2.60	3.58	9.44	0.89	0.25
H25-0-20-4	21.07	19.61	19.56	21.14	17.19	20.51	-0.30	7.99	8.69	7.38	9.39	2.77	0.38

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Table B-1
Pressure Drop Test Data of Silo Material (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
H25-0-20-6	20.78	19.48	19.40	21.83	18.42	30.99	8.80	16.18	17.23	11.17	9.42	5.41	0.59
H25-0-20-8	21.85	20.67	20.61	21.33	17.72	41.38	20.22	25.60	26.72	14.17	9.38	8.43	0.84
H25-0-20-10	21.20	20.05	19.99	21.85	18.56	54.61	34.03	37.16	39.15	17.99	9.42	10.74	1.07
H25-0-4-2	11.34	8.27	8.03	-1.08	1.20	12.76	-5.64	2.46	2.90	3.52	8.36	1.28	0.32
H25-0-4-4	11.94	9.34	9.09	-1.01	1.39	20.52	3.12	9.55	10.14	7.52	8.36	3.44	0.48
H25-0-4-8	11.88	9.60	9.34	-0.99	1.57	45.24	21.72	28.00	28.83	14.22	8.36	9.51	0.92
H25-0-4-10	12.03	9.89	9.64	-1.07	1.57	60.67	39.53	42.10	44.73	18.38	8.37	11.60	1.30
H35-0-40-2	39.84	40.89	41.10	30.80	37.70	17.47	-5.60	3.07	3.27	3.69	0.04	0.50	0.14
H35-0-40-4	39.87	40.95	41.17	30.83	37.45	25.28	-5.15	8.34	8.84	7.12	0.03	2.31	0.26
H35-0-40-8	39.59	40.65	40.87	30.78	37.09	47.45	12.83	25.07	26.05	14.40	0.03	7.34	0.67
H35-0-20-2	21.29	19.59	19.51	18.72	18.78	18.98	-5.64	3.81	4.13	3.85	9.20	1.28	0.38
H35-0-20-4	21.20	19.66	19.57	18.87	18.99	25.80	-4.65	8.98	9.56	6.92	7.86	2.92	0.49
H35-0-20-6	21.20	19.74	19.65	18.67	18.79	38.06	4.53	17.49	18.36	10.30	9.25	5.59	0.69
H35-0-20-8	21.77	20.36	20.28	15.91	16.35	49.14	19.48	28.19	30.20	14.70	9.22	7.00	-1.00
H35-0-20-10	21.63	20.39	20.32	18.30	18.45	65.95	29.09	39.99	42.06	17.45	9.18	11.21	1.31
H35-0-4-2	12.31	9.37	9.21	3.98	4.61	17.38	-5.64	5.38	4.92	3.75	8.66	1.67	0.41
H35-0-4-4	12.19	9.72	9.54	4.09	4.81	27.47	-2.56	10.69	11.28	7.09	8.71	3.67	0.59
H35-0-4-6	12.12	9.85	9.67	4.08	4.69	38.63	6.03	18.57	19.47	10.54	8.57	6.10	0.76
H35-0-4-8	12.13	9.81	9.61	3.93	4.83	53.11	19.70	30.45	31.72	13.59	8.66	9.72	1.19
H35-0-4-10	13.00	11.11	10.96	4.06	4.86	70.93	33.74	44.12	46.55	18.06	8.67	12.06	1.48
H40-0-40-2	40.22	41.30	41.48	36.81	37.47	24.12	-5.60	6.16	5.97	3.65	0.00	1.13	0.2[illegible]

Table B-1
Pressure Drop Test Data of Silo Material (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
H40-0-40-4	40.28	41.41	41.60	36.45	37.05	30.19	-5.60	9.80	10.36	7.07	-0.01	2.28	0.29
H40-0-40-6	40.14	41.21	41.44	35.20	36.20	46.53	1.41	19.63	20.78	11.45	-0.01	5.58	0.53
H40-0-40-8	38.23	39.10	39.27	28.35	31.60	60.55	11.88	30.06	31.51	14.84	-0.01	8.90	0.84
H40-0-40-10	39.55	40.57	40.79	32.36	35.96	76.22	25.39	42.54	45.48	18.34	-0.01	12.93	1.12
H40-0-20-2	22.23	20.94	20.87	23.06	23.10	26.30	-5.60	6.42	6.13	3.69	9.18	1.86	0.48
H40-0-20-4	21.02	19.60	19.48	20.92	21.23	36.92	-5.60	12.60	13.41	7.66	9.29	3.96	0.64
H40-0-20-6	20.86	19.18	19.09	14.53	15.39	49.66	0.19	20.60	21.62	11.01	9.18	6.54	0.83
H40-0-20-8	21.71	20.15	20.07	11.89	12.99	62.22	10.95	31.06	32.15	13.54	8.88	9.56	1.12
H40-0-20-10	22.64	21.27	21.21	11.43	12.68	79.80	24.50	43.80	45.98	17.53	8.89	11.62	1.46
H40-0-4-2	11.63	8.38	8.45	2.61	3.82	28.23	-5.64	6.68	6.28	3.76	9.01	2.20	0.55
H40-0-4-4	11.44	8.56	8.42	0.11	1.82	37.90	-5.64	11.19	12.12	7.09	8.71	3.82	0.67
H40-0-4-6	11.81	9.13	8.95	-0.90	1.41	52.87	-0.14	21.80	22.71	11.10	8.82	7.19	0.94
H40-0-4-8	12.43	9.76	9.63	-3.73	-0.59	68.62	14.26	34.47	36.25	14.06	8.59	11.03	1.29
H40-0-4-10	12.65	10.19	10.03	0.39	2.46	85.76	28.87	47.88	50.75	17.25	8.83	14.12	1.70
H5-5-10-2	11.5152	8.8666	8.7263	7.3853	7.4921	7.2653	-1.2139	2.0304	2.1707	3.716	9.2846	1.1006	0.2391
H5-5-10-4	11.3755	8.8433	8.6697	7.2053	7.4351	14.285	4.9412	7.9144	7.4612	7.3382	9.2167	2.8159	0.3617
H5-5-10-6	11.3561	8.7884	8.6241	4.0114	4.5991	25.2263	13.4876	16.0241	16.0595	10.9464	8.6786	5.3971	0.5395

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Table B-1
Pressure Drop Test Data of Silo Material (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
H5-5-10-8	11.6835	9.2083	9.0441	3.8715	4.4349	38.9429	24.0202	26.3278	26.7708	14.5025	8.3989	8.6519	0.7572
H5-5-10-10	11.7654	9.3309	9.1667	5.2271	5.6651	54.8551	36.741	38.5756	39.6881	17.9525	8.6913	11.5316	1.0789
H5-5-20-2	21.0412	19.895	19.879	20.2266	20.1134	6.9625	-1.1243	2.603	2.0829	3.8337	9.4066	0.8173	0.2331
H5-5-20-4	21.0049	19.8684	19.8521	20.1344	20.1095	12.769	4.2899	7.2615	6.6375	7.2057	9.4546	2.2724	0.334
H5-5-20-6	20.72	19.9526	19.9364	19.5083	19.4678	23.334	12.5318	15.1427	14.8947	10.9677	9.4686	4.7383	0.5117
H5-5-20-8	20.9005	20.2152	20.191	18.8168	18.8411	36.2879	23.3588	24.9452	25.843	14.7387	9.3942	7.8323	0.7877
H5-5-20-10	21.1614	20.5428	20.5275	18.855	18.8476	51.5846	35.4178	36.6372	38.0342	18.2112	9.5024	11.4317	1.1433
H5-5-40-2	38.586	39.89	40.1168	37.6913	38.9092	5.2166	-1.3199	2.3517	2.4215	3.7298	0.0479	0.1672	0.0985
H5-5-40-4	38.8876	40.2038	40.4318	38.353	39.5387	10.5916	3.9305	6.4559	6.402	7.205	0.0408	1.4927	0.1795
H5-5-40-6	38.9804	40.3965	40.6463	39.1041	40.2957	19.5762	11.0606	13.5523	13.0742	10.8018	0.0322	3.5823	0.3469
H5-5-40-8	39.0229	40.475	40.71	40.122	41.3512	32.3832	21.6864	23.282	23.1235	14.8417	0.0185	6.5995	0.5489
H5-5-40-10	38.9538	40.4112	40.7005	41.1708	42.4993	45.7601	32.6388	33.6098	34.2588	18.2219	0.0073	9.724	0.7448
H25-5-10-2	14.2956	11.3643	11.2991	11.6339	12.2068	19.1907	-5.6337	5.5157	5.7962	3.6508	9.544	2.2033	0.5272
H25-5-10-4	13.8126	10.7737	10.6183	9.3616	10.2558	26.173	-2.5295	9.9638	10.707	7.3937	9.5365	3.7426	0.5886
H25-5-10-6	13.5777	10.4796	10.3319	5.7054	7.1328	40.514	9.7432	21.6336	21.9923	11.2341	9.5148	7.212	0.8093
H25-5-10-8	13.4583	10.3573	10.2263	3.6392	5.4269	56.6742	24.6264	35.2177	35.6184	14.8045	9.5434	11.3276	1.1984
H25-5-10-10	13.5598	10.4973	10.3426	2.4874	4.4129	77.7221	42.7228	51.2137	53.377	18.5561	9.4265	16.7773	1.6916
H25-5-20-2	21.4499	19.6196	19.5387	19.3362	19.5944	17.7667	-5.6139	5.7916	5.6905	3.7098	9.4251	1.7516	0.3831
H25-5-20-4	21.1442	19.2958	19.2475	18.5747	19.0039	24.5648	-2.366	9.8232	10.4797	7.2162	9.4822	3.475	0.5118
H25-5-20-6	21.4976	19.6832	19.6186	17.2863	17.8697	37.2618	8.7934	19.8433	20.0945	10.9552	9.4586	6.6147	0.7145
H25-5-20-8	22.0572	20.4068	20.3425	17.2183	17.9087	52.347	22.4399	31.8148	32.808	14.3494	9.4543	10.0302	1.0789

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Table B-1
Pressure Drop Test Data of Silo Material (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
H25-5-20-10	21.8002	20.1812	20.1335	17.2853	17.9349	72.669	38.1883	46.9417	49.0497	18.0743	9.542	14.7634	1.502
H25-5-40-2	35.5509	36.4288	36.5709	34.0297	34.4645	16.2617	-4.9649	6.4615	6.7474	3.471	0.1144	1.4778	0.2229
H25-5-40-4	35.6028	36.483	36.6564	33.9887	34.4319	19.6603	-1.9678	9.4657	9.9145	7.2492	0.1035	2.7118	0.2955
H25-5-40-6	35.463	36.3438	36.5011	34.0223	34.4967	30.7488	8.5888	17.5655	17.8913	10.9453	0.0682	5.6509	0.4591
H25-5-40-8	35.107	35.9361	36.1172	34.1673	34.697	45.8799	20.2393	28.455	29.0681	14.3033	0.071	9.5173	0.7208
H25-5-40-10	34.4451	35.1961	35.3697	34.1375	34.6443	65.4485	34.7975	42.9676	44.4839	18.0202	4.8089	13.9359	1.134
H40-5-10-2	18.3333	6.9964	10.3459	7.7564	20.8702	45.9069	-3.1395	18.6977	19.7478	3.6198	9.5424	6.002	0.7879
H40-5-10-4	18.1593	10.3905	10.5142	7.8621	21.2449	52.8618	2.0695	23.78	24.9084	7.1812	9.5405	7.6715	0.9561
H40-5-10-6	18.4517	11.6072	11.183	7.973	21.3864	59.1271	19.0447	30.7488	31.3837	10.6609	9.5065	10.0838	1.2168
H40-5-10-8	18.6648	11.7819	11.6103	8.0897	21.3638	75.7099	27.6907	42.0123	46.9093	14.7725	9.4951	14.051	1.6856
H40-5-10-10	18.8687	12.0167	11.8787	8.7223	21.5088	87.9015	34.2143	53.6857	57.9982	16.8666	9.5026	17.3589	2.035
H40-5-20-2	25.3851	21.5445	22.7118	22.1563	27.185	42.8003	-2.1476	16.3383	17.6558	3.8137	9.544	5.089	0.739
H40-5-20-4	25.6027	22.945	23.0012	22.2208	27.4086	47.4843	-0.9901	20.6444	21.3167	7.1519	9.544	6.5674	0.7908
H40-5-20-6	25.9538	23.2542	23.1752	22.1776	27.4065	55.1198	5.405	26.6683	27.0468	10.4588	9.544	8.4287	0.944
H40-5-20-8	25.4289	23.2979	23.2909	22.2124	27.4251	71.5627	17.0829	39.9906	41.7828	14.7677	9.543	12.6161	1.2902
H40-5-20-10	25.2154	23.2352	23.2047	22.1112	27.3239	89.7977	32.2482	54.4483	56.9049	16.6068	9.5421	16.9702	1.6641
H40-5-40-2	37.1735	39.9324	40.1195	39.798	35.6376	45.8897	4.9683	19.8768	21.0896	3.4918	0.0994	5.699	0.6101
H40-5-40-4	37.431	40.2218	40.4097	40.5815	35.9217	47.7626	5.8872	22.7402	23.8874	7.0204	0.0745	6.425	0.6355
H40-5-40-6	37.6047	40.3581	40.5615	41.9228	36.1773	53.5054	12.2042	28.1437	28.9578	10.758	0.0432	8.2318	0.7968
H40-5-40-8	37.548	40.3496	40.6162	43.9672	36.4608	61.9297	17.6158	34.184	35.7191	15.0035	0.0169	10.3672	0.9725
H40-5-40-10	37.2064	40.1597	40.4334	45.9095	36.7331	83.9788	31.0811	52.4774	53.8179	17.6778	0.0449	15.8354	1.4281

Table B-1
Pressure Drop Test Data of Silo Material (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
RH40-5-10-2	18.9383	9.0986	12.2371	8.8273	21.2963	58.1074	10.2379	29.3947	30.3544	3.5821	9.334	8.8584	0.9533
RH40-5-10-4	19.1285	11.9066	12.5036	8.8158	21.5191	66.1002	16.4903	35.8843	36.9964	7.2724	9.3337	10.8343	1.1219
RH40-5-10-6	19.4997	13.1817	13.069	8.9245	21.6663	76.537	24.0247	43.1008	43.6297	10.6871	9.502	13.3142	1.3638
RH40-5-10-8	19.3799	13.213	13.2913	8.8931	21.5985	85.5126	29.4504	50.5618	49.9688	13.3768	9.5204	15.5437	1.5969
RH40-5-20-2	24.9007	20.5093	22.186	20.7511	26.6144	53.5588	12.8656	27.3	28.2143	3.5721	9.544	8.0004	0.8552
RH40-5-20-4	25.0653	22.2394	22.6978	20.7964	26.7789	60.0999	14.9101	32.972	33.7898	7.3585	9.544	9.6687	1.0115
RH40-5-20-6	25.3497	23.2633	23.199	20.7995	26.83	69.5256	23.8455	39.591	40.0191	10.8713	9.544	12.1043	1.3515
RH40-5-20-8	25.431	23.4607	23.4939	20.7967	26.7553	80.2366	26.9281	48.3382	47.1573	14.5897	9.543	14.7201	1.6365
RH40-5-40-2	37.234	40.2323	40.3725	38.1986	34.5418	59.1646	19.4811	32.9894	33.8725	3.6337	0.0473	8.9457	0.7734
RH40-5-40-4	37.4693	40.598	40.7309	39.1319	34.7227	62.4995	22.2835	36.0031	36.9596	7.1364	0.038	10.0218	0.8653
RH40-5-40-6	37.6233	40.7683	40.9169	40.7129	34.9889	68.9575	28.3293	40.8678	42.1322	10.9124	0.0116	11.8388	1.0337
RH40-5-40-8	37.275	40.5341	40.7274	42.0507	35.2023	78.7879	32.8452	49.0365	47.9566	14.7521	3.8299	14.4289	1.3944
HR40-5-20-2	26.861	24.201	25.5891	23.8963	27.9078	57.0417	17.1518	30.4772	31.0984	3.4389	9.544	9.0398	0.8365
HR40-5-20-4	26.9715	25.5574	25.8779	23.8972	27.9717	62.5538	23.0232	35.778	36.7115	7.2136	9.544	10.5111	1.0053
HR40-5-20-6	27.1037	26.1393	26.0918	23.8721	27.9713	72.2484	31.0673	43.1144	43.1241	10.8806	9.544	12.9427	1.2534
HR40-5-20-8*	26.9091	25.9962	25.9568	23.8489	27.8529	80.8169	32.712	50.2996	48.9857	13.5335	9.544	14.8524	1.4621
H5-10-9-2	18.9631	8.3933	8.641	6.2683	20.2663	10.5732	0.1726	4.5518	4.7493	3.6051	8.983	1.7746	0.2913
H5-10-9-4	18.9362	8.5968	8.5	6.3081	20.6115	15.8921	4.1461	8.1402	9.2973	7.2818	8.9492	1.2998	0.4106
H5-10-9-6	19.3508	9.4536	9.2828	6.5005	20.8006	28.4514	14.1951	19.0851	19.1076	11.0695	9.007	4.5775	0.6191

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Table B-1
Pressure Drop Test Data of Silo Material (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
H5-10-9-9	19.7319	10.6623	10.5017	8.0608	21.425	39.1084	23.7563	27.7078	27.8918	13.8768	9.0635	7.5184	0.8028
H5-10-20-2	24.8015	20.1909	20.6764	22.1116	27.2441	9.599	-0.15	3.8628	4.2808	3.6157	9.5456	1.2288	0.2483
H5-10-20-4	24.2202	20.2857	20.2387	21.9806	27.0589	14.8544	3.8877	8.0802	8.644	7.2859	9.544	2.759	0.3339
H5-10-20-6	23.9054	20.2511	20.1793	20.3655	26.6001	26.2648	13.3525	17.73	17.5494	10.982	9.544	4.4361	0.457
H5-10-20-8	23.9347	20.782	20.7187	20.3801	26.6468	39.6779	26.0576	28.5248	29.0972	14.8051	9.544	8.9973	0.7512
H5-10-40-2	35.924	38.1528	38.3424	35.9816	33.3193	8.6298	0.1763	3.8391	4.1054	3.7716	9.5451	0.6492	0.0738
H5-10-40-4	36.2581	38.3912	38.5803	35.9283	33.2186	12.5738	3.9154	7.4001	7.6564	7.3244	9.544	1.7811	0.1197
H5-10-40-6	36.4883	38.6382	38.8269	35.8766	33.175	21.585	11.6681	14.966	14.6139	10.7514	9.544	4.16	0.2822
H5-10-40-8	36.7659	39.0229	39.2037	35.8212	33.0641	24.4923	24.9229	20.8834	21.2598	14.6092	9.544	5.7203	0.3249
H5-10-40-10	37.1504	39.6774	39.8667	35.1152	32.5929	33.6642	37.27475	29.6611	30.43475	17.3312	9.5421	8.52785	0.512
H25-10-9-2	10.361	9.0807	9.5509	6.0107	20.483	26.3291	-4.2034	9.5046	9.9942	3.6471	9.5456	-0.3316	0.4902
H25-10-9-4	10.1297	9.5145	9.49	6.0077	20.6494	31.5473	-0.3951	13.6068	13.5843	7.1935	9.5315	-0.6302	0.6252
H25-10-9-6	10.2755	9.7605	9.6377	6.1149	20.8586	41.4971	6.548	20.2815	21.6962	10.7663	9.544	1.8739	0.7969
H25-10-9-8	10.9037	10.4807	10.333	6.1551	20.9235	50.2796	13.9789	27.8971	28.5257	12.3906	9.544	4.3145	0.9285
H25-10-20-2	22.4533	21.5726	22.0254	21.8892	25.7352	21.8915	-5.5082	7.0281	7.5773	3.7979	9.2919	1.2155	0.417
H25-10-20-4	22.305	21.7738	21.8702	21.8783	25.661	25.3825	-3.2516	9.6333	9.5758	7.1107	9.3045	2.2419	0.4629
H25-10-20-6	22.2241	21.6524	21.6685	20.8138	25.1557	38.309	6.508	19.1519	19.5756	11.4601	9.2823	4.409	0.6653
H25-10-20-8	22.7176	22.1556	22.1641	19.9302	24.9436	52.8342	18.1951	30.4897	30.3793	14.0854	9.2067	8.0698	0.9226
H25-10-40-2	40.2384	40.0525	40.4763	31.7015	33.5487	24.3024	-3.7042	9.2837	9.524	3.7295	0.1487	1.0376	0.2422
H25-10-40-4	40.4799	40.5039	40.6847	27.8238	33.2788	26.4758	-1.3305	11.7688	11.9178	7.3297	0.1691	1.7765	0.3335
H25-10-40-6	40.6879	40.7003	40.8956	27.4968	31.2319	37.0316	6.2747	19.473	19.8116	11.2619	0.1901	4.1344	0.5038

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Table B-1
Pressure Drop Test Data of Silo Material (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
H25-10-40-8	40.9872	40.89	41.0544	21.6003	28.4475	49.0945	16.8496	28.9697	29.2177	14.3813	0.2328	7.2309	0.7135
HR25-10-20-03	24.277	19.5837	22.3183	21.2394	26.2195	24.1148	-4.8824	15.642	15.939	0.014	9.547	-1.9784	0.5795
HR25-10-20-04	23.8809	19.7585	22.2269	21.2612	26.2643	28.5614	-2.6565	16.3168	16.4816	0.2204	9.547	-1.4579	0.5917
HR25-10-20-05	23.7098	19.9619	22.3091	21.2781	26.3096	31.00495	0.302	16.8461	17.1724	0.57475	9.547	-0.8877	0.6239
HR25-10-20-1	23.4699	20.3058	22.6597	21.3148	26.4139	38.6308	4.1873	19.3197	19.0043	1.5278	9.5464	0.1269	0.6314
HR25-10-20-2	23.3968	21.3304	23.5198	21.3623	26.4775	42.3057	6.3182	21.2762	21.1976	3.2905	9.545	0.8931	0.6653
HR25-10-20-4	23.8518	23.1748	23.8187	21.3655	26.5198	46.3296	10.7361	24.8113	25.2406	7.2088	9.544	1.2583	0.7511
HR25-10-20-6	24.4381	24.3143	24.3394	21.4367	26.5993	53.8533	15.8792	30.4897	30.0256	10.9253	9.544	3.1723	0.9256

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Table B-2
Pressure Drop Test Data of Surrogates

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
	Surrogate Formula: (40% sand, 40% soil, 11% Diato earth, 3% Al2O3, 3%Fe2O3, 1.5% CaCO3, 1.5% MgCO3)												
C5-0-10-2	11.7142	11.237	10.9191	3.9759	11.7856	3.5952	1.6228	1.8922	1.9374	3.7017	3.6681	0.816	0.2848
4	12.0707	11.7931	11.4666	3.9573	11.6984	10.284	6.644	6.8762	7.0378	7.3673	4.5862	2.188	0.4045
6	12.3102	12.1323	11.8473	3.9873	11.7033	20.161	13.9836	14.3228	14.6018	11.044	4.5801	3.8967	0.5396
8	12.4035	12.3135	11.9879	3.9483	11.5488	32.9136	23.5348	23.8824	24.5256	14.7136	4.5834	6.257	0.7569
10	12.1291	12.0194	11.7321	3.9039	11.4138	48.1106	35.1008	35.2705	36.2802	18.3602	4.667	9.9656	1.0205
C5-0-20-2	20.0005	19.8749	19.8423	17.43	17.3665	3.2458	1.6274	1.9566	1.8868	3.6975	5.6133	0.4945	0.1626
4	20.2451	20.1741	20.1258	16.4559	16.8146	9.4294	6.3358	6.5322	6.6514	7.3396	5.5606	1.5444	0.2546
6	20.1477	20.1196	20.0875	16.2795	16.8077	18.7737	13.2108	13.3542	13.6414	10.9985	5.4433	4.1343	0.4414
8	20.3351	20.2694	20.2459	14.015	15.7024	30.773	22.073	22.2382	22.7924	14.6162	5.469	6.1343	0.5976
10	20.6199	20.5887	20.5649	13.6445	15.4855	45.0968	32.9297	33.0704	33.9627	18.281	5.4567	9.4829	0.8334
C5-0-40-2	40.4438	40.4198	41.1168	39.307	26.9239	2.0513	2.0137	2.0073	1.3716	3.7133	-0.0489	-0.0342	-0.1898
4	40.9705	40.9333	41.6928	40.6527	27.4714	7.6926	5.8078	5.4706	5.3864	7.2287	-0.0486	1.2303	-0.1437
6	41.1223	41.2241	41.9678	41.5467	27.8985	15.7326	11.8042	11.6082	11.5576	10.8199	5.9291	2.8775	-0.0152
8	40.9434	41.0046	41.8352	41.4688	27.8504	25.7382	19.8834	19.6886	19.9138	14.4103	5.9708	5.1459	0.1779
10	40.5796	40.6491	41.4949	41.416	27.8836	36.9382	29.7934	28.6833	29.0648	18.0192	5.7629	8.4255	0.3312
C25-0-4-2	7.8447	7.2209	6.7251	-0.1677	8.8329	7.2152	-0.9614	2.7836	2.5216	3.7147	0.0154	0.9851	0.5394
4	8.4061	8.0817	7.4654	-0.0083	8.9517	15.0249	4.782	8.4106	8.449	7.3506	0.0089	2.778	0.6744
6	8.8692	8.6497	8.0618	-0.0078	8.9544	27.3091	12.7051	16.983	17.0397	11.0174	0.0073	5.2377	0.8334
8	9.0724	8.9747	8.4	0.03	8.8353	41.4678	23.2864	27.4472	28.085	14.6857	0.0055	6.9159	1.0604

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Table B-2
Pressure Drop Test Data of Surrogates (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
10	8.6709	7.7569	8.0494	0.0233	8.7028	60.0181	34.9766	39.9467	41.5268	18.2276	0.004	11.3526	1.3883
C25-0-20-2	19.8238	19.6091	19.449	17.8796	17.4613	6.0478	-0.231	3.0688	2.1996	3.7011	0.0093	0.5557	0.2665
4	20.163	20.0425	19.9316	17.8612	17.2222	14.1794	3.8528	7.7492	7.6808	7.314	0.0088	2.1803	0.3893
6	20.1511	20.0712	19.9601	17.3474	16.8406	24.9753	11.197	15.32	15.3608	10.9789	0.0064	4.2874	0.5517
8	20.4292	20.3538	20.2514	16.164	15.9981	39.9884	19.6075	24.9761	25.7308	14.635	0.0076	6.4715	0.7692
10	20.6119	20.5666	20.5094	16.1609	15.9012	58.6583	28.2856	36.7359	38.0732	18.1491	0.0026	10.4713	1.0604
C25-0-20-2	18.8805	18.7248	18.6189	17.4762	16.9819	7.9317	-2.047	2.6364	2.3974	3.6193	-0.029	0.6092	0.2484
4	19.192	19.1102	18.9958	17.522	16.9622	14.7308	3.6918	7.7584	7.759	7.2758	-0.0307	2.2032	0.3247
6	19.9066	19.8529	19.7801	17.6262	17.1235	27.1896	10.6588	15.917	16.2394	10.9884	-0.0299	4.4025	0.5119
8	20.6191	20.5203	20.4627	16.7629	16.7635	42.46	17.0186	25.054	25.6112	14.2865	-0.0305	6.8086	0.7353
10	21.7707	21.667	21.6591	16.775	16.9057	56.3888	25.9498	34.5495	35.7144	17.3919	-0.037	10.5406	0.8979
C25-0-40-2	38.7676	38.7454	39.538	23.7297	20.1951	5.6624	-0.897	2.2924	1.9558	3.9237	0.0082	0.0424	-0.0642
4	39.0251	39.0164	39.8086	23.75	20.2316	12.0295	3.4848	6.7668	6.633	7.2481	0.0066	1.3374	0.0614
6	39.139	39.0883	39.9339	23.7636	20.2358	21.8055	9.8033	13.1932	13.439	10.8572	0.0135	4.4026	0.1625
8	39.0445	38.9903	39.8524	23.8428	20.2756	36.001	16.6552	22.1785	22.8752	14.4612	0.004	7.1228	0.3922
10	38.6245	38.5293	39.3146	23.9993	20.3126	53.2464	23.4336	32.2204	33.765	17.8575	0.0016	9.5827	0.6773
C40-0-4-2	7.3885	6.826	6.1642	-0.8925	9.1562	26.3535	-6.6184	6.7389	5.7497	3.9989	0.0148	2.027	0.7202
4	7.6848	7.3741	6.6494	-0.8803	9.0254	39.1064	-6.6092	12.9678	13.2826	7.2896	0.0191	4.2341	0.9163
6	8.588	8.403	7.6896	-0.7771	9.011	57.18311	2.827333	25.01533	25.83967	10.89811	0.018778	7.93	1.168
8	9.172	9.034	8.3434	-0.833	9.0051	62.9584	24.0592	36.0377	37.0805	14.8589	0.0186	9.1456	1.3055
10	9.2463	9.1226	8.5096	-0.7335	8.94	82.005	38.0806	50.0668	52.55	17.9474	0.0133	13.0691	1.7097

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Table B-2
Pressure Drop Test Data of Surrogates (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
C40-0-20-2	19.9122	19.7351	19.6055	17.7198	18.1008	20.5467	-6.6	5.857	4.5584	3.4447	0.0202	1.2149	0.3922
4	19.8573	19.7952	19.6496	17.4964	18.0243	34.2551	-6.6	11.0985	11.6634	7.2997	0.0156	3.3679	0.6284
6	20.006	19.933	19.7873	17.0346	17.8048	51.5927	0.9834	21.9672	22.5302	10.8794	0.0191	6.6477	0.8796
8	19.8342	19.7713	19.6255	16.2225	17.4406	63.0411	13.2614	31.949	33.0842	15.4057	0.017	8.8239	1.1032
10	20.0468	19.9574	19.8197	15.0923	16.718	77.2824	24.4226	42.7951	44.755	18.5138	0.0141	12.2876	1.3238
C40-0-40-2	40.8463	40.7924	41.6064	24.0608	20.9723	17.5147	-6.6	4.056	3.5611	3.7005	0.0186	0.3489	0.0156
4	41.2129	41.1765	42.052	24.028	21.0268	31.9215	-6.6	9.5548	9.714	7.1949	0.0132	2.3565	0.184
6	41.2515	41.1507	42.0742	23.9871	20.9226	46.2456	-3.059	18.0484	18.5016	10.7637	0.0162	6.6016	0.3586
8	40.8245	40.7759	41.676	23.9717	20.7615	58.4379	7.8952	27.8058	28.7428	14.2096	0.0144	8.9083	0.5947
10	38.5076	38.4925	39.2618	23.9069	20.8515	73.9103	19.7408	39.4003	41.3566	17.8547	0.0074	12.1343	0.8673
C5-5-4-2	7.8458	7.9868	7.2462	3.0468	10.6172	4.863	0.6476	2.4984	2.3192	3.4682	-0.0446	1.0463	0.3615
4	6.2495	6.2844	5.5243	0.0787	9.3111	13.0768	6.966	8.7096	8.7204	7.3977	-0.0374	3.1533	0.5394
6	6.4004	6.2932	5.4665	-0.6331	8.7392	24.6354	15.6212	17.1846	17.5862	11.0486	-0.04	5.7435	0.72
8	6.8452	6.7669	5.9995	-0.6543	8.7007	38.2702	25.775	27.1076	28.062	14.4821	-0.0379	8.9542	0.9439
10	7.32118	7.26991	6.52964	-0.5869	8.634	48.88136	33.66309	34.97891	36.24382	16.77491	-0.04009	10.7181	1.1335
C5-5-20-2	22.9776	23.0864	23.0859	20.6776	19.2482	4.4123	0.7948	2.343	2.2962	3.57	-0.0328	0.3644	0.1317
4	22.7321	22.8219	22.8296	20.3967	19.1116	11.2579	5.9914	7.3591	7.5244	7.2639	-0.0358	1.9427	0.2117
8	21.422	21.5402	21.4995	19.5875	18.69	34.0898	23.1622	24.4431	24.7372	14.6857	-0.0322	6.8317	0.6162
10	20.383	20.5013	20.3971	19.2589	18.4754	47.6146	33.8266	34.4898	35.5166	17.9968	-0.034	10.5249	0.8673
C5-5-40-2	40.6647	40.6885	41.4716	38.9959	27.749	4.2108	1.0248	2.7008	2.0156	3.7669	-0.0446	0.0422	-0.3033
4	41.3447	41.3534	42.1821	40.2268	28.2834	10.284	5.7526	7.2258	6.7204	7.2369	-0.044	1.3987	-0.2051
6	41.9501	41.9445	42.8425	41.5464	28.9177	19.8942	12.99	14.2308	14.1372	11.0527	-0.044	3.6898	-0.0671

Table B-2
Pressure Drop Test Data of Surrogates (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
8	42.4941	42.524	43.4314	43.5107	29.7094	31.021	21.429	22.4998	22.8798	14.528	-0.043	6.5634	0.0888
10	42.6517	42.8421	43.8574	46.5803	31.5272	46.2639	32.746	33.6537	34.537	18.4128	-0.0366	10.4329	0.38
C25-5-4-2	7.4448	4.659	6.5907	-1.1559	8.0404	27.5294	-1.564	12.5226	12.749	3.4833	-0.0421	3.6057	0.6926
4	7.6532	5.6359	6.8363	-1.3267	7.9004	34.8797	2.9466	16.6566	16.612	7.3661	-0.0421	5.1995	0.8733
6	8.5267	8.0368	7.7171	-1.1392	8.1577	50.8853	13.1096	26.3587	29.1384	11.4261	-0.0391	8.571	1.1124
8	7.8021	7.5723	7.0257	-1.2272	8.0984	67.9841	29.936	42.3036	44.309	14.6154	-0.0394	12.8547	1.3853
10	8.0016	7.7989	7.2883	-1.2579	8.0027	72.0359	33.3068	45.5606	47.5145	15.2108	-0.0394	13.774	1.422
C25-5-20-2	20.0235	19.1179	19.9424	18.4295	17.3439	27.4834	-0.0286	12.449	12.7398	3.7716	-0.0326	3.276	0.515
4	20.0767	19.5485	20.0251	18.3756	17.2731	31.6092	2.9374	14.8699	14.9882	7.4776	-0.0322	4.2109	0.604
6	20.0145	19.912	19.92	17.8329	17.0546	44.4354	10.5622	23.5199	25.2892	11.1419	-0.0316	7.031	0.7815
8	20.1334	20.1318	20.1156	18.3048	17.1712	65.4112	27.8256	40.3376	41.5406	14.7569	-0.0308	11.843	1.085
10	19.7924	19.7817	19.7262	16.7541	16.4217	78.5869	39.3177	50.9214	52.3062	16.9657	-0.033	15.2223	1.3055
C25-5-40-2	39.9839	40.7956	41.0685	42.0698	28.1986	31.6548	2.3036	14.4149	14.3212	3.6512	-0.0403	3.5213	0.2543
4	40.1458	41.3476	41.2065	43.4714	29.0685	35.2382	3.632	16.4772	17.3378	7.2673	-0.04	4.2875	0.2729
6	40.0285	40.2165	40.9446	41.648	28.1523	42.607	7.6238	21.7371	22.9672	11.3908	-0.0367	5.8968	0.4567
8	40.6991	40.8183	41.7337	44.2152	29.3313	62.0763	22.9647	36.7682	37.9904	14.8334	-0.0385	10.165	0.6285
10	39.234	39.5999	40.4781	44.1112	29.5435	83.7781	40.067	53.3468	54.9042	18.4975	-0.0335	15.2148	1.036
C5-10-4-2	9.1522	5.9619	8.2618	-0.9991	8.462	60.3396	35.5654	41.5592	41.3934	3.6086	-0.0418	12.4561	1.0666
4	10.0592	7.4745	9.2513	-1.0119	8.5216	75.3068	45.8572	52.0654	53.5298	7.2308	-0.0391	15.4216	1.3577
6	10.8217	8.5041	10.0495	-0.9361	8.4596	91.5418	57.091	62.7363	65.7342	10.9837	-0.0305	19.1686	1.7407
8	11.2585	9.2343	10.5318	-0.9034	8.3673	105.2687	65.5438	70.6101	74.7979	14.3847	-0.0303	22.0958	2.0931
10	10.0744	8.3098	9.4478	-0.9623	8.2512	111.1673	68.7582	73.0126	77.9432	15.3224	-0.0373	23.3676	2.2309
C5-10-40-2	40.0254	41.4525	41.2967	41.8986	29.1583	77.3374	58.4755	58.9467	59.1951	3.676	-0.0415	16.4177	0.833[illegible]
4	39.0904	40.4201	40.1533	41.5605	28.9224	89.1897	60.6458	63.3518	65.2144	7.1665	-0.0427	17.6667	1.026[illegible]

Table B-2
Pressure Drop Test Data of Surrogates (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
6	39.5276	37.5091	40.0769	29.7704	22.9817	99.5079	66.8863	70.7571	73.3682	10.9181	-0.0409	20.1496	1.2135
8	42.0296	42.9652	43.0205	47.3489	31.2358	111.5533	75.1501	77.7763	82.3352	14.6371	-0.04	23.069	1.5258
10	33.296	35.1235	34.3095	48.8493	32.7534	115.8717	75.4537	78.8833	84.1014	17.9678	-0.0306	24.1343	1.8907
C5-10-20-2	20.98	19.6938	20.9623	18.595	17.8264	52.8609	28.6766	34.9856	35.7834	3.576	-0.0427	9.912	0.7876
4	20.9692	19.9377	21.0033	18.6358	17.7773	61.4608	33.9508	41.0496	42.18	7.0704	-0.0424	12.0347	1.0236
6	20.7534	19.3038	20.669	16.1993	16.622	73.9653	42.5046	48.8176	51.423	10.9566	-0.0409	14.7013	1.2749
8	21.3067	20.4837	21.2429	16.0791	16.3719	81.5272	47.4202	52.3636	55.3367	14.5532	-0.0388	16.5864	1.4831
10	21.5226	21.1377	21.5256	16.0968	16.3423	93.5817	54.0331	61.4776	65.7572	17.4765	-0.0388	19.4521	1.7374
	Surrogate Formula: (44.5% sand, 44.5% soil, 5% Diato earth, 3% Al2O3, 3%Fe2O3)												
CC5-0-20-2	19.2493	19.6074	19.0253	17.0565	16.9594	3.0713	1.6826	2.3428	1.3762	3.551	0.004	0.3948	0.1625
4	19.6677	20.0286	19.5519	17.0657	16.9768	9.5582	6.3174	6.89	6.3248	7.3424	0.001	1.3374	0.2849
6	20.2886	20.5991	20.1871	17.0391	16.9178	19.0304	13.312	13.9006	13.5494	11.052	0.0028	3.4982	0.4105
8	21.1551	21.3691	21.1039	17.1336	16.8423	22.9262	16.14	16.7578	16.4418	12.3308	0.0283	4.3947	0.4598
CC5-5-40-2	36.1033	34.577	36.7615	34.9081	24.8427	5.69	0.4406	2.8296	2.4618	3.6823	0.0049	0.0807	-0.1255
4	36.7963	35.1559	37.48	36.0702	25.3335	13.3068	6.4048	8.6866	8.4076	7.335	0.0016	1.8815	0.0186
6	37.6557	35.9297	38.4165	37.9685	26.3761	24.066	14.6	16.7348	16.7684	10.8475	0.0022	4.3182	0.1351
8	38.4091	36.5738	39.2389	42.4787	28.2511	36.4052	23.7372	25.9817	26.062	13.9788	-0.0122	7.1763	0.374
CC5-10-10-2	10.7601	8.3886	9.7931	-2.1801	7.4687	19.7194	7.0304	11.8842	11.3276	3.5443	0.0123	0.1574	0.5702
4	11.3202	8.8972	10.2897	-2.1172	7.5991	30.9202	14.6414	19.2066	19.1594	7.3188	0.0114	4.6246	0.812
6	11.8859	9.3851	11.0175	-2.6281	7.4949	42.901	22.9414	27.0844	27.2395	10.6189	0.0117	7.8429	1.0849
8	12.6719	9.9923	11.8282	-2.3599	7.0003	47.6235	26.0187	30.4606	29.902	12.1068	-0.0023	8.7933	1.155
CC5-10-20-2	19.9368	18.7987	19.7201	16.9013	16.9989	15.8335	4.4876	9.1364	8.449	3.2986	0.0114	2.2495	0.3585

Table B-2
Pressure Drop Test Data of Surrogates (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
4	20.0301	18.8426	19.9015	15.6452	16.385	24.1669	10.1252	13.9144	14.0958	7.1922	0.0094	3.5289	0.5211
6	20.5208	19.9585	20.4595	15.459	16.2001	37.5996	18.6194	23.2671	21.7666	11.3089	0.0127	6.4944	0.7875
8	20.9534	20.8657	20.8902	15.8596	16.3003	46.2089	26.4916	28.0675	28.9222	12.6358	-0.0088	8.5864	0.8488
CC5-10-40-2	40.3473	40.4184	41.6866	43.3032	29.4561	23.239	11.4362	15.6142	15.1584	3.5734	0.0116	3.7894	0.1289
4	40.5343	40.3125	41.8062	43.1505	29.4371	33.07	17.888	21.1816	21.8126	7.6299	0.0106	5.866	0.3434
6	40.5741	39.8953	41.7359	43.1881	29.4528	45.3084	26.372	28.5546	29.7686	10.9796	0.0073	8.9849	0.6191
8	39.9293	39.2362	41.1563	43.3984	29.5323	56.086	33.408	36.0193	35.4798	13.669	-0.0021	11.1688	0.8059
CC25-0-20-2	24.6457	24.4921	24.8579	18.7297	18.437	5.0102	0.0174	2.1084	1.689	3.6132	-0.012	0.096	0.0155
4	24.5481	24.4253	24.762	18.2891	18.3469	12.2682	4.4554	7.0188	6.7664	7.3006	-0.0174	1.3144	0.1288
6	24.2589	24.1631	24.4374	17.956	18.0152	23.3399	10.1022	14.1348	14.0683	10.8428	-0.0165	3.3988	0.2789
8	24.6138	24.4688	24.855	23.6922	20.5801	29.5783	13.2844	18.0944	18.1796	12.5195	-0.026	4.6247	0.389
CC25-5-4-2	7.7779	8.3484	6.8124	-0.9561	8.5141	12.075	-0.0746	4.961	4.8114	3.6186	0.0006	1.6593	0.4811
4	7.7896	8.7241	6.88	-0.905	8.5467	20.6844	5.3156	11.1582	9.7554	7.1869	0.0002	2.7243	0.6439
6	7.9092	9.0808	7.0741	-0.9264	8.4481	38.5554	19.3002	25.5548	25.832	11.0046	-0.0004	6.985	0.9101
CC25-5-20-2	25.5914	25.2885	25.8423	19.7611	18.5318	8.5748	-2.622	3.2154	2.0478	3.7642	-0.0112	0.2187	0.0674
4	25.8882	25.5717	26.1714	19.9162	18.7602	19.0859	4.8878	10.6433	10.0774	7.3801	-0.0135	2.0728	0.1994
6	25.8938	25.5739	26.1976	20.1526	18.9048	33.5016	13.2384	20.2948	20.0288	10.9236	-0.0144	5.0616	0.4105
8	25.5039	25.2379	25.8469	19.9442	18.845	40.1447	18.394	25.1734	25.1788	12.6081	-0.0231	6.5941	0.5366
CC25-5-40-2	39.5345	38.1788	40.7522	41.2142	28.2361	8.2804	-1.5364	2.6686	2.4894	3.7675	-0.0153	-0.1185	-0.2081
4	39.7161	38.1335	40.9723	41.1676	28.2109	16.532	4.9936	9.187	8.9826	7.3125	-0.0174	1.9965	-0.0673
6	39.7708	38.1972	40.9585	41.3817	28.3593	29.735	14.7196	19.1374	18.9984	11.0825	-0.0201	4.617	0.1196
8	39.3807	37.8236	40.5977	41.7561	28.5733	39.1156	21.8752	26.1656	26.338	13.3325	-0.0239	6.9926	0.2788

Table B-2
Pressure Drop Test Data of Surrogates (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
CC40-0-20-2	19.74	19.83	19.47	16.70	22.16	9.87	-4.41	2.79	2.11	3.52	-0.05	-0.57	0.25
4	20.12	20.29	19.98	16.60	22.26	24.07	-2.86	9.18	8.91	7.30	-0.04	1.08	0.40
6	20.32	20.46	20.28	16.67	22.18	39.60	1.75	17.56	17.87	10.92	-0.04	3.84	0.63
8	20.12	20.29	20.09	17.15	22.13	43.38	5.15	20.41	20.73	12.05	-0.04	4.82	0.69
CC-40-5-20-2	20.81	20.59	20.80	19.69	22.39	38.06	-6.65	13.80	14.57	3.66	-0.05	-1.68	0.62
4	20.62	20.65	20.67	19.85	22.44	50.81	-3.96	19.73	20.80	7.05	-0.05	0.95	0.89
6	19.99	20.11	20.04	17.16	22.32	64.21	2.71	26.83	27.40	10.31	-0.04	5.61	1.14
CC40-5-40-2	39.60	39.40	41.00	44.94	22.93	35.87	-6.65	12.80	13.55	3.94	-0.05	-7.36	0.28
4	39.56	39.72	41.13	46.67	22.93	47.35	-3.16	18.18	19.50	7.25	-0.05	-5.74	0.53
6	38.26	38.13	39.77	46.53	22.82	64.09	6.31	28.24	29.50	11.32	-0.04	-0.78	0.84
CC40-5-9-2	9.34	8.96	8.21	-5.11	22.22	45.21	-6.62	17.20	18.39	3.62	-0.05	-1.07	0.93
4	10.01	9.96	9.06	-5.29	22.26	63.13	5.55	27.71	29.88	7.27	-0.05	3.07	1.25
CC25-5-20-2	25.27	25.10	25.66	21.64	22.25	9.53	-0.87	3.37	2.10	3.64	-2.37	45.24	-0.75
4	25.22	25.05	25.60	21.67	22.31	18.46	5.91	10.11	9.19	7.28	-2.37	80.82	-0.78
6	25.82	25.62	26.26	21.76	22.58	30.89	15.95	20.20	18.94	10.92	-2.37	122.52	-0.77
8	24.6898	24.557	25.1036	21.6577	22.4638	50.482	28.4889	33.6623	33.1622	14.56	-2.37	163.275	-0.7751
CC25-6-20-2	23.1271	21.8465	23.1416	16.3614	22.4837	10.8851	-0.8155	4.0237	2.6088	3.64	-2.37	42.2262	-0.7493
4	23.3381	23.1915	23.4161	16.8743	22.6282	19.9808	6.2684	10.8228	10.1053	7.28	-2.37	80.1432	-0.7719
6	24.7799	24.5638	24.8608	16.4604	22.6367	34.1196	16.9142	21.6897	21.0982	10.92	-2.37	122.67	-0.772
8	26.7068	26.3736	27.0456	19.4438	22.6695	51.419	30.3246	35.2024	34.5147	14.56	-2.37	165.833	-0.772
CC25-7-20-2	21.4243	20.2836	21.421	18.2533	22.3715	14.4312	0.5534	5.8432	4.8874	-0.622	-2.37	40.9855	-0.748
4	21.7128	21.1159	21.7761	18.0025	22.4361	21.7628	5.3401	10.6572	11.3828	7.28	-2.37	79.8675	-0.7716
6	22.1253	22.1014	22.182	17.787	22.608	38.0059	17.7697	23.3113	23.6602	10.92	-2.37	120.074	-0.770

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Table B-2
Pressure Drop Test Data of Surrogates (continued)

Case	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C	ΔP1, in H_2O	ΔP2, in H_2O	ΔP3, in H_2O	ΔP4, in H_2O	Fs, GPM	Fc, GPM	P1, psig	P2, psig
8	22.333	22.3344	22.4637	17.9816	22.6902	57.6755	31.9729	38.6767	38.7217	14.56	-2.37	160.419	-0.772
CC25-8-20-2	21.8772	21.2039	21.9451	19.8226	22.444	21.4137	5.8592	10.7081	10.3258	3.64	-2.37	39.2242	-0.7469
4	22.0748	21.7535	22.2203	19.3885	22.567	31.1153	12.7146	17.4332	17.6474	7.28	-2.37	82.6549	-0.7749
6	22.1304	21.922	22.2847	19.6629	22.7923	42.9485	20.7197	27.6297	25.5612	10.92	-2.37	123.934	-0.7782
8	21.9353	21.9695	22.0989	19.8163	22.6555	63.877	36.5076	41.0867	43.8639	14.56	-2.37	161.253	-0.7751
CC25-9-10-2	9.6537	9.6573	8.4575	-5.9757	22.5843	48.1484	24.8852	31.3562	30.2575	3.64	-2.37	37.3479	-0.7467
4	10.1107	9.8421	9.1938	-5.9878	22.528	75.37	44.4176	50.2909	51.0623	7.28	-2.37	79.8674	-0.772
6	10.4621	10.9804	9.6854	-5.6177	22.5016	100.4235	62.4126	67.3621	69.5832	10.92	-2.3704	123.168	-0.7596
8	10.3688	11.1166	9.6171	-5.5272	22.5325	108.0582	68.0036	73.3527	75.0496	11.67	-2.371	136.792	-0.7658
CC25-9-20-2	22.382	21.6546	22.4513	19.4497	22.4023	28.938	10.8236	16.5746	15.6351	3.64	-2.37	43.1453	-0.7568
4	22.6335	22.1233	22.7915	19.5817	22.735	37.3808	16.705	21.3601	22.2665	7.28	-2.37	82.5553	-0.775
6	22.8078	22.2117	22.9841	20.0016	22.8477	49.8942	25.3467	32.1436	30.7013	10.92	-2.37	122.058	-0.7751
8	22.4935	22.3102	22.6972	19.8017	22.7467	69.9772	38.1153	47.6922	47.4942	14.56	-2.37	163.895	-0.772
CC25-9-40-2	41.38	42.0794	43.0944	44.8629	23.5179	37.0414	17.0182	23.5656	21.9904	3.64	-2.37	39.8061	-0.7499
4	42.0495	41.6735	43.6027	44.9181	23.5993	52.9996	32.1152	35.7111	35.0378	7.28	-2.37	81.5904	-0.7779
6	40.863	40.3389	42.3659	45.3909	23.388	70.7952	45.4293	49.6476	49.3733	10.92	-2.37	124.547	-0.7812
8	39.0696	39.7451	40.5224	46.1707	23.3109	88.3608	56.0085	63.4572	62.9866	14.56	-2.37	167.127	-0.772
RCC25-9-20-2	23.7774	22.4334	23.8563	19.5607	22.9082	59.3845	39.9392	42.3038	40.3937	3.64	-2.37	39.5535	-0.7462
4	24.7479	23.3502	24.9797	19.4492	22.9494	92.7798	64.163	67.6011	67.5988	7.28	-2.37	81.5216	-0.772
6	24.5418	23.3455	24.8385	20.0092	22.6943	124.9624	86.0952	91.15	93.9935	10.92	-2.3715	125.603	-0.772
CC25-10-20-2	26.6912	24.5274	26.7615	19.8009	23.1631	128.0404	101.8436	100.3567	95.7851	3.64	-2.3717	39.9975	-0.7518
4	27.4657	25.419	27.8418	19.6177	23.3668	176.1167	133.8572	134.7837	133.2244	7.28	-2.373	74.0394	-0.741

Note: The case name is defined as follows. The letters at the beginning represent the testing loop and slurry condition. H = K-65 material hot loop test. HR or RH = K-65 material slurry hot loop repeated test. C = surrogate #1 cold loop test. CC = surrogate #2 cold loop test. RCC = repeated test of corresponding CC. The first digital number is the concentration percentage of K-65 material or surrogate. The second one is the concentration percentage of bentonite material. The third one is slurry temperature in °C. The fourth digital number is flow velocity in feet per second.

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APPENDIX C

FRICTION GRADIENT AND BEND RESISTANCE

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Table C-1
Dimensional Results Data of Silo Material Pressure Drop Tests

Case	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
5% K-65	6.21E+00	2.08E+00	3.22E-01	3.39E-01	3.80E-01	
	7.36E+00	4.08E+00	1.14E+00	1.18E+00	1.30E+00	5.73E-01
	6.52E+00	8.09E+00	3.87E+00	3.96E+00	4.35E+00	3.26E+00
	2.72E+01	1.99E+00	2.45E-01	3.00E-01	3.35E-01	1.61E-01
	2.69E+01	4.14E+00	9.87E-01	1.05E+00	1.18E+00	9.29E-01
	2.59E+01	7.98E+00	3.32E+00	3.41E+00	3.78E+00	3.15E+00
	2.32E+01	2.00E+00	2.53E-01	2.71E-01	3.48E-01	
	2.29E+01	4.10E+00	9.87E-01	1.05E+00	1.15E+00	6.96E-01
	2.23E+01	7.99E+00	3.33E+00	3.43E+00	3.74E+00	2.98E+00
	4.22E+01	2.03E+00	2.49E-01	2.70E-01	3.21E-01	7.98E-02
	4.29E+01	3.99E+00	8.81E-01	9.13E-01	1.03E+00	6.56E-01
	4.27E+01	7.97E+00	3.11E+00	3.17E+00	3.49E+00	2.66E+00
25% K-65	3.77E+01	2.04E+00	3.67E-01		2.73E-01	4.70E-01
	3.79E+01	3,95E+00	1.05E+00	1.12E+00	1.24E+00	1.45E+00
	3.69E+01	7.89E+00	3.75E+00	4.13E+00	3.98E+00	3.68E+00
	1.92E+01	1.97E+00	3.19E-01		3.44E-01	7.66E-01
	1.96E+01	4.06E+00	1.24E+00	1.32E+00	1.38E+00	1.58E+00
	1.94E+01	6.14E+00	2.51E+00	2.73E+00	2.76E+00	2.83E+00
	2.06E+01	7.79E+00	3.96E+00	4.50E+00	4.12E+00	3.93E+00
	2.00E+01	9.89E+00	5.75E+00	6.64E+00	5.85E+00	6.07E+00
	8.15E+00	1.94E+00	3.81E-01		3.66E-01	7.10E-01
	9.22E+00	4.14E+00	1.48E+00	1.85E+00	1.38E+00	1.64E+00
	9.47E+00	7.82E+00	4.34E+00	4.73E+00	4.62E+00	3.90E+00
	9.77E+00	1.01E+01	6.52E+00	7.49E+00	6.65E+00	7.25E+00
35% K-65	4.10E+01	2.03E+00	4.75E-01		7.34E-02	5.37E-01
	4.11E+01	3.92E+00	1.29E+00		1.10E+00	1.42E+00
	4.08E+01	7.92E+00	3.88E+00	4.31E+00	4.00E+00	3.73E+00
	1.96E+01	2.12E+00	5.90E-01		2.71E-01	7.38E-01
	1.96E+01	3.81E+00	1.39E+00		1.17E+00	1.57E+00
	1.97E+01	5.67E+00	2.71E+00	3.02E+00	2.77E+00	2.79E+00
	2.03E+01	8.09E+00	4.37E+00	5.34E+00	4.23E+00	5.10E+00
	2.04E+01	9.60E+00	6.19E+00	6.82E+00	6.43E+00	6.46E+00

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Table C-1
Dimensional Results Data of Silo Material Pressure Drop Tests (continued)

Case	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
	9.29E+00	2.06E+00	8.33E-01		6.19E-02	1.30E-01
	9.63E+00	3.90E+00	1.66E+00	1.92E+00	1.38E+00	1.76E+00
	9.76E+00	5.80E+00	2.88E+00	3.25E+00	2.85E+00	2.94E+00
	9.71E+00	7.47E+00	4.72E+00	5.37E+00	4.75E+00	4.61E+00
	1.10E+01	9.93E+00	6.83E+00	7.54E+00	7.08E+00	7.27E+00
43% K-65	4.14E+01	2.01E+00	9.54E-01		1.21E-01	4.86E-01
	4.15E+01	3.89E+00	1.52E+00		9.17E-01	1.64E+00
	4.13E+01	6.30E+00	3.04E+00	3.40E+00	3.06E+00	3.30E+00
	3.92E+01	8.16E+00	4.66E+00	5.02E+00	4.90E+00	4.75E+00
	4.07E+01	1.01E+01	6.59E+00	7.11E+00	6.95E+00	7.61E+00
	2.09E+01	2.03E+00	9.94E-01		4.07E-01	4.14E-01
	1.95E+01	4.21E+00	1.95E+00		1.80E+00	2.19E+00
	1.91E+01	6.06E+00	3.19E+00	3.21E+00	3.47E+00	3.28E+00
	2.01E+01	7.45E+00	4.81E+00	4.88E+00	5.12E+00	4.50E+00
	2.12E+01	9.64E+00	6.78E+00	6.98E+00	7.42E+00	6.98E+00
	8.42E+00	2.07E+00	1.03E+00		6.60E-01	3.33E-01
	8.49E+00	3.90E+00	1.73E+00		1.93E+00	2.16E+00
	9.04E+00	6.11E+00	3.38E+00	3.16E+00	3.89E+00	3.30E+00
	9.70E+00	7.73E+00	5.34E+00	5.39E+00	5.96E+00	5.56E+00
	1.01E+01	9.49E+00	7.41E+00	7.65E+00	8.20E+00	8.12E+00
5% K-65	8.80E+00	2.04E+00	3.14E-01	1.97E-01	5.84E-01	3.63E-01
5% B	8.76E+00	4.04E+00	1.23E+00	1.15E+00	1.51E+00	4.15E-01
	8.71E+00	6.02E+00	2.48E+00	2.47E+00	2.94E+00	1.79E+00
	9.13E+00	7.98E+00	4.08E+00	4.11E+00	4.74E+00	3.33E+00
	9.25E+00	9.87E+00	5.97E+00	6.07E+00	6.82E+00	5.34E+00
	1.99E+01	2.11E+00	4.03E-01	2.11E-01	5.45E-01	-2.35E-01
	1.99E+01	3.96E+00	1.12E+00	1.05E+00	1.31E+00	1.72E-01
	1.99E+01	6.03E+00	2.35E+00	2.33E+00	2.69E+00	1.41E+00
	2.02E+01	8.11E+00	3.86E+00	4.00E+00	4.39E+00	3.63E+00
	2.05E+01	1.00E+01	5.67E+00	5.87E+00	6.39E+00	5.42E+00
	4.00E+01	2.05E+00	3.64E-01	1.81E-01	3.16E-01	3.28E-01
	4.03E+01	3.96E+00	1.00E+00	9.94E-01	1.02E+00	6.54E-01
	4.05E+01	5.94E+00	2.10E+00	2.10E+00	2.20E+00	1.01E+00
	4.06E+01	8.16E+00	3.61E+00	3.74E+00	3.88E+00	2.40E+00

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Table C-1
Dimensional Results Data of Silo Material Pressure Drop Tests (continued)

Case	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
	4.06E+01	1.00E+01	5.20E+00	5.44E+00	5.63E+00	4.34E+00
25% K-65	1.13E+01	2.01E+00	8.54E-01		7.68E-01	8.85E-01
5% B	1.07E+01	4.07E+00	1.54E+00	1.44E+00	1.68E+00	1.84E+00
	1.04E+01	6.18E+00	3.35E+00	3.34E+00	3.56E+00	2.73E+00
	1.03E+01	8.14E+00	5.45E+00	5.64E+00	5.68E+00	4.26E+00
	1.04E+01	1.02E+01	7.93E+00	8.44E+00	8.44E+00	7.78E+00
	1.96E+01	2.04E+00	8.97E-01		5.81E-01	5.34E-01
	1.93E+01	3.97E+00	1.52E+00	1.46E+00	1.47E+00	1.73E+00
	1.97E+01	6.03E+00	3.07E+00	3.19E+00	3.14E+00	2.43E+00
	2.04E+01	7.89E+00	4.93E+00	5.30E+00	5.11E+00	4.48E+00
	2.02E+01	9.94E+00	7.27E+00	7.74E+00	7.78E+00	7.26E+00
	3.65E+01	1.91E+00	1.00E+00		3.83E-01	9.95E-01
	3.66E+01	3.99E+00	1.47E+00	1.52E+00	8.29E-01	1.49E+00
	3.64E+01	6.02E+00	2.72E+00	3.16E+00	2.28E+00	2.25E+00
	3.60E+01	7.87E+00	4.41E+00	4.96E+00	4.27E+00	3.73E+00
	3.53E+01	9.91E+00	6.65E+00	7.22E+00	6.83E+00	6.23E+00
36% K-65	8.67E+00	1.99E+00	2.90E+00	2.46E+00	3.20E+00	3.10E+00
5% B	1.05E+01	3.95E+00	3.68E+00	3.27E+00	4.11E+00	3.74E+00
	1.14E+01	5.86E+00	4.76E+00	5.90E+00	4.94E+00	4.01E+00
	1.17E+01	8.13E+00	6.51E+00	7.23E+00	7.11E+00	9.51E+00
	1.20E+01	9.28E+00	8.31E+00	8.24E+00	8.71E+00	1.02E+01
	2.21E+01	2.10E+00	2.53E+00	2.61E+00	2.79E+00	3.11E+00
	2.30E+01	3.93E+00	3.20E+00	2.79E+00	3.41E+00	2.94E+00
	2.32E+01	5.75E+00	4.13E+00	3.78E+00	4.41E+00	3.30E+00
	2.33E+01	8.12E+00	6.19E+00	5.59E+00	6.56E+00	6.18E+00
	2.32E+01	9.13E+00	8.43E+00	7.94E+00	8.96E+00	8.43E+00
	4.00E+01	1.92E+00	3.08E+00	3.72E+00	3.20E+00	3.39E+00
	4.03E+01	3.86E+00	3.52E+00	3.86E+00	3.44E+00	3.64E+00
	4.05E+01	5.92E+00	4.36E+00	4.84E+00	4.20E+00	3.90E+00
	4.05E+01	8.25E+00	5.29E+00	5.67E+00	5.30E+00	5.28E+00
	4.03E+01	9.72E+00	8.13E+00	7.76E+00	8.19E+00	7.10E+00
36% K-65	1.07E+01	1.97E+00	4.55E+00	4.53E+00	4.80E+00	4.18E+00
5% B	1.22E+01	4.00E+00	5.56E+00	5.50E+00	5.85E+00	5.05E+00
after 72 hr	1.31E+01	5.88E+00	6.67E+00	6.67E+00	7.22E+00	5.26E+00

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Table C-1
Dimensional Results Data of Silo Material Pressure Drop Tests (continued)

Case	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
	1.33E+01	7.36E+00	7.83E+00	7.51E+00	8.40E+00	4.95E+00
	2.14E+01	1.97E+00	4.23E+00	4.94E+00	4.20E+00	3.91E+00
	2.25E+01	4.05E+00	5.11E+00	5.26E+00	5.06E+00	4.43E+00
	2.32E+01	5.98E+00	6.13E+00	6.64E+00	6.30E+00	4.77E+00
	2.35E+01	8.02E+00	7.49E+00	7.12E+00	7.70E+00	4.12E+00
	4.03E+01	2.00E+00	5.11E+00	5.96E+00	4.94E+00	4.50E+00
	4.07E+01	3.93E+00	5.58E+00	6.40E+00	5.38E+00	4.91E+00
	4.08E+01	6.00E+00	6.33E+00	7.33E+00	6.22E+00	5.75E+00
	4.06E+01	8.11E+00	7.59E+00	8.03E+00	7.51E+00	4.30E+00
36% K-65	2.49E+01	1.89E+00	4.72E+00	5.60E+00	4.66E+00	3.96E+00
5% B	2.57E+01	3.97E+00	5.54E+00	6.51E+00	5.38E+00	4.86E+00
after 90 hr	2.61E+01	5.98E+00	6.68E+00	7.76E+00	6.66E+00	4.74E+00
	2.60E+01	7.44E+00	7.79E+00	8.01E+00	7.78E+00	4.20E+00
5% K-65	8.52E+00	1.98E+00	7.05E-01	6.79E-01	7.63E-01	6.97E-01
10% B	8.55E+00	4.01E+00	1.26E+00	1.29E+00	1.46E+00	2.05E+00
	9.37E+00	6.09E+00	2.96E+00	2.85E+00	3.11E+00	2.12E+00
	1.06E+01	7.63E+00	4.29E+00	4.33E+00	4.50E+00	3.22E+00
	2.04E+01	1.99E+00	5.98E-01	6.29E-01	6.35E-01	8.42E-01
	2.03E+01	4.01E+00	1.25E+00	1.25E+00	1.32E+00	1.45E+00
	2.02E+01	6.04E+00	2.75E+00	2.72E+00	2.82E+00	1.76E+00
	2.08E+01	8.14E+00	4.42E+00	4.69E+00	4.58E+00	3.70E+00
	3.83E+01	2.07E+00	5.94E-01	6.79E-01	5.08E-01	6.87E-01
	3.85E+01	4.03E+00	1.15E+00	1.26E+00	1.03E+00	1.07E+00
	3.87E+01	5.91E+00	2.32E+00	2.46E+00	2.21E+00	1.29E+00
	3.91E+01	8.04E+00	3.23E+00	4.51E+00	2.59E+00	2.67E+00
	3.98E+01	9.53E+00	4.59E+00	6.42E+00	3.79E+00	4.03E+00
25% K-65	9.32E+00	2.01E+00	1.47E+00	1.41E+00	1.48E+00	1.53E+00
10% B	9.50E+00	3.96E+00	2.11E+00	2.00E+00	2.16E+00	1.47E+00
	9.70E+00	5.92E+00	3.14E+00	3.08E+00	3.47E+00	3.64E+00
	1.04E+01	6.82E+00	4.32E+00	4.23E+00	4.62E+00	3.69E+00
	2.18E+01	2.09E+00	1.09E+00	1.21E+00	8.98E-01	1.32E+00
	2.18E+01	3.91E+00	1.49E+00	1.56E+00	1.36E+00	9.99E-01
	2.17E+01	6.30E+00	2.97E+00	3.07E+00	3.05E+00	2.52E+00
	2.22E+01	7.75E+00	4.72E+00	4.88E+00	4.96E+00	3.23E+00

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Table C-1
Dimensional Results Data of Silo Material Pressure Drop Tests (continued)

Case	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
	4.03E+01	2.05E+00	1.44E+00	1.49E+00	1.21E+00	1.26E+00
	4.06E+01	4.03E+00	1.82E+00	1.86E+00	1.50E+00	1.44E+00
	4.08E+01	6.19E+00	3.02E+00	3.03E+00	2.88E+00	2.47E+00
	4.10E+01	7.91E+00	4.49E+00	4.67E+00	4.46E+00	3.43E+00
	2.10E+01	7.70E-03	2.42E+00	1.31E+00	1.19E+00	2.01E+00
	2.10E+01	1.21E-01	2.53E+00	1.65E+00	1.77E+00	1.95E+00
	2.11E+01	3.16E-01	2.61E+00	2.11E+00	2.09E+00	2.17E+00
	2.15E+01	8.40E-01	2.99E+00	2.71E+00	3.09E+00	1.80E+00
	2.24E+01	1.81E+00	3.29E+00	3.04E+00	3.58E+00	2.26E+00
	2.35E+01	3.97E+00	3.84E+00	3.73E+00	4.10E+00	3.15E+00
	2.43E+01	6.01E+00	4.72E+00	4.52E+00	5.09E+00	2.88E+00

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Table C-2
Dimensional Results Data of Surrogate Pressure Drop Tests

Surrogate concentration	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
5% Surrogate #1	1.11E+01	2.04E+00	2.93E-01	2.70E-01	4.53E-01	2.53E-01
	1.16E+01	4.05E+00	1.07E+00	1.05E+00	1.33E+00	9.16E-01
	1.20E+01	6.07E+00	2.22E+00	2.18E+00	2.63E+00	1.85E+00
	1.22E+01	8.09E+00	3.70E+00	3.66E+00	4.30E+00	3.26E+00
	1.19E+01	1.01E+01	5.46E+00	5.45E+00	6.29E+00	4.88E+00
	1.99E+01	2.03E+00	3.03E-01	2.71E-01	4.07E-01	1.45E-01
	2.02E+01	4.04E+00	1.01E+00	1.00E+00	1.22E+00	8.36E-01
	2.01E+01	6.05E+00	2.07E+00	2.07E+00	2.44E+00	1.75E+00
	2.03E+01	8.04E+00	3.44E+00	3.44E+00	4.02E+00	2.99E+00
	2.06E+01	1.01E+01	5.12E+00	5.12E+00	5.89E+00	4.52E+00
	4.08E+01	2.04E+00	3.11E-01	3.31E-01	2.51E-01	
	4.13E+01	3.98E+00	8.47E-01	9.18E-01	9.90E-01	5.16E-01
	4.16E+01	5.95E+00	1.80E+00	1.85E+00	2.04E+00	1.22E+00
	4.14E+01	7.93E+00	3.05E+00	3.10E+00	3.36E+00	2.39E+00
	4.11E+01	9.91E+00	4.44E+00	4.63E+00	4.82E+00	3.53E+00
25% Surrogate #1	6.97E+00	2.04E+00	4.31E-01	1.54E+00		4.33E-02
	7.77E+00	4.04E+00	1.30E+00	2.43E+00	3.52E-01	9.61E-01
	8.36E+00	6.06E+00	2.63E+00	3.66E+00	1.96E+00	1.92E+00
	8.69E+00	8.08E+00	4.25E+00	5.30E+00	3.82E+00	3.65E+00
	7.90E+00	1.00E+01	6.19E+00	7.11E+00	6.25E+00	5.96E+00
	1.95E+01	2.04E+00				
	2.00E+01	4.02E+00	1.20E+00	2.29E+00	2.41E-01	7.82E-01
	2.00E+01	6.04E+00	2.37E+00	3.43E+00	1.66E+00	1.72E+00
	2.03E+01	8.05E+00	3.87E+00	4.73E+00	3.62E+00	3.49E+00
	2.05E+01	9.98E+00	5.69E+00	6.07E+00	6.07E+00	5.37E+00
	1.87E+01	1.99E+00	4.08E-01	1.38E+00		5.02E-02
	1.91E+01	4.00E+00	1.20E+00	2.26E+00	3.13E-01	8.52E-01
	1.98E+01	6.04E+00	2.47E+00	3.34E+00	1.95E+00	2.07E+00
	2.05E+01	7.86E+00	3.88E+00	4.33E+00	3.95E+00	3.31E+00
	2.17E+01	9.57E+00	5.35E+00	5.71E+00	5.77E+00	4.95E+00
	3.91E+01	2.16E+00	3.55E-01	1.55E+00		
	3.94E+01	3.99E+00	1.05E+00	2.23E+00		6.08E-01
	3.95E+01	5.97E+00	2.04E+00	3.21E+00	1.24E+00	1.69E+00
	3.94E+01	7.95E+00	3.43E+00	4.27E+00	3.10E+00	3.13E+00

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Table C-2
Dimensional Results Data of Surrogate Pressure Drop Tests (continued)

Surrogate concentration	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
	3.89E+01	9.82E+00	4.99E+00	5.32E+00	5.36E+00	5.08E+00
40% Surrogate #1	6.50E+00	2.20E+00	1.04E+00	3.33E+00		
	7.01E+00	4.01E+00	2.01E+00	3.33E+00	9.68E-01	1.74E+00
	8.05E+00	5.99E+00	3.87E+00	4.79E+00	3.34E+00	3.57E+00
	8.69E+00	8.17E+00	5.58E+00	8.08E+00	4.09E+00	5.00E+00
	8.82E+00	9.87E+00	7.75E+00	1.03E+01	6.59E+00	7.97E+00
	1.97E+01	1.90E+00	9.07E-01	3.33E+00		
	1.97E+01	4.02E+00	1.72E+00	3.33E+00	3.32E-01	1.78E+00
	1.99E+01	5.98E+00	3.40E+00	4.50E+00	2.61E+00	2.97E+00
	1.97E+01	8.47E+00	4.95E+00	6.40E+00	4.11E+00	4.64E+00
	1.99E+01	1.02E+01	6.63E+00	8.13E+00	5.97E+00	6.65E+00
	4.12E+01	2.04E+00	6.28E-01	3.33E+00		
	4.16E+01	3.96E+00	1.48E+00	3.33E+00	2.60E-02	1.21E+00
	4.16E+01	5.92E+00	2.80E+00	3.88E+00	1.90E+00	2.43E+00
	4.12E+01	7.82E+00	4.31E+00	5.57E+00	3.50E+00	3.99E+00
	3.89E+01	9.82E+00	6.10E+00	7.41E+00	5.53E+00	6.28E+00
5% Surrogate #1	7.62E+00	1.91E+00	3.87E-01	3.37E-01	4.11E-01	9.48E-02
5% Bentonite	5.90E+00	4.07E+00	1.35E+00	1.32E+00	1.49E+00	9.66E-01
	5.88E+00	6.08E+00	2.66E+00	2.66E+00	3.00E+00	2.29E+00
	6.38E+00	7.97E+00	4.20E+00	4.23E+00	4.79E+00	3.93E+00
	6.90E+00	9.23E+00	5.42E+00	5.45E+00	6.18E+00	5.10E+00
	2.31E+01	1.96E+00	3.63E-01	3.60E-01	3.52E-01	2.10E-01
	2.28E+01	4.00E+00	1.14E+00	1.17E+00	1.25E+00	9.72E-01
	2.25E+01	6.17E+00	2.38E+00	2.40E+00	2.67E+00	2.10E+00
	2.15E+01	8.08E+00	3.79E+00	3.82E+00	4.24E+00	2.98E+00
	2.05E+01	9.90E+00	5.34E+00	5.48E+00	6.02E+00	4.81E+00
	4.11E+01	2.07E+00	4.18E-01	3.96E-01	3.26E-01	
	4.18E+01	3.98E+00	1.12E+00	1.13E+00	1.12E+00	2.87E-01
	4.24E+01	6.08E+00	2.20E+00	2.25E+00	2.38E+00	1.47E+00
	4.30E+01	7.99E+00	3.48E+00	3.56E+00	3.84E+00	2.85E+00
	4.34E+01	1.01E+01	5.21E+00	5.31E+00	5.84E+00	4.57E+00
25% Surrogate #1	5.63E+00	1.92E+00	1.94E+00	2.20E+00	1.27E+00	1.60E+00
5% Bentonite	6.24E+00	4.05E+00	2.58E+00	2.90E+00	2.24E+00	1.78E+00
	7.88E+00	6.28E+00	4.08E+00	4.48E+00	4.33E+00	5.67E+00

Table C-2
Dimensional Results Data of Surrogate Pressure Drop Tests (continued)

Surrogate concentration	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
	7.30E+00	8.04E+00	6.55E+00	7.08E+00	6.58E+00	6.65E+00
	7.54E+00	8.37E+00	7.06E+00	7.60E+00	7.11E+00	6.95E+00
	1.95E+01	2.07E+00	1.93E+00	2.44E+00	1.27E+00	1.66E+00
	1.98E+01	4.11E+00	2.30E+00	2.90E+00	1.81E+00	1.75E+00
	1.99E+01	6.13E+00	3.64E+00	4.08E+00	3.49E+00	4.35E+00
	2.01E+01	8.12E+00	6.25E+00	6.75E+00	6.24E+00	5.63E+00
	1.98E+01	9.33E+00	7.89E+00	8.53E+00	7.97E+00	6.97E+00
	4.09E+01	2.01E+00	2.23E+00	2.80E+00	1.81E+00	1.49E+00
	4.13E+01	4.00E+00	2.55E+00	3.01E+00	2.28E+00	2.67E+00
	4.06E+01	6.27E+00	3.37E+00	3.63E+00	3.25E+00	3.61E+00
	4.13E+01	8.16E+00	5.69E+00	6.00E+00	5.80E+00	5.26E+00
	4.00E+01	1.02E+01	8.26E+00	8.65E+00	8.65E+00	7.41E+00
5% Surrogate #1	7.11E+00	1.99E+00	6.44E+00	6.10E+00	7.35E+00	4.39E+00
10% Bentonite	8.36E+00	3.98E+00	8.06E+00	7.69E+00	9.31E+00	7.18E+00
	9.28E+00	6.04E+00	9.71E+00	9.43E+00	1.14E+01	9.88E+00
	9.88E+00	7.91E+00	1.09E+01	1.07E+01	1.32E+01	1.19E+01
	8.88E+00	8.43E+00	1.13E+01	1.12E+01	1.40E+01	1.29E+01
	4.14E+01	2.02E+00	9.13E+00	9.64E+00	9.58E+00	6.71E+00
	4.03E+01	3.94E+00	9.81E+00	9.98E+00	1.11E+01	8.81E+00
	3.88E+01	6.01E+00	1.10E+01	1.10E+01	1.25E+01	1.04E+01
	4.30E+01	8.05E+00	1.20E+01	1.22E+01	1.41E+01	1.31E+01
	3.47E+01	9.88E+00	1.22E+01	1.23E+01	1.46E+01	1.39E+01
	2.03E+01	1.97E+00	5.42E+00	5.03E+00	6.37E+00	4.64E+00
	2.05E+01	3.89E+00	6.36E+00	5.85E+00	7.50E+00	5.63E+00
	2.00E+01	6.03E+00	7.56E+00	7.17E+00	9.13E+00	7.96E+00
	2.09E+01	8.00E+00	8.11E+00	7.93E+00	1.01E+01	8.72E+00
	2.13E+01	9.61E+00	9.52E+00	8.96E+00	1.17E+01	1.10E+01
5% Surrogate #2	1.93E+01	1.95E+00	3.63E-01	3.03E-01	3.63E-01	
	1.98E+01	4.04E+00	1.07E+00	1.02E+00	1.21E+00	1.91E-01
	2.04E+01	6.08E+00	2.15E+00	2.10E+00	2.46E+00	1.17E+00
	2.12E+01	6.78E+00	2.60E+00	2.54E+00	2.97E+00	1.52E+00
25% Surrogate #2	2.47E+01	1.99E+00	3.27E-01	1.71E+00		
	2.46E+01	4.02E+00	1.09E+00	2.39E+00		5.17E-01
	2.43E+01	5.96E+00	2.19E+00	3.27E+00	1.43E+00	1.48E+00

Table C-2
Dimensional Results Data of Surrogate Pressure Drop Tests (continued)

Surrogate concentration	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
	2.47E+01	6.89E+00	2.80E+00	3.76E+00	2.25E+00	2.07E+00
40% Surrogate #2	1.97E+01	1.94E+00	4.32E-01	2.46E+00		
	2.01E+01	4.02E+00	1.42E+00	2.70E+00	1.47E-01	7.37E-01
	2.04E+01	6.01E+00	2.72E+00	3.42E+00	2.18E+00	2.24E+00
	2.02E+01	6.63E+00	3.16E+00	3.94E+00	2.68E+00	2.56E+00
5% Surrogate #2	3.57E+01	2.03E+00	4.38E-01	4.98E-01	3.35E-01	-5.75E-02
5% Bentonite	3.63E+01	4.03E+00	1.35E+00	1.42E+00	1.33E+00	6.74E-01
	3.72E+01	5.97E+00	2.59E+00	2.69E+00	2.74E+00	1.87E+00
	3.79E+01	7.69E+00	4.02E+00	4.11E+00	4.36E+00	2.93E+00
25% Surrogate #2	7.58E+00	1.99E+00	7.68E-01	2.16E+00		3.95E-01
5% Bentonite	7.80E+00	3.95E+00	1.73E+00	2.99E+00	6.41E-01	
	8.08E+00	6.05E+00	3.96E+00	5.16E+00	2.98E+00	3.08E+00
	2.56E+01	2.07E+00	4.98E-01	1.76E+00		
	2.59E+01	4.06E+00	1.65E+00	2.92E+00	4.31E-01	6.01E-01
	2.59E+01	6.01E+00	3.14E+00	4.22E+00	2.32E+00	1.96E+00
	2.55E+01	6.93E+00	3.90E+00	5.02E+00	3.19E+00	2.77E+00
	3.95E+01	2.07E+00	4.13E-01	1.93E+00		1.14E-01
	3.96E+01	4.02E+00	1.42E+00	2.94E+00	9.58E-02	8.03E-01
	3.96E+01	6.10E+00	2.96E+00	4.45E+00	1.83E+00	1.96E+00
	3.92E+01	7.33E+00	4.05E+00	5.55E+00	3.06E+00	3.04E+00
40% Surrogate #2	2.07E+01	2.01E+00	2.14E+00	2.64E+00	1.49E+00	2.28E+00
5% Bentonite	2.07E+01	3.88E+00	3.06E+00	3.05E+00	3.16E+00	3.23E+00
	2.01E+01	5.67E+00	4.15E+00	4.08E+00	4.92E+00	3.51E+00
	4.02E+01	2.17E+00	1.98E+00	2.64E+00	1.20E+00	2.15E+00
	4.04E+01	3.99E+00	2.82E+00	3.18E+00	2.70E+00	3.31E+00
	3.90E+01	6.23E+00	4.37E+00	4.64E+00	4.90E+00	4.36E+00
	8.59E+00	1.99E+00	2.66E+00	2.64E+00	2.42E+00	3.08E+00
	9.51E+00	4.00E+00	4.29E+00	4.52E+00	4.77E+00	5.21E+00
5% Surrogate #2	9.09E+00	1.95E+00	1.84E+00	1.93E+00	1.79E+00	7.47E-01
10% Bentonite	9.59E+00	4.03E+00	2.97E+00	3.10E+00	3.26E+00	2.06E+00
	1.02E+01	5.84E+00	4.19E+00	4.39E+00	4.83E+00	3.13E+00
	1.09E+01	6.66E+00	4.72E+00	4.87E+00	5.45E+00	2.78E+00
	1.93E+01	1.81E+00	1.42E+00	1.53E+00	1.28E+00	3.15E-01
	1.94E+01	3.96E+00	2.16E+00	2.40E+00	2.37E+00	1.71E+00

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Table C-2
Dimensional Results Data of Surrogate Pressure Drop Tests (continued)

Surrogate concentration	T °C	V ft/s	dp/dl-h	dp/dl-d	dp/dl-u	DP InH_2O
	2.02E+01	6.22E+00	3.60E+00	3.72E+00	4.13E+00	1.05E+00
	2.09E+01	6.95E+00	4.35E+00	4.94E+00	5.26E+00	3.93E+00
	4.11E+01	1.97E+00	2.42E+00	2.61E+00	2.25E+00	1.26E+00
	4.11E+01	4.20E+00	3.28E+00	3.61E+00	3.54E+00	2.95E+00
	4.08E+01	6.04E+00	4.42E+00	4.92E+00	5.14E+00	4.35E+00
	4.02E+01	7.52E+00	5.58E+00	6.01E+00	6.55E+00	3.41E+00
25% Surrogate #2	9.06E+00	2.00E+00	4.86E+00	6.40E+00	3.88E+00	2.34E+00
9% Bentonite	9.52E+00	4.00E+00	7.79E+00	9.43E+00	7.44E+00	6.29E+00
	1.03E+01	6.01E+00	1.04E+01	1.22E+01	1.07E+01	9.61E+00
	1.04E+01	6.42E+00	1.14E+01	1.31E+01	1.17E+01	9.74E+00
	2.21E+01	2.00E+00	2.57E+00	4.23E+00	1.36E+00	8.78E-01
	2.25E+01	4.00E+00	3.31E+00	5.14E+00	2.46E+00	3.25E+00
	2.26E+01	6.01E+00	4.98E+00	6.47E+00	4.10E+00	2.08E+00
	2.25E+01	8.01E+00	7.39E+00	8.45E+00	6.74E+00	5.03E+00
	4.26E+01	2.00E+00	3.65E+00	5.19E+00	2.42E+00	1.01E+00
	4.26E+01	4.00E+00	5.53E+00	7.52E+00	4.51E+00	3.24E+00
	4.14E+01	6.01E+00	7.69E+00	9.58E+00	6.84E+00	5.17E+00
	4.01E+01	8.01E+00	9.83E+00	1.12E+01	9.15E+00	6.49E+00

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APPENDIX D

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PRESSURE DROP DIMENSIONLESS RESULTS

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Table D-1
Dimensionless Result Data of Silo Material Pressure Drop Tests

Case	T	Re	f-horizontal	f-downward	f-upward	K-bend
5%-K-65	6.21E+00	4.77E+03	2.84E-02	3.00E-02	3.36E-02	
	7.36E+00	9.49E+03	2.61E-02	2.71E-02	2.97E-02	1.82E-01
	6.52E+00	1.87E+04	2.25E-02	2.30E-02	2.53E-02	2.64E-01
	2.72E+01	5.39E+03	2.35E-02	2.87E-02	3.21E-02	2.14E-01
	2.69E+01	1.12E+04	2.19E-02	2.34E-02	2.63E-02	2.88E-01
	2.59E+01	2.15E+04	1.99E-02	2.04E-02	2.26E-02	2.62E-01
	2.32E+01	5.29E+03	2.42E-02	2.59E-02	3.33E-02	
	2.29E+01	1.09E+04	2.24E-02	2.38E-02	2.60E-02	2.20E-01
	2.23E+01	2.11E+04	1.99E-02	2.05E-02	2.24E-02	2.47E-01
	4.22E+01	5.60E+03	2.29E-02	2.48E-02	2.95E-02	1.02E-01
	4.29E+01	1.10E+04	2.11E-02	2.19E-02	2.47E-02	2.19E-01
	4.27E+01	2.19E+04	1.86E-02	1.90E-02	2.09E-02	2.22E-01
25% K-65	3.77E+01	1.40E+03	3.07E-02		2.28E-02	5.47E-01
	3.79E+01	2.72E+03	2.33E-02	2.48E-02	2.76E-02	4.45E-01
	3.69E+01	5.56E+03	2.09E-02	2.30E-02	2.22E-02	2.85E-01
	1.92E+01	1.92E+03	2.85E-02		3.07E-02	9.52E-01
	1.96E+01	3.96E+03	2.60E-02	2.78E-02	2.90E-02	4.61E-01
	1.94E+01	5.99E+03	2.30E-02	2.50E-02	2.53E-02	3.61E-01
	2.06E+01	7.55E+03	2.26E-02	2.56E-02	2.35E-02	3.12E-01
	2.00E+01	9.62E+03	2.04E-02	2.35E-02	2.07E-02	2.99E-01
	8.15E+00	1.74E+03	3.52E-02		3.38E-02	9.13E-01
	9.22E+00	3.78E+03	2.99E-02	3.74E-02	2.80E-02	4.62E-01
	9.47E+00	7.17E+03	2.45E-02	2.68E-02	2.62E-02	3.08E-01
	9.77E+00	9.31E+03	2.21E-02	2.54E-02	2.25E-02	3.42E-01
35% K-65	4.10E+01	7.53E+02	3.73E-02		5.76E-03	5.86E-01
	4.11E+01	1.45E+03	2.72E-02		2.31E-02	4.15E-01
	4.08E+01	2.95E+03	2.00E-02	2.22E-02	2.06E-02	2.68E-01
	1.96E+01	1.04E+03	4.25E-02		1.96E-02	7.41E-01
	1.96E+01	1.86E+03	3.10E-02		2.60E-02	4.86E-01
	1.97E+01	2.77E+03	2.73E-02	3.04E-02	2.79E-02	3.91E-01
	2.03E+01	3.93E+03	2.16E-02	2.64E-02	2.09E-02	3.51E-01
	2.04E+01	4.66E+03	2.17E-02	2.39E-02	2.26E-02	3.15E-01
	9.29E+00	1.04E+03	6.33E-02		4.70E-03	1.38E-01
	9.63E+00	1.96E+03	3.52E-02	4.09E-02	2.94E-02	5.22E-01
	9.76E+00	2.92E+03	2.77E-02	3.13E-02	2.74E-02	3.93E-01
	9.71E+00	3.77E+03	2.73E-02	3.11E-02	2.75E-02	3.71E-01

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Table D-1
Dimensionless Result Data of Silo Material Pressure Drop Tests (continued)

Case	T	Re	f-horizontal	f-downward	f-upward	K-bend
	1.10E+01	5.01E+03	2.24E-02	2.47E-02	2.32E-02	3.32E-01
43% K-65	4.14E+01	1.47E+02	7.21E-02		9.17E-03	5.11E-01
	4.15E+01	2.85E+02	3.06E-02		1.85E-02	4.59E-01
	4.13E+01	4.61E+02	2.34E-02	2.61E-02	2.35E-02	3.54E-01
	3.92E+01	5.96E+02	2.13E-02	2.30E-02	2.24E-02	3.02E-01
	4.07E+01	7.37E+02	1.97E-02	2.13E-02	2.08E-02	3.17E-01
	2.09E+01	1.65E+02	7.36E-02		3.01E-02	4.27E-01
	1.95E+01	3.49E+02	3.35E-02		3.09E-02	5.24E-01
	1.91E+01	5.04E+02	2.65E-02	2.67E-02	2.88E-02	3.80E-01
	2.01E+01	6.12E+02	2.64E-02	2.68E-02	2.81E-02	3.44E-01
	2.12E+01	7.81E+02	2.22E-02	2.29E-02	2.43E-02	3.19E-01
	8.42E+00	2.13E+02	7.37E-02		4.71E-02	3.30E-01
	8.49E+00	4.01E+02	3.47E-02		3.86E-02	6.02E-01
	9.04E+00	6.18E+02	2.76E-02	2.58E-02	3.18E-02	3.76E-01
	9.70E+00	7.70E+02	2.72E-02	2.75E-02	3.04E-02	3.95E-01
	1.01E+01	9.36E+02	2.51E-02	2.59E-02	2.78E-02	3.83E-01
5% K-65	8.80E+00	1.15E+03	2.81E-02	1.77E-02	5.23E-02	4.52E-01
5% B	8.76E+00	2.28E+03	2.81E-02	2.64E-02	3.45E-02	1.33E-01
	8.71E+00	3.41E+03	2.56E-02	2.55E-02	3.03E-02	2.57E-01
	9.13E+00	4.47E+03	2.39E-02	2.41E-02	2.78E-02	2.72E-01
	9.25E+00	5.52E+03	2.29E-02	2.33E-02	2.62E-02	2.85E-01
	1.99E+01	9.64E+02	3.39E-02	1.78E-02	4.58E-02	-2.75E-01
	1.99E+01	1.81E+03	2.68E-02	2.50E-02	3.11E-02	5.71E-02
	1.99E+01	2.76E+03	2.41E-02	2.39E-02	2.76E-02	2.02E-01
	2.02E+01	3.69E+03	2.20E-02	2.28E-02	2.50E-02	2.88E-01
	2.05E+01	4.54E+03	2.11E-02	2.19E-02	2.38E-02	2.81E-01
	4.00E+01	7.95E+02	3.23E-02	1.61E-02	2.80E-02	4.05E-01
	4.03E+01	1.54E+03	2.38E-02	2.37E-02	2.43E-02	2.17E-01
	4.05E+01	2.30E+03	2.22E-02	2.22E-02	2.33E-02	1.49E-01
	4.06E+01	3.16E+03	2.02E-02	2.10E-02	2.18E-02	1.87E-01
	4.06E+01	3.88E+03	1.94E-02	2.02E-02	2.10E-02	2.25E-01
25% K-65	1.13E+01	1.83E+02	7.09E-02		6.37E-02	1.02E+00

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Table D-1
Dimensionless Result Data of Silo Material Pressure Drop Tests (continued)

Case	T	Re	f-horizontal	f-downward	f-upward	K-bend
5% B	1.07E+01	3.67E+02	3.12E-02	2.91E-02	3.41E-02	5.17E-01
	1.04E+01	5.55E+02	2.94E-02	2.93E-02	3.12E-02	3.33E-01
	1.03E+01	7.30E+02	2.75E-02	2.85E-02	2.87E-02	3.00E-01
	1.04E+01	9.17E+02	2.55E-02	2.71E-02	2.71E-02	3.48E-01
	1.96E+01	1.77E+02	7.21E-02		4.67E-02	5.98E-01
	1.93E+01	3.46E+02	3.23E-02	3.11E-02	3.13E-02	5.13E-01
	1.97E+01	5.20E+02	2.83E-02	2.94E-02	2.89E-02	3.12E-01
	2.04E+01	6.70E+02	2.65E-02	2.85E-02	2.75E-02	3.35E-01
	2.02E+01	8.49E+02	2.46E-02	2.62E-02	2.63E-02	3.42E-01
	3.65E+01	8.61E+01	9.19E-02		3.52E-02	1.27E+00
	3.66E+01	1.79E+02	3.09E-02	3.21E-02	1.75E-02	4.36E-01
	3.64E+01	2.72E+02	2.51E-02	2.92E-02	2.11E-02	2.90E-01
	3.60E+01	3.62E+02	2.38E-02	2.68E-02	2.31E-02	2.81E-01
	3.53E+01	4.72E+02	2.27E-02	2.46E-02	2.33E-02	2.96E-01
36% K-65	8.67E+00	2.57E+01	2.26E-01	1.92E-01	2.50E-01	3.37E+00
5% B	1.05E+01	5.17E+01	7.31E-02	6.48E-02	8.16E-02	1.03E+00
	1.14E+01	7.74E+01	4.29E-02	5.31E-02	4.44E-02	5.03E-01
	1.17E+01	1.08E+02	3.05E-02	3.39E-02	3.33E-02	6.21E-01
	1.20E+01	1.23E+02	2.99E-02	2.97E-02	3.13E-02	5.11E-01
	2.21E+01	2.97E+01	1.78E-01	1.84E-01	1.97E-01	3.05E+00
	2.30E+01	5.59E+01	6.40E-02	5.59E-02	6.82E-02	8.18E-01
	2.32E+01	8.19E+01	3.86E-02	3.54E-02	4.13E-02	4.30E-01
	2.33E+01	1.16E+02	2.91E-02	2.62E-02	3.08E-02	4.04E-01
	2.32E+01	1.30E+02	3.13E-02	2.95E-02	3.32E-02	4.36E-01
	4.00E+01	2.85E+01	2.58E-01	3.12E-01	2.69E-01	3.97E+00
	4.03E+01	5.73E+01	7.31E-02	8.01E-02	7.15E-02	1.05E+00
	4.05E+01	8.78E+01	3.85E-02	4.28E-02	3.71E-02	4.80E-01
	4.05E+01	1.22E+02	2.41E-02	2.58E-02	2.41E-02	3.35E-01
	4.03E+01	1.44E+02	2.66E-02	2.54E-02	2.68E-02	3.24E-01
36% K-65	1.07E+01	2.59E+01	3.63E-01	3.62E-01	3.83E-01	4.65E+00
5% B	1.22E+01	5.31E+01	1.08E-01	1.06E-01	1.13E-01	1.36E+00
after 72 hr	1.31E+01	7.86E+01	5.98E-02	5.97E-02	6.47E-02	6.56E-01
	1.33E+01	9.85E+01	4.48E-02	4.29E-02	4.80E-02	3.94E-01
	2.14E+01	2.77E+01	3.39E-01	3.96E-01	3.37E-01	4.37E+00

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Table D-1
Dimensionless Result Data of Silo Material Pressure Drop Tests (continued)

Case	T	Re	f-horizontal	f-downward	f-upward	K-bend
	2.25E+01	5.74E+01	9.65E-02	9.93E-02	9.57E-02	1.17E+00
	2.32E+01	8.51E+01	5.31E-02	5.75E-02	5.45E-02	5.75E-01
	2.35E+01	1.14E+02	3.60E-02	3.42E-02	3.70E-02	2.76E-01
	4.03E+01	2.97E+01	3.96E-01	4.62E-01	3.83E-01	4.86E+00
	4.07E+01	5.82E+01	1.12E-01	1.29E-01	1.08E-01	1.37E+00
	4.08E+01	8.90E+01	5.44E-02	6.30E-02	5.35E-02	6.88E-01
	4.06E+01	1.20E+02	3.57E-02	3.78E-02	3.53E-02	2.82E-01
36% K-65	2.49E+01	2.71E+01	4.08E-01	4.85E-01	4.03E-01	4.78E+00
5% B	2.57E+01	5.71E+01	1.09E-01	1.28E-01	1.06E-01	1.33E+00
after 90 hr	2.61E+01	8.63E+01	5.77E-02	6.71E-02	5.75E-02	5.70E-01
	2.60E+01	1.07E+02	4.35E-02	4.48E-02	4.35E-02	3.27E-01

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Table D-2
Dimensionless Result Data of Surrogate Pressure Drop Tests

Slurry Concentration	T	Re	f-horizontal	f-downward	f-upward	K-bend
5% Surrogate #1	1.11E+01	4.95E+03	2.72E-02	2.51E-02	4.21E-02	3.27E-01
	1.16E+01	9.68E+03	2.50E-02	2.46E-02	3.12E-02	2.99E-01
	1.20E+01	1.43E+04	2.32E-02	2.28E-02	2.74E-02	2.69E-01
	1.22E+01	1.90E+04	2.18E-02	2.15E-02	2.53E-02	2.67E-01
	1.19E+01	2.39E+04	2.06E-02	2.06E-02	2.38E-02	2.57E-01
	1.99E+01	4.15E+03	2.82E-02	2.53E-02	3.79E-02	1.88E-01
	2.02E+01	8.22E+03	2.39E-02	2.36E-02	2.88E-02	2.75E-01
	2.01E+01	1.23E+04	2.18E-02	2.17E-02	2.57E-02	2.57E-01
	2.03E+01	1.64E+04	2.05E-02	2.05E-02	2.39E-02	2.48E-01
	2.06E+01	2.04E+04	1.95E-02	1.95E-02	2.25E-02	2.40E-01
	4.08E+01	6.15E+03	2.87E-02	3.06E-02	2.32E-02	
	4.13E+01	1.24E+04	2.06E-02	2.24E-02	2.41E-02	1.75E-01
	4.16E+01	1.88E+04	1.96E-02	2.01E-02	2.22E-02	1.85E-01
	4.14E+01	2.48E+04	1.87E-02	1.90E-02	2.06E-02	2.04E-01
	4.11E+01	3.04E+04	1.74E-02	1.82E-02	1.89E-02	1.93E-01
25% Surrogate #1	6.97E+00	1.55E+03	3.49E-02	1.25E-01		4.88E-02
	7.77E+00	3.07E+03	2.69E-02	5.03E-02	7.27E-03	2.77E-01
	8.36E+00	4.59E+03	2.42E-02	3.37E-02	1.81E-02	2.46E-01
	8.69E+00	6.12E+03	2.20E-02	2.75E-02	1.98E-02	2.63E-01
	7.90E+00	7.60E+03	2.08E-02	2.39E-02	2.10E-02	2.79E-01
	1.95E+01	1.48E+03	3.88E-02	1.35E-01		
	2.00E+01	2.92E+03	2.51E-02	4.78E-02	5.03E-03	2.27E-01
	2.00E+01	4.39E+03	2.20E-02	3.18E-02	1.54E-02	2.22E-01
	2.03E+01	5.84E+03	2.02E-02	2.47E-02	1.89E-02	2.54E-01
	2.05E+01	7.23E+03	1.93E-02	2.06E-02	2.06E-02	2.54E-01
	1.87E+01	1.46E+03	3.48E-02	1.17E-01		5.96E-02
	1.91E+01	2.92E+03	2.54E-02	4.78E-02	6.61E-03	2.50E-01
	1.98E+01	4.40E+03	2.28E-02	3.09E-02	1.80E-02	2.67E-01
	2.05E+01	5.69E+03	2.12E-02	2.37E-02	2.16E-02	2.52E-01
	2.17E+01	6.88E+03	1.98E-02	2.11E-02	2.13E-02	2.55E-01
	3.91E+01	1.31E+03	2.58E-02	1.13E-01		
	3.94E+01	2.41E+03	2.23E-02	4.75E-02		1.80E-01

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Table D-2
Dimensionless Result Data of Surrogate Pressure Drop Tests (continued)

Slurry Concentration	T	Re	f-horizontal	f-downward	f-upward	K-bend
	3.95E+01	3.61E+03	1.94E-02	3.04E-02	1.18E-02	2.23E-01
	3.94E+01	4.81E+03	1.84E-02	2.28E-02	1.66E-02	2.33E-01
	3.89E+01	5.97E+03	1.75E-02	1.86E-02	1.88E-02	2.48E-01
40% Surrogate #1	6.50E+00	8.65E+02	6.11E-02	1.95E-01		
	7.01E+00	1.57E+03	3.54E-02	5.86E-02	1.70E-02	4.26E-01
	8.05E+00	2.34E+03	3.05E-02	3.77E-02	2.63E-02	3.91E-01
	8.69E+00	3.18E+03	2.36E-02	3.42E-02	1.74E-02	2.95E-01
	8.82E+00	3.83E+03	2.25E-02	2.98E-02	1.91E-02	3.23E-01
	1.97E+01	6.91E+02	7.15E-02	2.62E-01		
	1.97E+01	1.47E+03	3.02E-02	5.84E-02	5.82E-03	4.36E-01
	1.99E+01	2.18E+03	2.69E-02	3.56E-02	2.06E-02	3.27E-01
	1.97E+01	3.09E+03	1.95E-02	2.52E-02	1.62E-02	2.55E-01
	1.99E+01	3.71E+03	1.81E-02	2.22E-02	1.63E-02	2.53E-01
	4.12E+01	6.57E+02	4.29E-02	2.27E-01		
	4.16E+01	1.28E+03	2.67E-02	6.02E-02	4.70E-04	3.04E-01
	4.16E+01	1.91E+03	2.26E-02	3.13E-02	1.54E-02	2.74E-01
	4.12E+01	2.52E+03	2.00E-02	2.58E-02	1.62E-02	2.57E-01
	3.89E+01	3.21E+03	1.79E-02	2.17E-02	1.62E-02	2.57E-01
5% Surrogate #1	7.62E+00	1.47E+03	4.02E-02	3.51E-02	4.27E-02	1.37E-01
5% Bentonite	5.90E+00	3.16E+03	3.08E-02	3.01E-02	3.40E-02	3.07E-01
	5.88E+00	4.73E+03	2.73E-02	2.72E-02	3.08E-02	3.26E-01
	6.38E+00	6.17E+03	2.50E-02	2.52E-02	2.86E-02	3.26E-01
	6.90E+00	7.12E+03	2.41E-02	2.42E-02	2.75E-02	3.16E-01
	2.31E+01	1.31E+03	3.56E-02	3.53E-02	3.45E-02	2.87E-01
	2.28E+01	2.67E+03	2.70E-02	2.76E-02	2.96E-02	3.21E-01
	2.25E+01	4.13E+03	2.37E-02	2.39E-02	2.66E-02	2.91E-01
	2.15E+01	5.47E+03	2.19E-02	2.22E-02	2.46E-02	2.40E-01
	2.05E+01	6.77E+03	2.06E-02	2.11E-02	2.32E-02	2.59E-01
	4.11E+01	1.12E+03	3.69E-02	3.49E-02	2.87E-02	
	4.18E+01	2.13E+03	2.67E-02	2.69E-02	2.68E-02	9.54E-02
	4.24E+01	3.24E+03	2.26E-02	2.30E-02	2.44E-02	2.09E-01
	4.30E+01	4.22E+03	2.06E-02	2.11E-02	2.28E-02	2.35E-01

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Table D-2
Dimensionless Result Data of Surrogate Pressure Drop Tests (continued)

Slurry Concentration	T	Re	f-horizontal	f-downward	f-upward	K-bend
	4.34E+01	5.33E+03	1.92E-02	1.96E-02	2.15E-02	2.35E-01
25% Surrogate #1	5.63E+00	1.02E+01	1.69E-01	1.92E-01	1.11E-01	1.94E+00
5% Bentonite	6.24E+00	2.15E+01	5.03E-02	5.66E-02	4.36E-02	4.84E-01
	7.88E+00	3.31E+01	3.31E-02	3.63E-02	3.52E-02	6.41E-01
	7.30E+00	4.24E+01	3.25E-02	3.51E-02	3.26E-02	4.59E-01
	7.54E+00	4.41E+01	3.23E-02	3.48E-02	3.25E-02	4.43E-01
	1.95E+01	1.05E+01	1.44E-01	1.82E-01	9.42E-02	1.72E+00
	1.98E+01	2.09E+01	4.36E-02	5.49E-02	3.42E-02	4.61E-01
	1.99E+01	3.11E+01	3.11E-02	3.48E-02	2.98E-02	5.17E-01
	2.01E+01	4.12E+01	3.04E-02	3.28E-02	3.03E-02	3.81E-01
	1.98E+01	4.74E+01	2.90E-02	3.14E-02	2.93E-02	3.57E-01
	4.09E+01	9.84E+00	1.77E-01	2.23E-01	1.44E-01	1.65E+00
	4.13E+01	1.96E+01	5.12E-02	6.03E-02	4.58E-02	7.45E-01
	4.06E+01	3.07E+01	2.75E-02	2.96E-02	2.65E-02	4.11E-01
	4.13E+01	4.00E+01	2.74E-02	2.89E-02	2.79E-02	3.52E-01
	4.00E+01	4.99E+01	2.56E-02	2.68E-02	2.68E-02	3.19E-01
5% Surrogate #1	7.11E+00	3.17E+01	6.01E-01	5.69E-01	6.86E-01	5.71E+00
9% Bentonite	8.36E+00	6.27E+01	1.87E-01	1.79E-01	2.16E-01	2.32E+00
	9.28E+00	9.44E+01	9.79E-02	9.50E-02	1.15E-01	1.39E+00
	9.88E+00	1.23E+02	6.42E-02	6.31E-02	7.78E-02	9.76E-01
	8.88E+00	1.32E+02	5.85E-02	5.82E-02	7.25E-02	9.33E-01
	4.14E+01	2.42E+01	8.21E-01	8.67E-01	8.61E-01	8.41E+00
	4.03E+01	4.75E+01	2.32E-01	2.36E-01	2.63E-01	2.90E+00
	3.88E+01	7.30E+01	1.12E-01	1.12E-01	1.27E-01	1.47E+00
	4.30E+01	9.53E+01	6.83E-02	6.94E-02	7.98E-02	1.03E+00
	3.47E+01	1.24E+02	4.60E-02	4.62E-02	5.51E-02	7.27E-01
	2.03E+01	2.76E+01	5.15E-01	4.78E-01	6.05E-01	6.13E+00
	2.05E+01	5.45E+01	1.55E-01	1.42E-01	1.82E-01	1.91E+00
	2.00E+01	8.48E+01	7.65E-02	7.26E-02	9.25E-02	1.12E+00
	2.09E+01	1.12E+02	4.65E-02	4.55E-02	5.81E-02	6.97E-01
	2.13E+01	1.34E+02	3.79E-02	3.56E-02	4.66E-02	6.11E-01
5% Surrogate #2	1.93E+01	7.09E+03	3.66E-02	3.05E-02	3.66E-02	

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Table D-2
Dimensionless Result Data of Surrogate Pressure Drop Tests (continued)

Slurry Concentration	T	Re	f-horizontal	f-downward	f-upward	K-bend
	1.98E+01	1.46E+04	2.51E-02	2.41E-02	2.86E-02	6.25E-02
	2.04E+01	2.18E+04	2.24E-02	2.19E-02	2.55E-02	1.70E-01
	2.12E+01	2.42E+04	2.17E-02	2.12E-02	2.48E-02	1.77E-01
25% Surrogate #2	2.47E+01	1.41E+03	2.79E-02	1.46E-01		
	2.46E+01	2.84E+03	2.28E-02	5.02E-02		1.51E-01
	2.43E+01	4.23E+03	2.08E-02	3.10E-02	1.36E-02	1.96E-01
	2.47E+01	4.88E+03	2.00E-02	2.68E-02	1.60E-02	2.05E-01
40% Surrogate #2	1.97E+01	5.79E+02	3.52E-02	2.01E-01		
	2.01E+01	1.19E+03	2.69E-02	5.12E-02	2.79E-03	1.94E-01
	2.04E+01	1.78E+03	2.30E-02	2.90E-02	1.85E-02	2.64E-01
	2.02E+01	1.97E+03	2.20E-02	2.74E-02	1.86E-02	2.48E-01
5% Surrogate #2	3.57E+01	1.19E+03	3.98E-02	4.52E-02	3.04E-02	
5% Bentonite	3.63E+01	2.37E+03	3.08E-02	3.25E-02	3.05E-02	2.15E-01
	3.72E+01	3.49E+03	2.71E-02	2.81E-02	2.87E-02	2.72E-01
	3.79E+01	4.49E+03	2.53E-02	2.59E-02	2.75E-02	2.57E-01
25% Surrogate #2	7.58E+00	1.81E+02	6.34E-02	1.78E-01		4.53E-01
5% Bentonite	7.80E+00	3.59E+02	3.61E-02	6.25E-02	1.34E-02	
	8.08E+00	5.49E+02	3.53E-02	4.60E-02	2.66E-02	3.82E-01
	2.56E+01	1.78E+02	3.79E-02	1.34E-01		
	2.59E+01	3.48E+02	3.27E-02	5.80E-02	8.54E-03	1.66E-01
	2.59E+01	5.15E+02	2.84E-02	3.82E-02	2.10E-02	2.47E-01
	2.55E+01	5.96E+02	2.65E-02	3.41E-02	2.17E-02	2.62E-01
	3.95E+01	1.66E+02	3.14E-02	1.47E-01		1.20E-01
	3.96E+01	3.21E+02	2.87E-02	5.94E-02	1.94E-03	2.26E-01
	3.96E+01	4.87E+02	2.61E-02	3.91E-02	1.61E-02	2.40E-01
	3.92E+01	5.87E+02	2.46E-02	3.37E-02	1.86E-02	2.57E-01
40% Surrogate #2	2.07E+01	2.24E+01	1.56E-01	1.92E-01	1.08E-01	2.32E+00
5% Bentonite	2.07E+01	4.32E+01	6.00E-02	6.00E-02	6.20E-02	8.85E-01
	2.01E+01	6.33E+01	3.82E-02	3.75E-02	4.52E-02	4.49E-01
	4.02E+01	2.24E+01	1.25E-01	1.66E-01	7.54E-02	1.89E+00
	4.04E+01	4.11E+01	5.23E-02	5.90E-02	5.02E-02	8.57E-01
	3.90E+01	6.46E+01	3.33E-02	3.54E-02	3.73E-02	4.62E-01

Table D-2
Dimensionless Result Data of Surrogate Pressure Drop Tests (continued).

Slurry Concentration	T	Re	f-horizontal	f-downward	f-upward	K-bend
	8.59E+00	2.30E+01	1.99E-01	1.97E-01	1.81E-01	3.19E+00
	9.51E+00	4.60E+01	7.93E-02	8.36E-02	8.82E-02	1.34E+00
5% Surrogate #2	9.09E+00	4.56E+01	1.75E-01	1.83E-01	1.70E-01	9.87E-01
10% Bentonite	9.59E+00	9.44E+01	6.62E-02	6.91E-02	7.24E-02	6.38E-01
	1.02E+01	1.37E+02	4.43E-02	4.64E-02	5.10E-02	4.60E-01
	1.09E+01	1.57E+02	3.84E-02	3.96E-02	4.43E-02	3.15E-01
	1.93E+01	4.24E+01	1.55E-01	1.68E-01	1.40E-01	4.80E-01
	1.94E+01	9.24E+01	4.97E-02	5.54E-02	5.46E-02	5.48E-01
	2.02E+01	1.45E+02	3.36E-02	3.47E-02	3.85E-02	1.36E-01
	2.09E+01	1.61E+02	3.24E-02	3.69E-02	3.93E-02	4.09E-01
	4.11E+01	3.64E+01	2.26E-01	2.43E-01	2.10E-01	1.63E+00
	4.11E+01	7.76E+01	6.72E-02	7.38E-02	7.24E-02	8.42E-01
	4.08E+01	1.12E+02	4.37E-02	4.86E-02	5.08E-02	5.98E-01
	4.02E+01	1.41E+02	3.56E-02	3.83E-02	4.18E-02	3.03E-01

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APPENDIX E

LOOP TEST DATA REDUCTION PROGRAM SOURCE CODE

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*--------SLURRY FLOW DATA DEDUCTION PROGRAM---Heterogeneous Model-----------*
*Inputs include temperature T1-T5, slurry flow rate, coolant flow rate,
*pressure drops(DP1-DP4), gage pressure at in and out of the loop(P1,P2)
*Outputs include Re, friction factors for horizontal straight, vertical
*straight, vertical bend, horizontal bend, and prediction of correlation for
*horizontal pipe.
*
      DIMENSION T1(120),T2(120),T3(120),T4(120),T5(120),SF(120)
      DIMENSION DP1(120),DP2(120),DP3(120),DP4(120),CF(120),P1(120)
      DIMENSION RE(120),FH(120),FVD(120),FVU(120),BK(120),TM(120)
      DIMENSION V(120),HDP(120),VDPD(120),BDP(120),
     *   VDPU(120),ANM(120),P2(120)
*
*     geometric data
*
      DATA BR,DT,PI,SL,HBL,VBL,VH1,VH2/0.14,0.02189,3.1415927,1.9685,
     *   1.9716,2.5431,2.2225,1.9685/
      DATA HBL1,HBL2,VBL1,VBL2/1.5113,0.2413,2.0828,0.2413/
      DATA RW0,RHOS,CD/998.3454,2.7E+03,1.0/
*
*     Input Data
*
      OPEN(7,FILE='c:\project\rheology\program\INPUT.DAT')
      READ(7,*) N,CS,CB
      DO 10 I=1,N
      READ(7,*) T1(I),T2(I),T3(I),T4(I),T5(I),DP1(I),DP2(I),DP3(I),
     *   DP4(I),SF(I),CF(I),P1(I),P2(I)
 10   CONTINUE
*
*     Unit Conversion
*
      OPEN(8,FILE='c:\project\rheology\program\FACTOR.DAT')
      OPEN(9,FILE='c:\project\rheology\program\GRADIENT.DAT')
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```
      DO 20 I=1,N
      TM(I)=(T2(I)+T3(I))/2.
      DP1(I)=DP1(I)*249.07
      DP2(I)=DP2(I)*249.07
      DP3(I)=DP3(I)*249.07
      DP4(I)=DP4(I)*249.07
      P1(I)=P1(I)*6901.12
      P2(I)=P2(I)*6901.12
      SF(I)=SF(I)*6.309E-05
      CF(I)=CF(I)*6.309E-05
 20   CONTINUE
*
*      Reynolds Number and Friction Factor Calculation
*
      C=(CS+CB)/100
      ANW0=(1.57938-0.0358386*20+3.85119E-04*20**2-1.57828E-06
     * *20**3)*1.E-06
*
      DO 50 I=1,N
      RHOW=1001.98-0.11685*TM(I)-0.003244*TM(I)**2
*     RHOM=997.9+230*C+900*C**2
*     RHOM=992.92+29.147*C+2225.7*C**2
      RHOM=971.1+599.4*C+310.02*C**2
*     RHOM=(1.1146+0.0124*C)*1000
      ANW=(1.57938-0.0358386*TM(I)+3.85119E-04*TM(I)**2-1.57828E-06
     * *TM(I)**3)*1.E-06
      PHI=RHOM*C/RHOS
*     ANM(I)=(3.1429-0.0376*TM(I)+0.0005*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(9.9709-0.2739*TM(I)+0.0078*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(16.418-0.1288*TM(I)+0.0061*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(60.884+2.7709*TM(I)-0.0354*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(9.172+0.373*TM(I)-0.004*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(116.3-4.7579*TM(I)+0.1706*TM(I)**2)*ANW0*RW0/RHOM
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*     ANM(I)=(693.85-6.8037*TM(I)+0.0852*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(260.16+3.2577*TM(I)-0.0122*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(243.65+0.6127*TM(I)-0.0063*TM(I)**2)*ANW0*RW0/RHOM
*-----------------------------------------------------------
*     ANM(I)=(1.263+0.1741*TM(I)-0.0037*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(10.075-0.0279*TM(I)+0.0023*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(22.19+0.1258*TM(I)+0.0004*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(8.3894+0.0474*TM(I)+0.0013*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(1470.2+6.7183*TM(I)-0.0675*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(401.26+4.9995*TM(I)-0.0146*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(1.3894+0.029*TM(I)-0.0003*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(10.617+0.0194*TM(I)+0.0003*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(322.7-3.1254*TM(I)+0.1127*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(9.7926+0.0548*TM(I)-0.0007*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(85.706+0.0465*TM(I)+0.0068*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(22.648+0.2236*TM(I)+0.0026*TM(I)**2)*ANW0*RW0/RHOM
*     ANM(I)=(739.74+1.1839*TM(I)+0.0331*TM(I)**2)*ANW0*RW0/RHOM
      ANM(I)=(782.77-13.194*TM(I)+0.4254*TM(I)**2)*ANW0*RW0/RHOM
*
* Gravity correction
      DP1(I)=DP1(I)-VH1*(RHOM-RW0)*9.81
      DP2(I)=DP2(I)+VH2*(RHOM-RW0)*9.81
*
      V(I)=SF(I)/(PI*DT**2/4)
      REW=V(I)*DT/ANW
      RE(I)=V(I)*DT/ANM(I)
      FH(I)=DP3(I)/SL*DT/(0.5*RHOM*V(I)**2)
      HDP(I)=DP3(I)/249.07/(SL*3.2808)
      BDP(I)=(DP4(I)-DP3(I)/SL*(HBL1+HBL2))/249.07
      BK(I)=(DP4(I)-DP3(I)/SL*(HBL1+HBL2))/(0.5*RHOM*V(I)**2)
      FVD(I)=DP2(I)/SL*DT/(0.5*RHOM*V(I)**2)
      VDPD(I)=DP2(I)/249.07/(SL*3.2808)
      VDPU(I)=(DP1(I)-BDP(I))/(VBL1+VBL2)/(249.07*3.2808)
```

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```
      FVU(I)=(DP1(I)-BDP(I))/(VBL1+VBL2)*DT/(0.5*RHOM*V(I)**2)
      WRITE(8,100) TM(I),RE(I),FH(I),FVD(I),FVU(I),BK(I)
      WRITE(9,100) TM(I),V(I)*3.2808,HDP(I),VDPD(I),VDPU(I),BDP(I)
50    CONTINUE
100   FORMAT(1X,6(E10.4,1X))
      STOP
    END
```

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APPENDIX F

FIGURES REFERENCED IN THIS FINAL REPORT

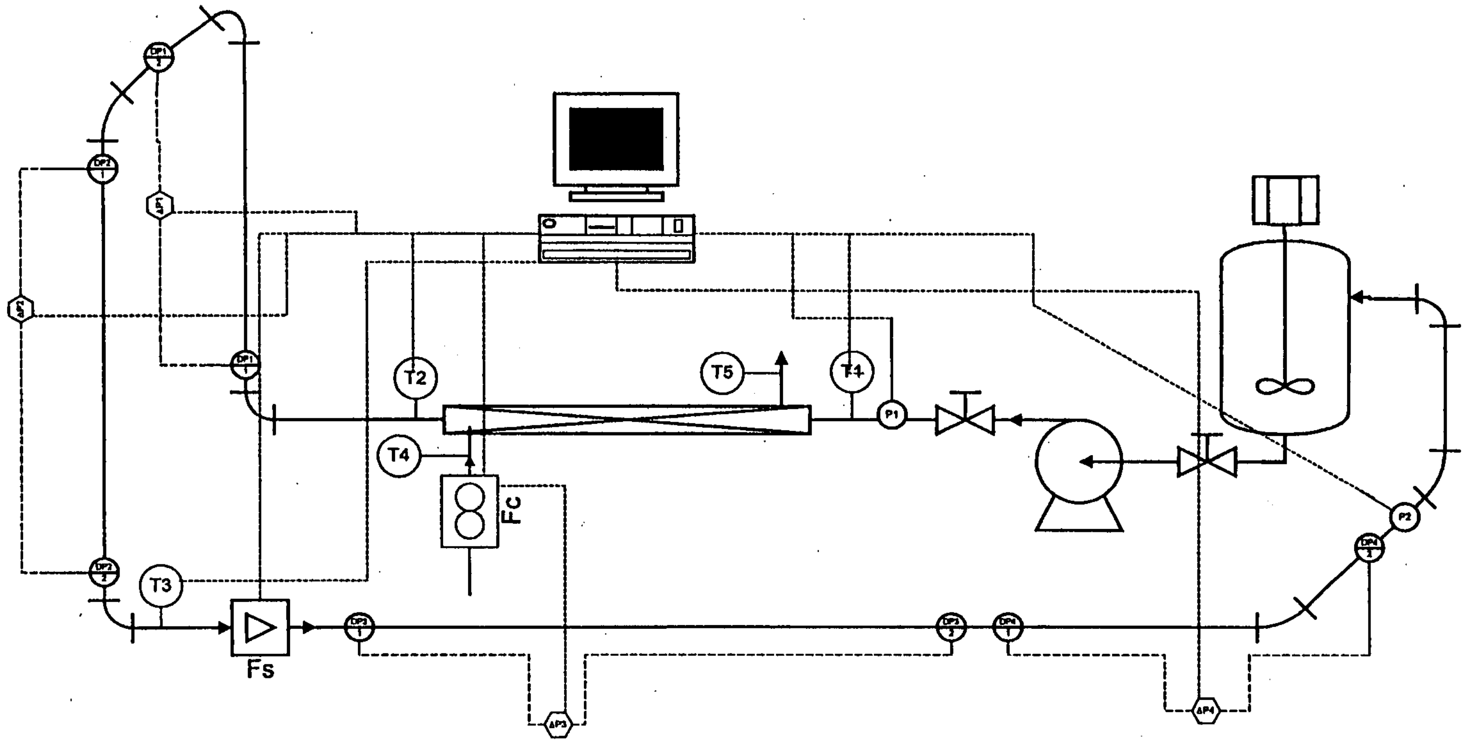

Figure 2.3.1 Diagram of Pressure Drop Test Loops.

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

Figure 2.3.2 Test system for silo material slurry.

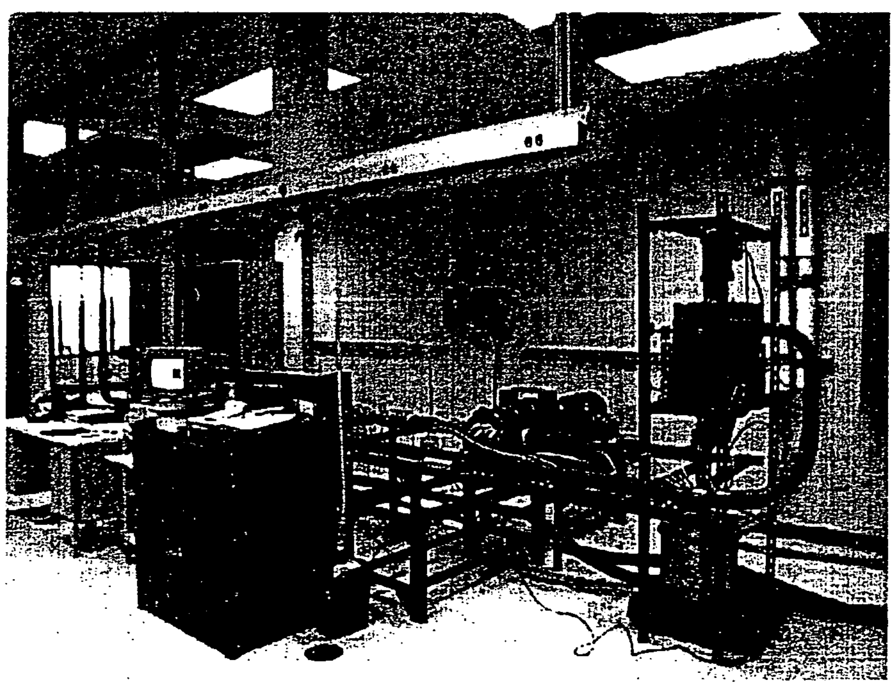

Figure 2.3.3 Test system for surrogate slurry.

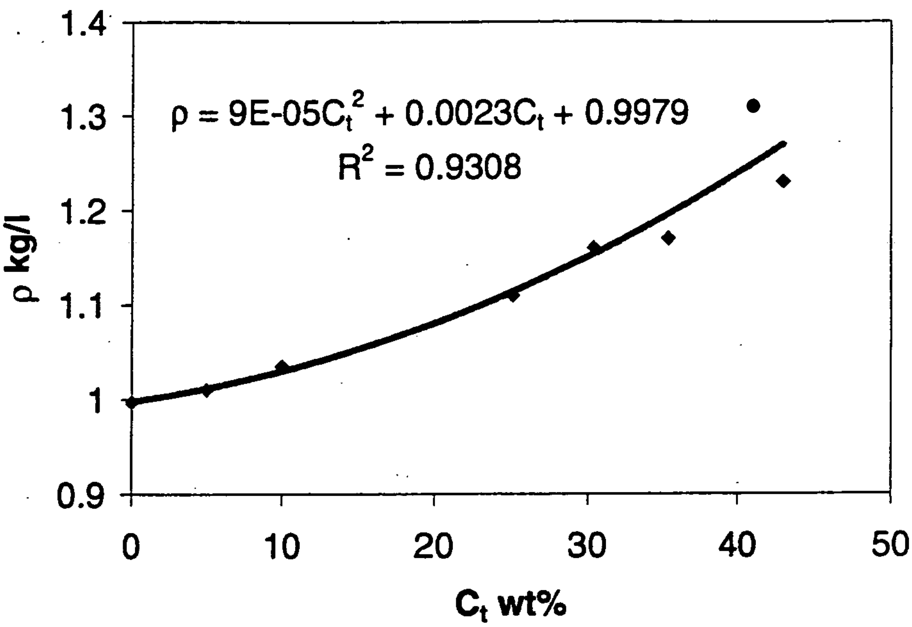

Figure 3.1.1 Density versus K-65 concentration for K-65 slurries with and without bentonite.

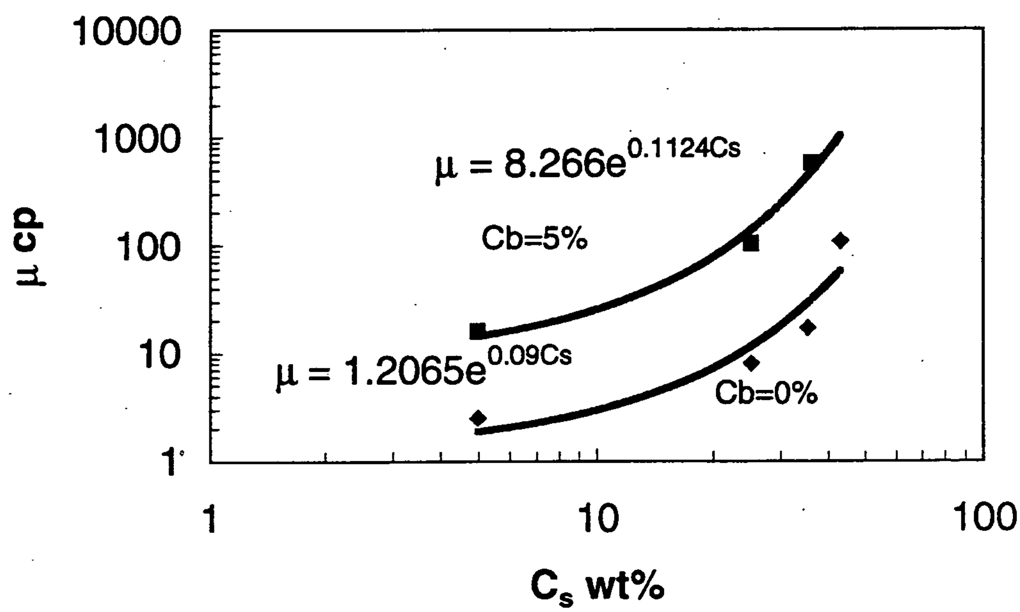

Figure 3.1.2 Viscosity versus K-65 concentration for K-65 slurries with and without bentonite.

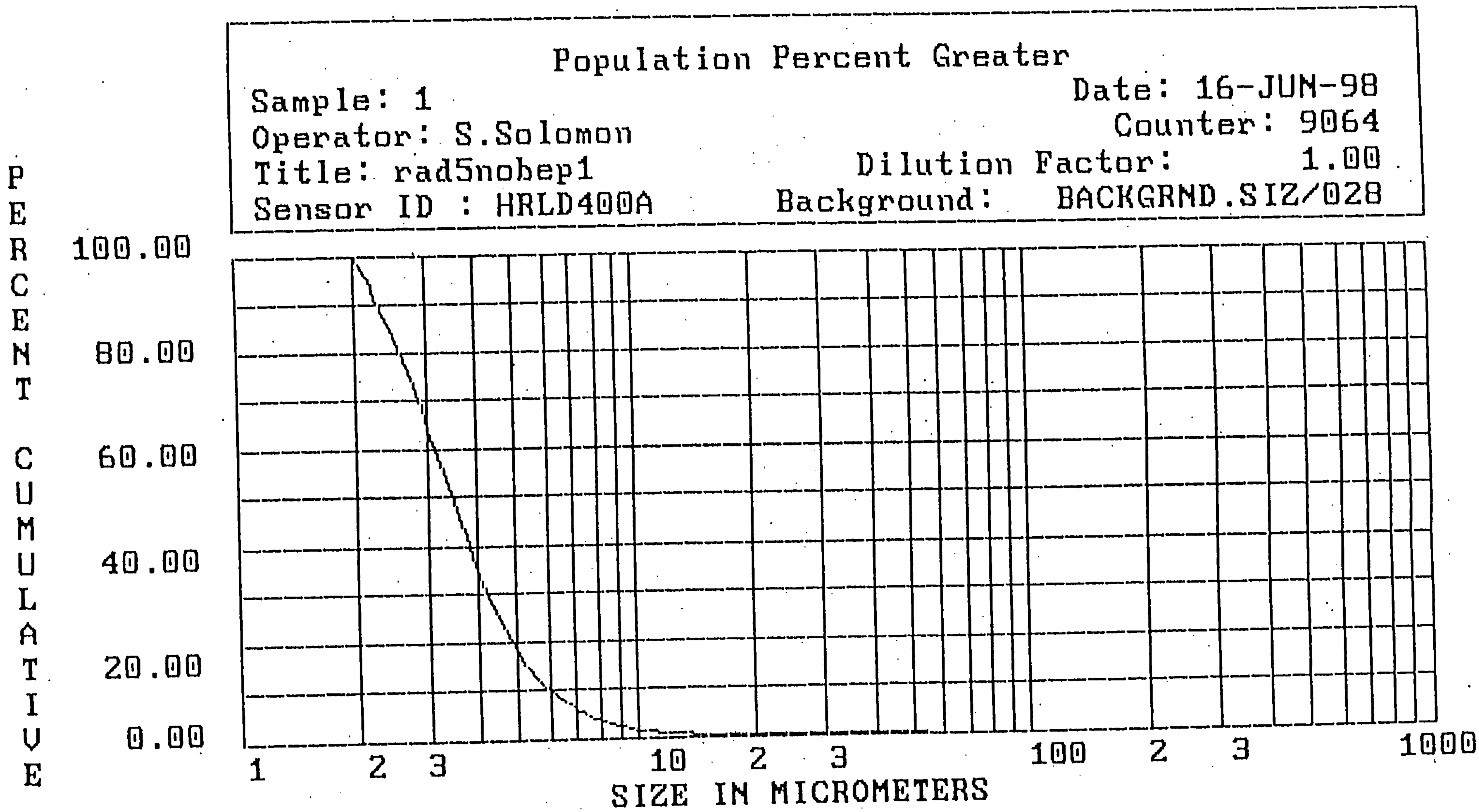

Figure 3.2.1
5% Unpumped K-65 Slurry Without Bentonite Supernatant of Settled Material, at 10mm Depth, Undiluted.

8102

Population Percent Greater

Sample: 1
Operator: S.Solomon
Title: rad5nobep6
Sensor ID : HRLD400A

Date: 16-JUN-98
Counter: 9064
Dilution Factor: 1.00
Background: BACKGRND.SIZ/028

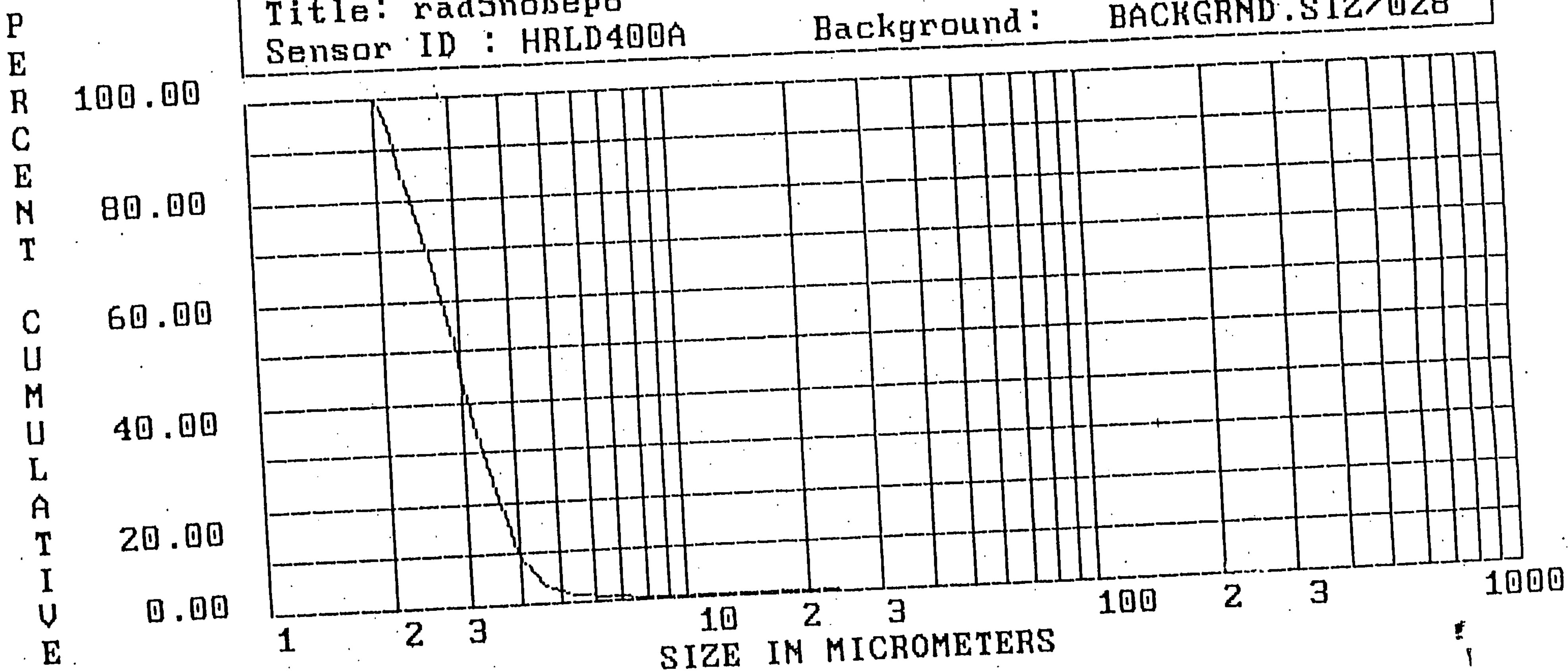

Figure 3.2.2
5% Unpumped K-65 Slurry Without Bentonite-Supernatant of Settled Material, at 60mm Depth Undiluted.

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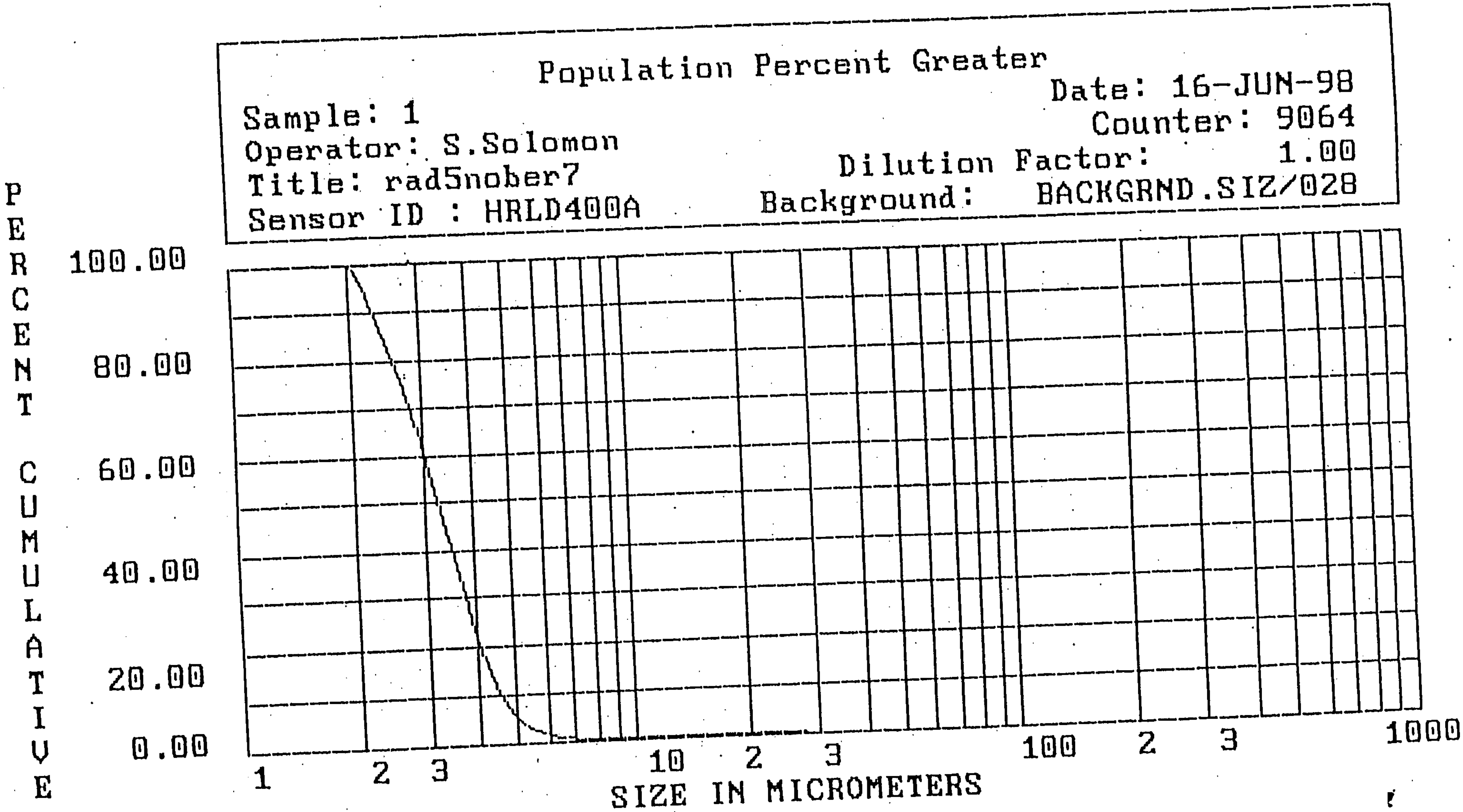

Figure 3.2.3
5% Unpumped K-65 Slurry Without Bentonite - Sample at Top of Solid Settled Material, Undiluted.

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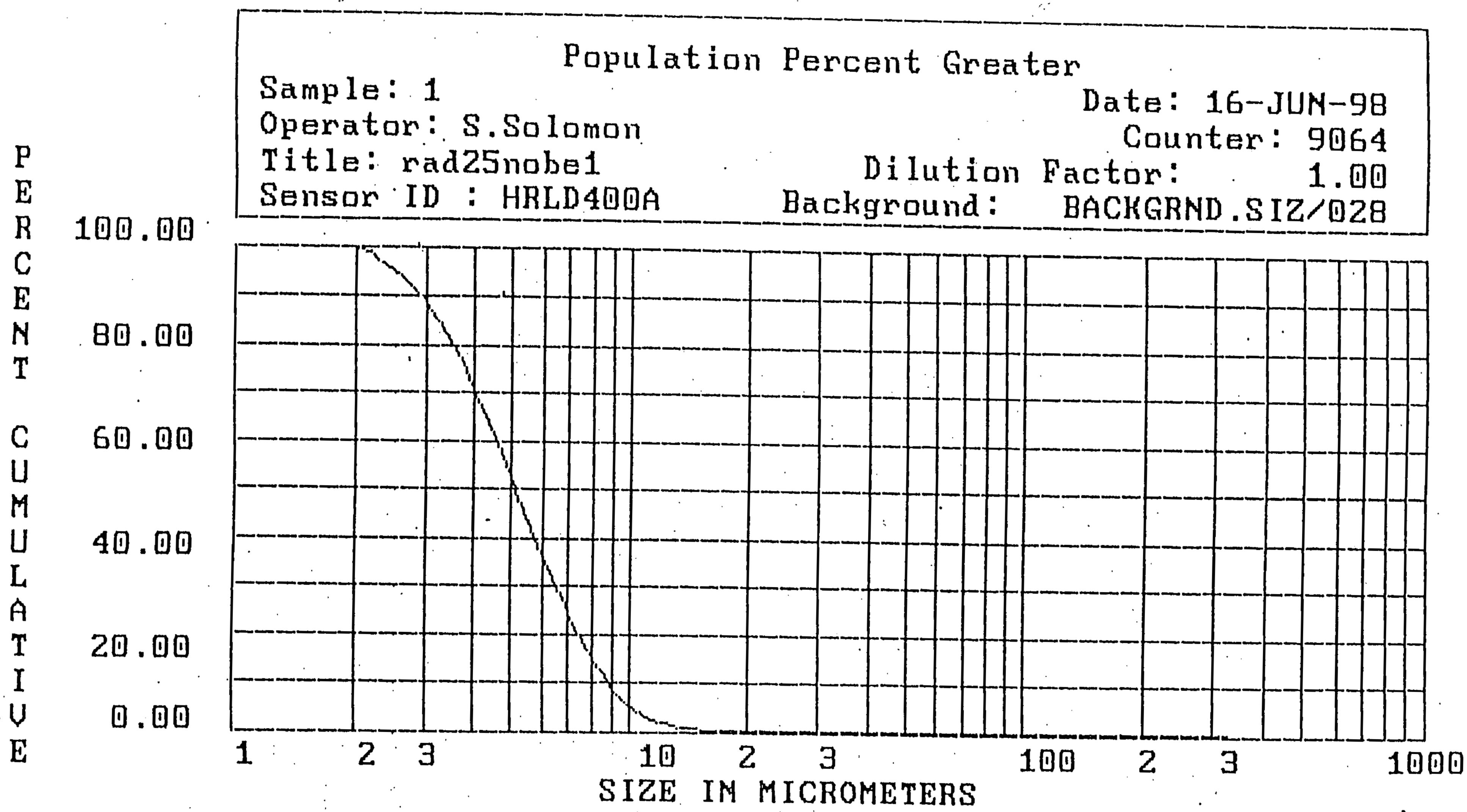

Figure 3.2.4
25% Unpumped K-65 Slurry Without Bentonite - Supernatant of Settled Material, at 10mm Depth, Undiluted.

8102

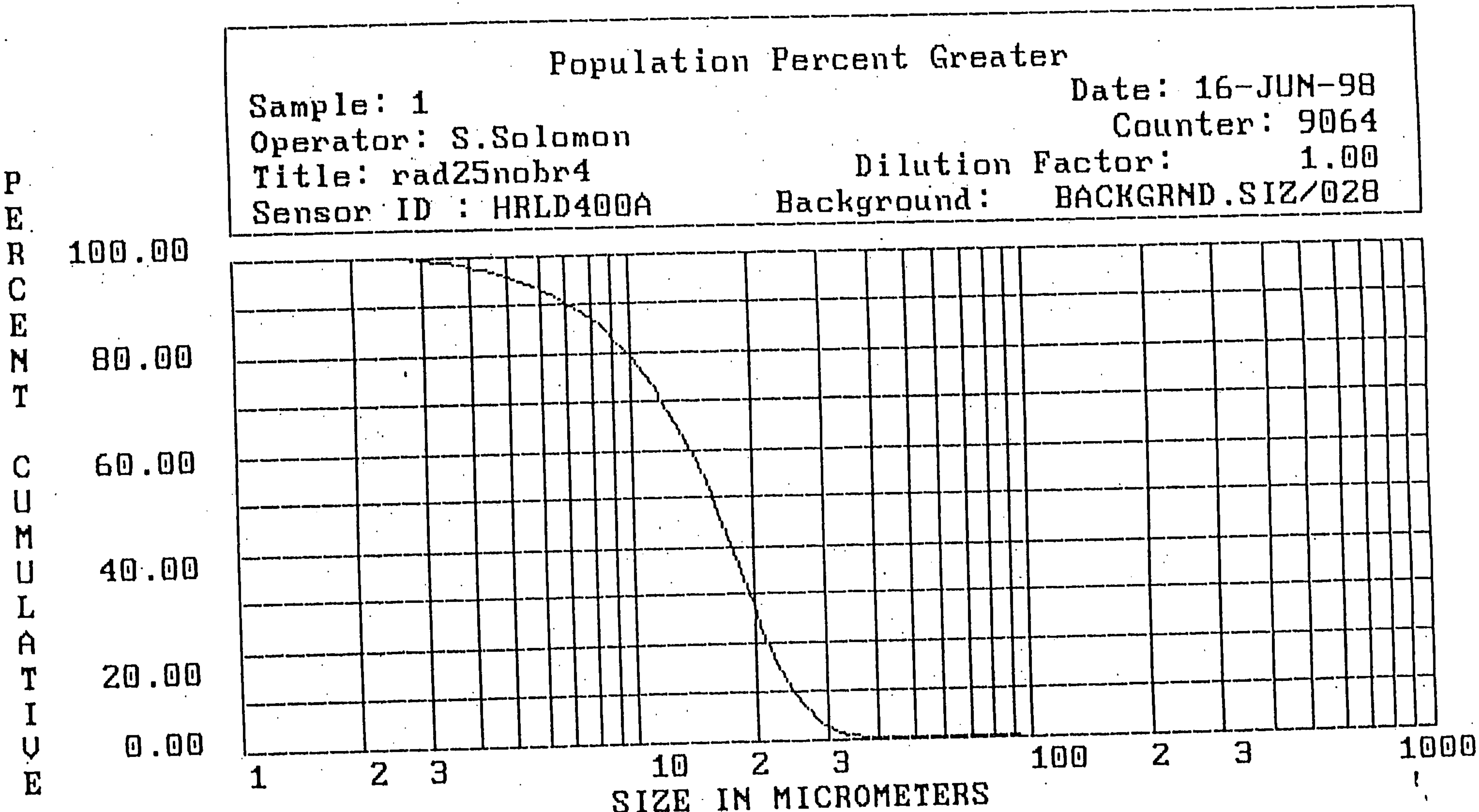

Figure 3.2.5
25% Unpumped K-65 Slurry Without Bentonite – Sample at Top of Solid Settled Material, Undiluted.

8102

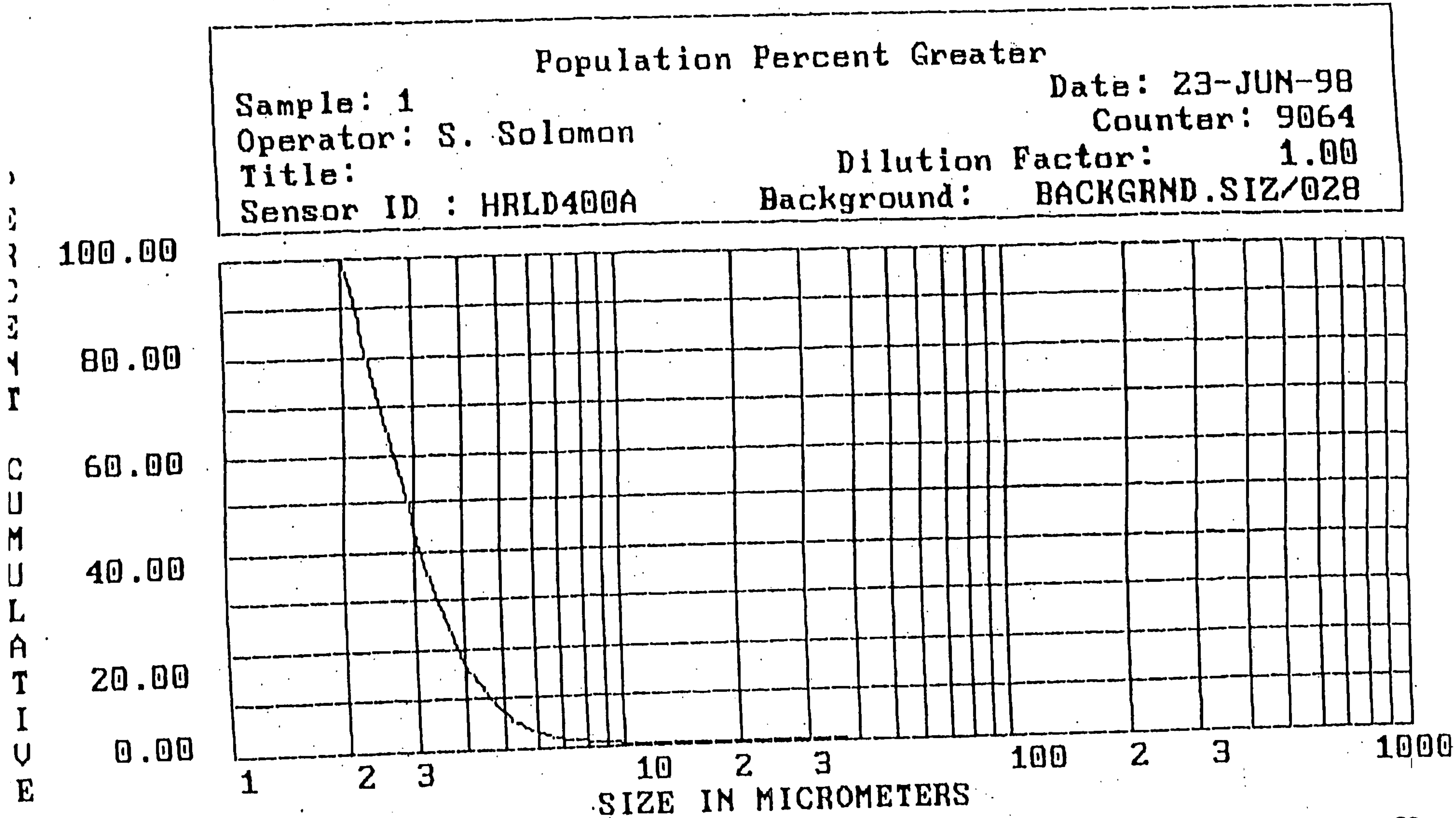

Figure 3.2.6
5% Pumped K-65 With 5% Bentonite-Supernatant of Settled Sample, at 10mm Depth, Undiluted.

8102

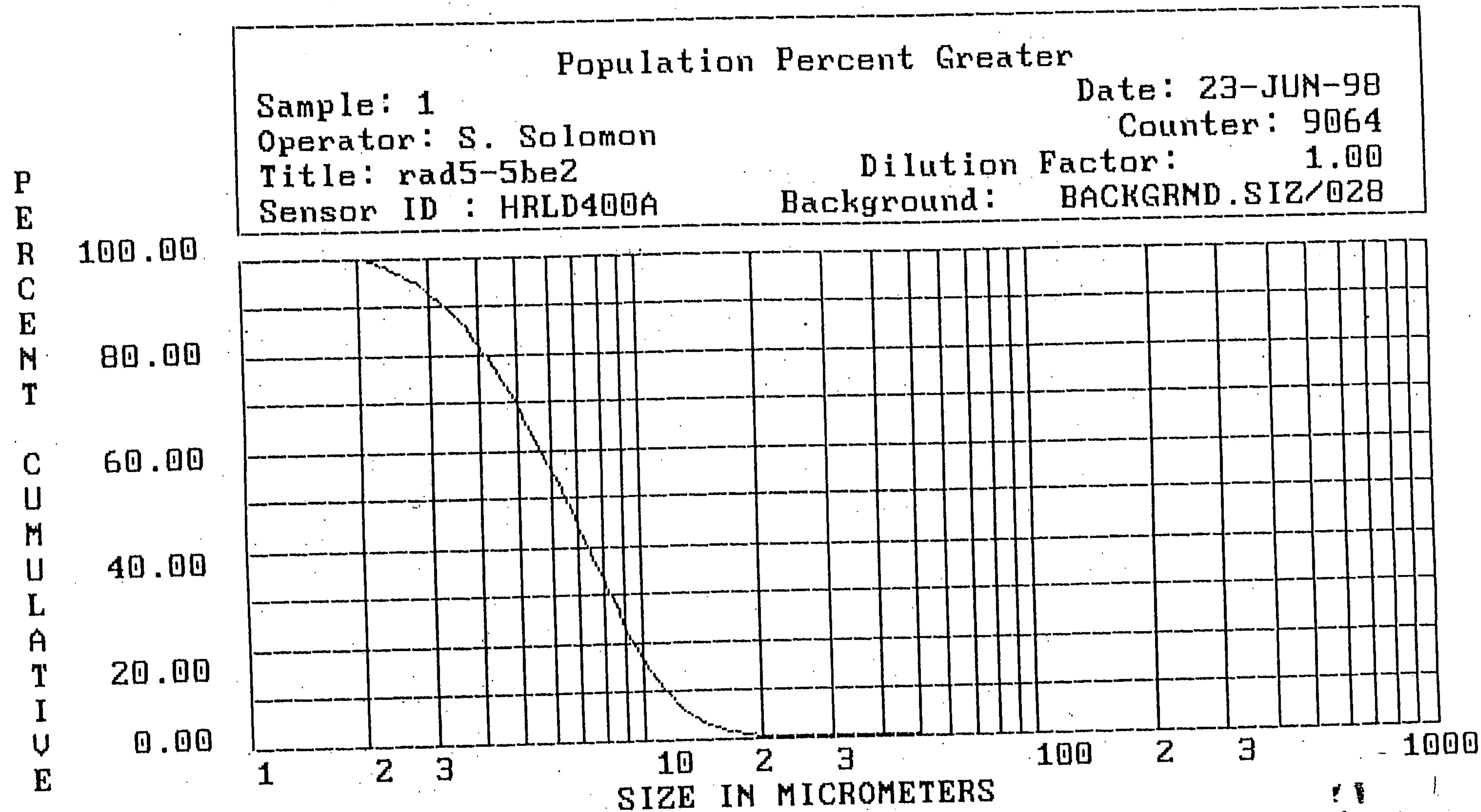

Figure 3.2.7
5% Pumped K-65 With 5% Bentonite – Settled Sample, at Top of Residue, Undiluted.

8102

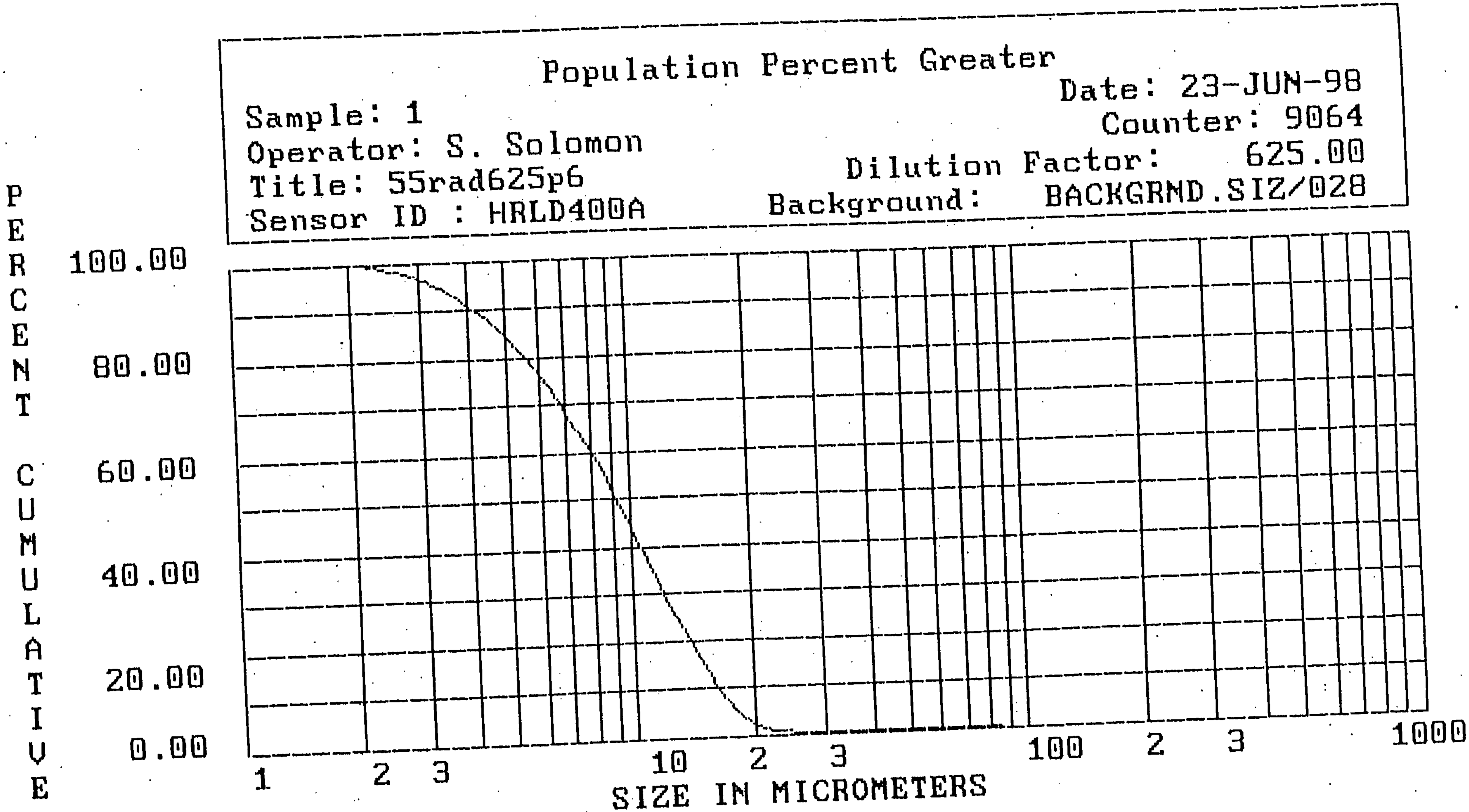

Figure 3.2.8
5% Pumped K-65 With 5% Bentonite – Settled Sample, at Full Depth, Diluted 1:625

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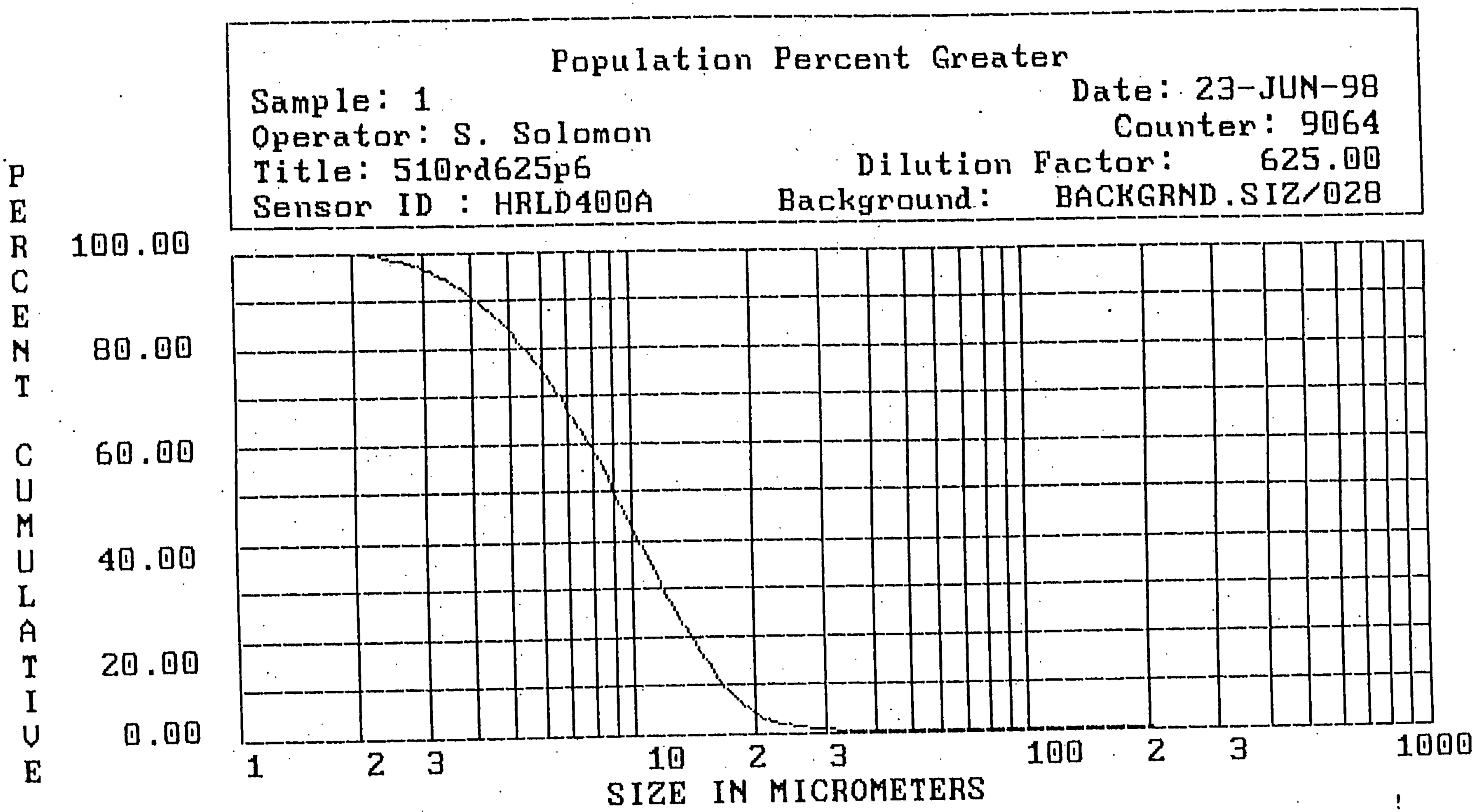

Figure 3.2.9
5% Pumped K-65 With 10% Bentonite – Settled Sample, at Full Depth, Diluted 1:625

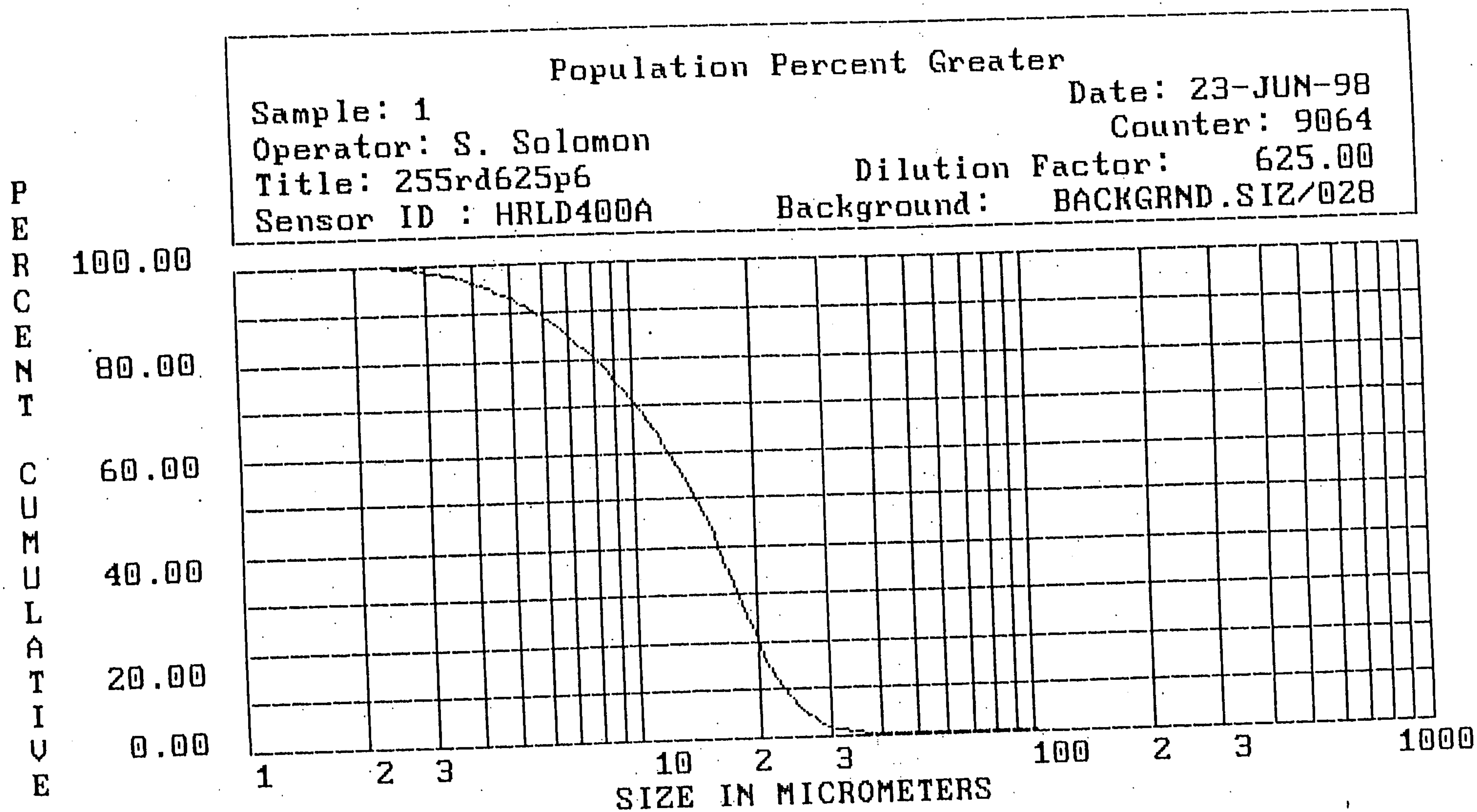

Figure 3.2.10
25% Pumped K-65 With 5% Bentonite – Settled Sample, at Full Depth, Diluted 1:625

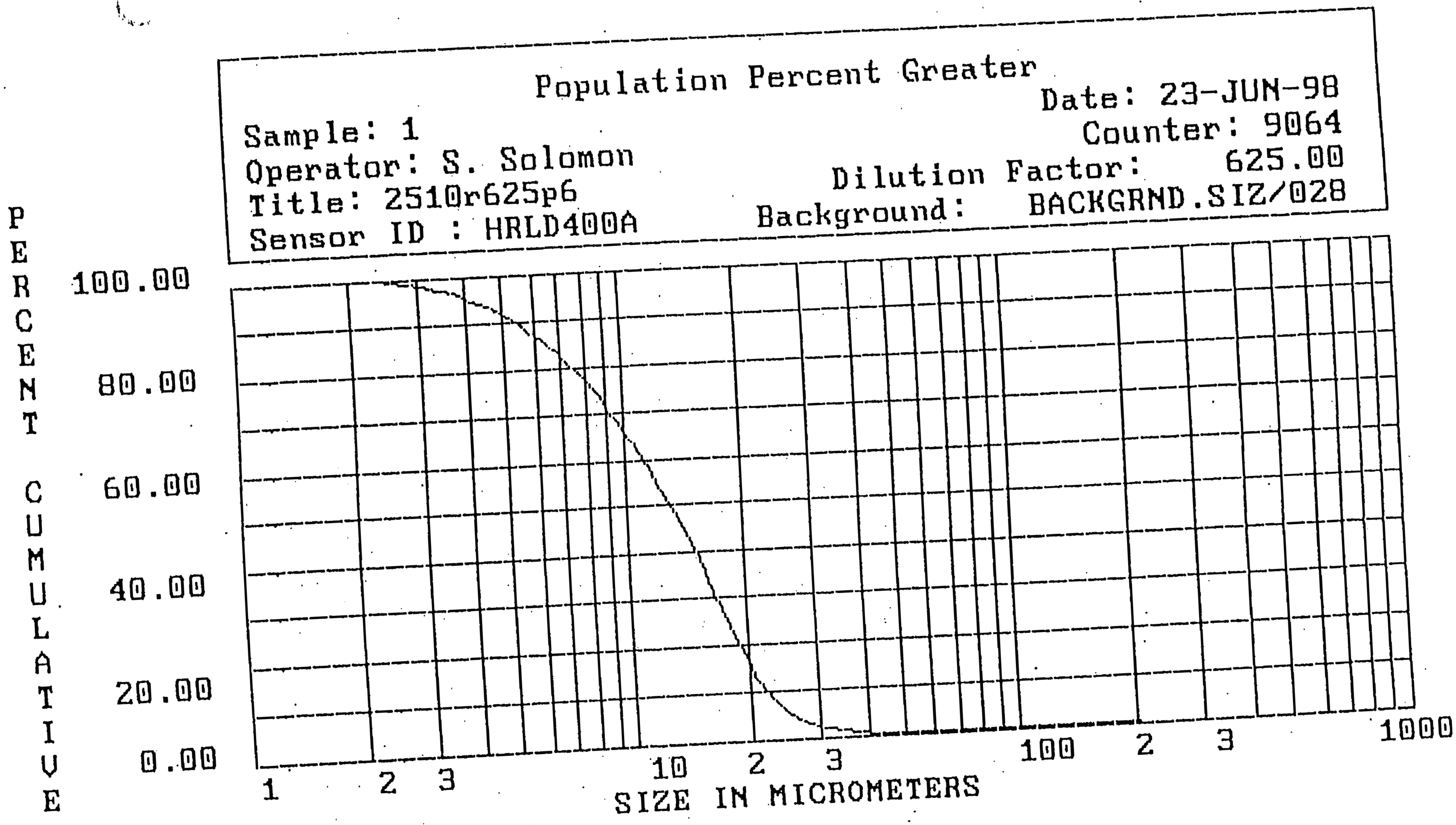

Figure 3.2.11

25% Pumped K-65 With 10% Bentonite -- - Settled Sample, at Full Depth, Diluted 1:625

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Figure 3.3.1: K65-5-T Incremental and Total Settling Distances (H_3)

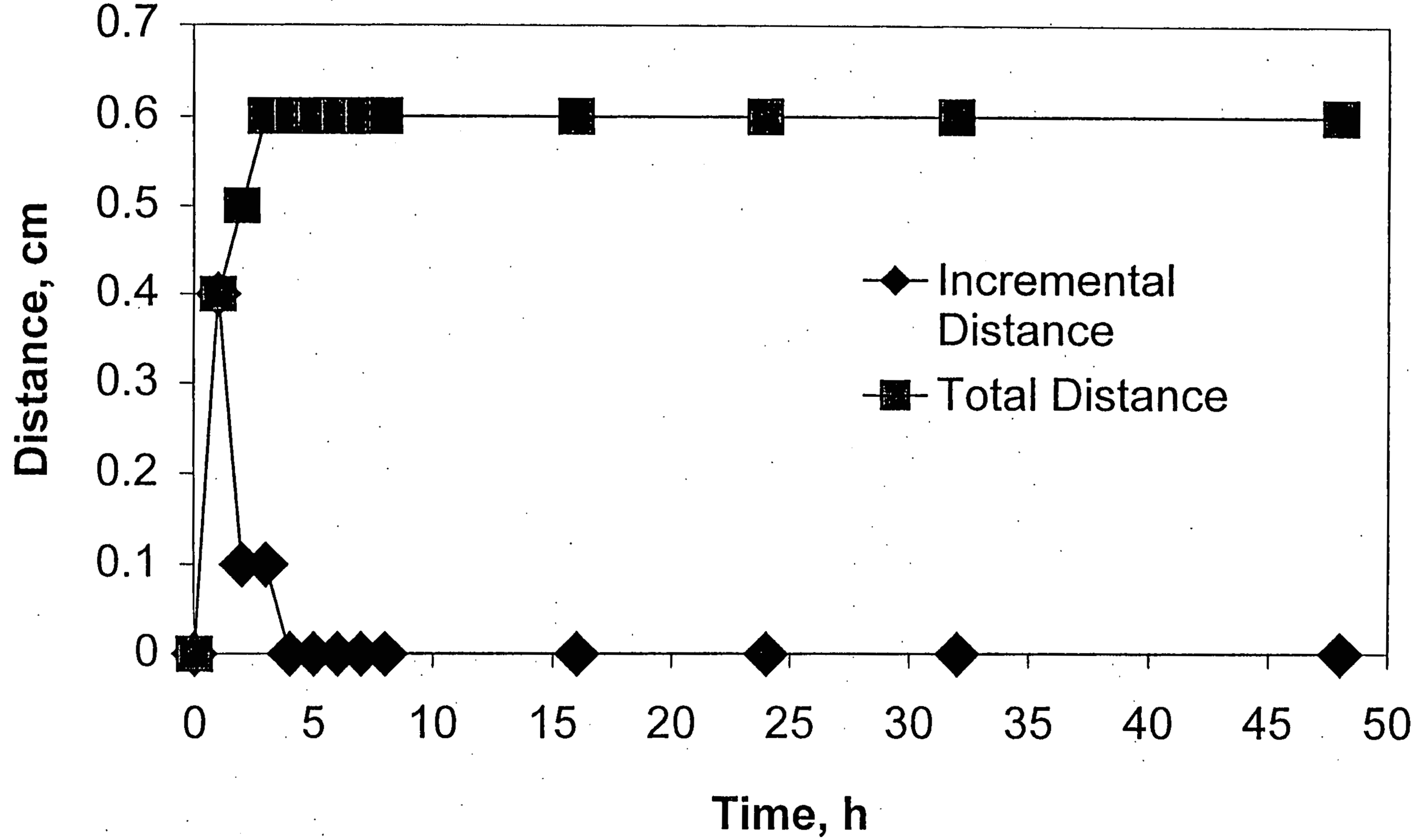

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Figure 3.3.2: K65-5-5-T Incremental and Total Settling Distances (H_3)

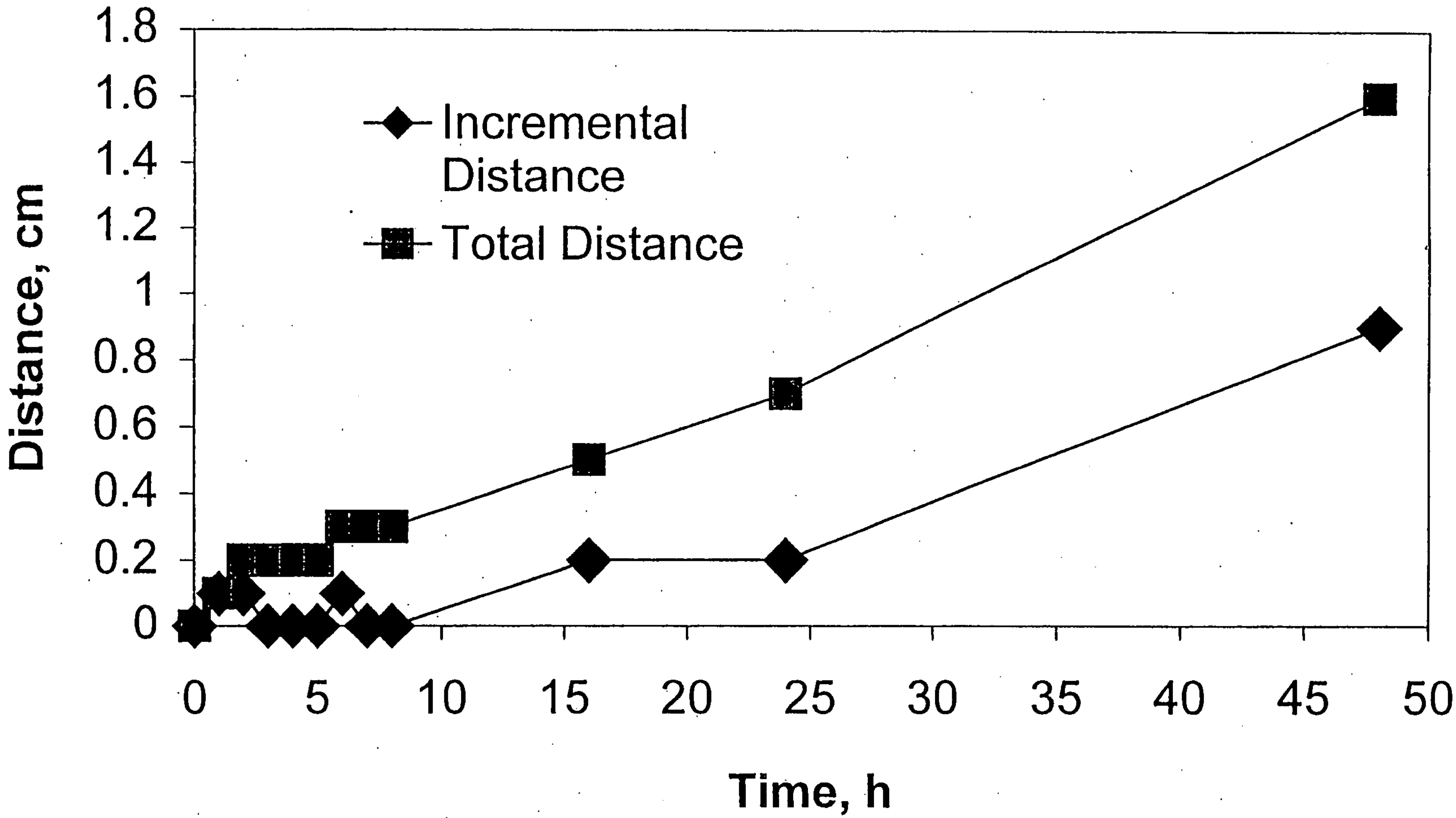

Figure 3.3.3: K65-25-F Incremental and Total Settling Distances (H_3)

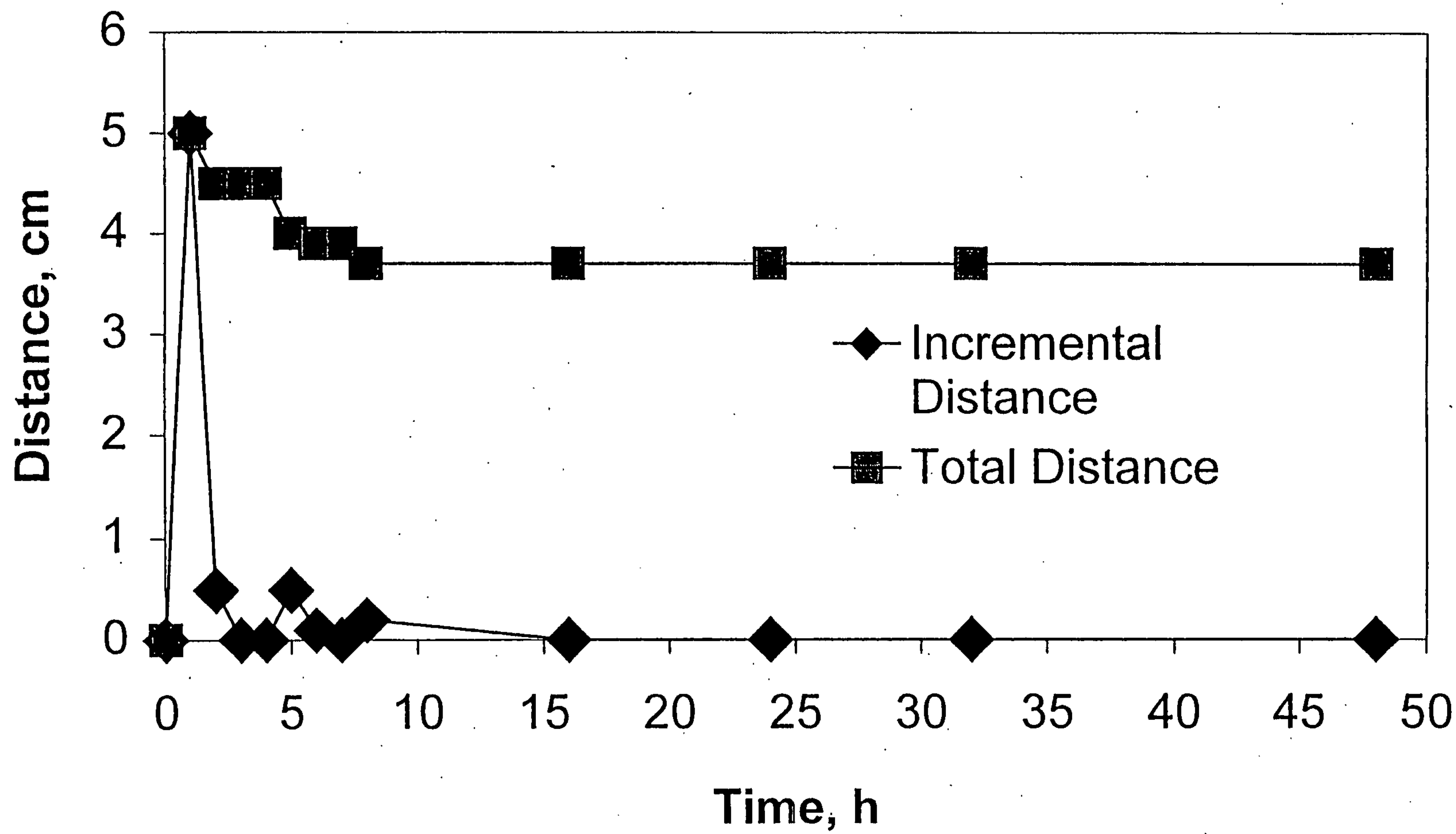

Figure 3.3.4: K65-25-T Incremental and Total Settling Distances (H_3)

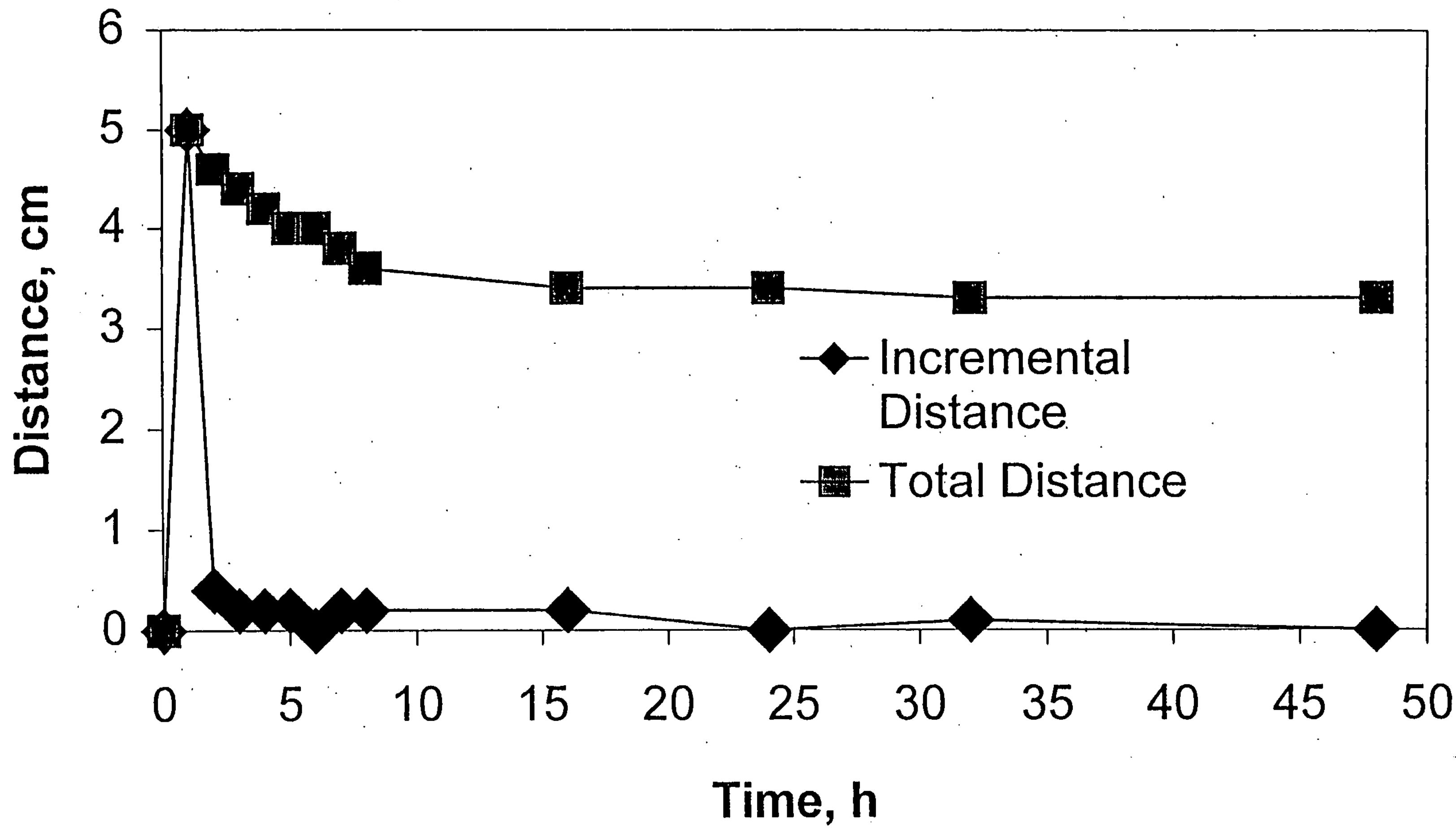

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Figure 3.3.5: K65-25-5-T Incremental and Total Settling Distances (H_3)

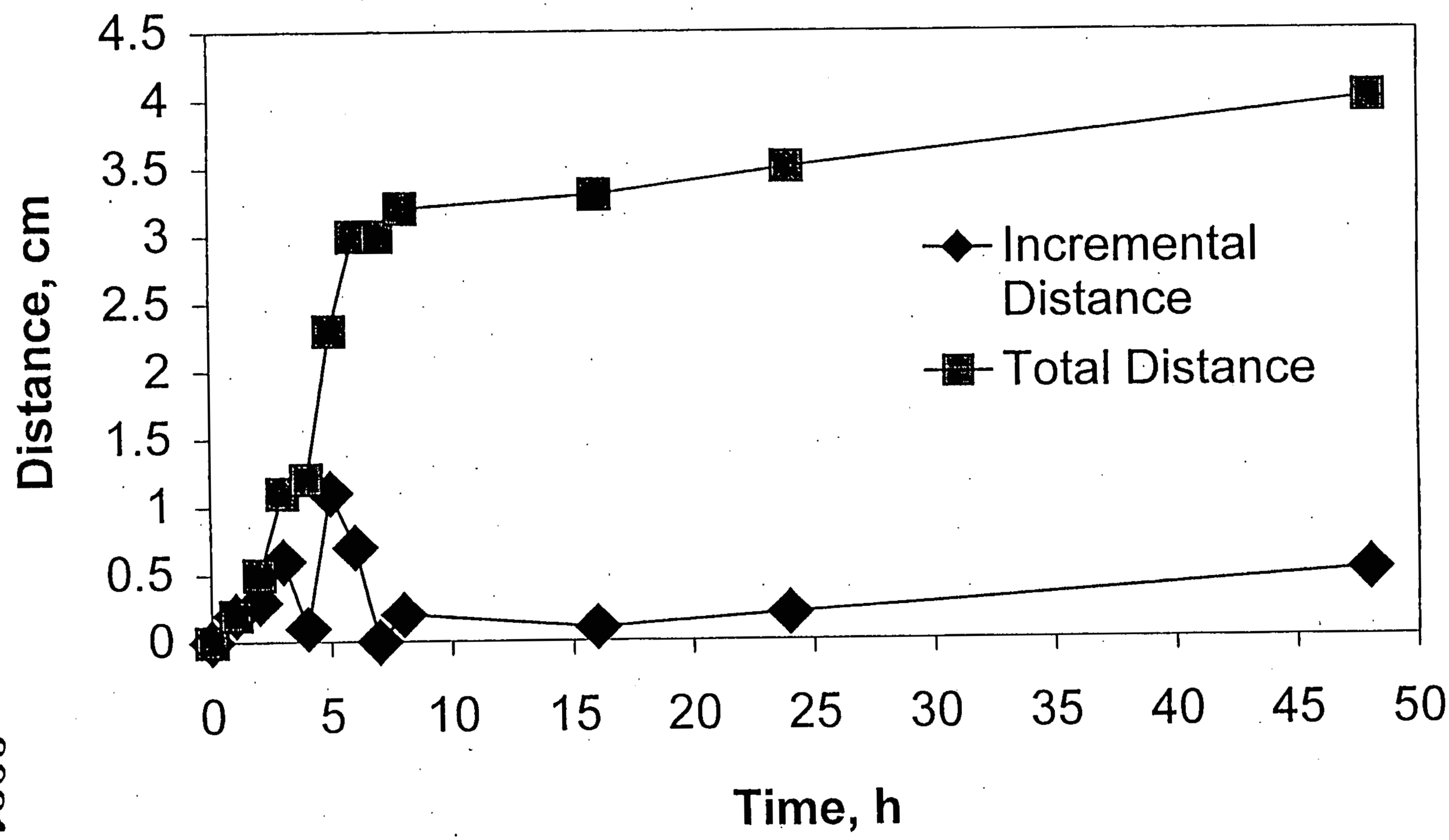

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Figure 3.3.6: K65-35-T Incremental and Total Settling Distances (H_3)

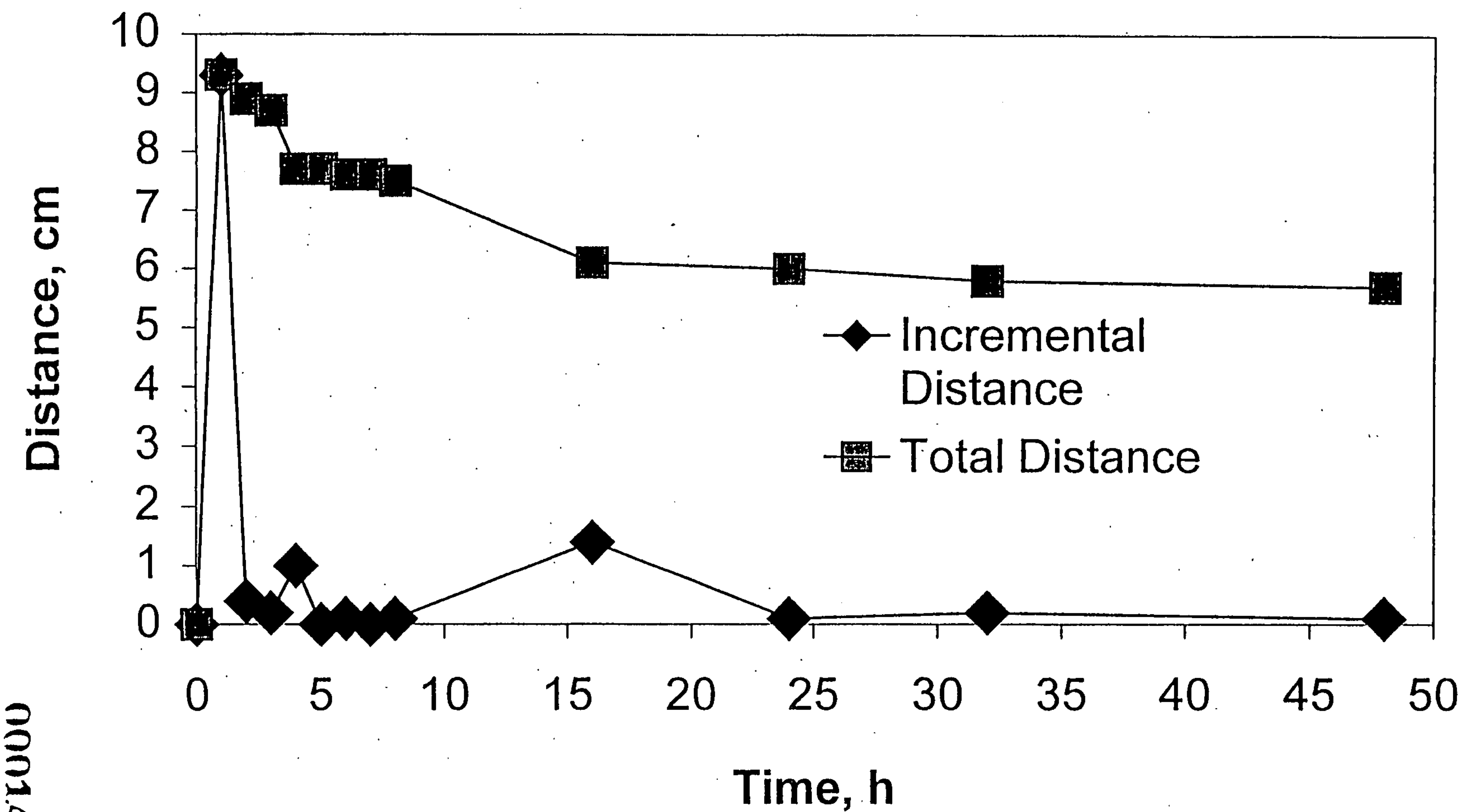

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Figure 3.3.7: K65-40-F Incremental and Total Settling Distances (H_3)

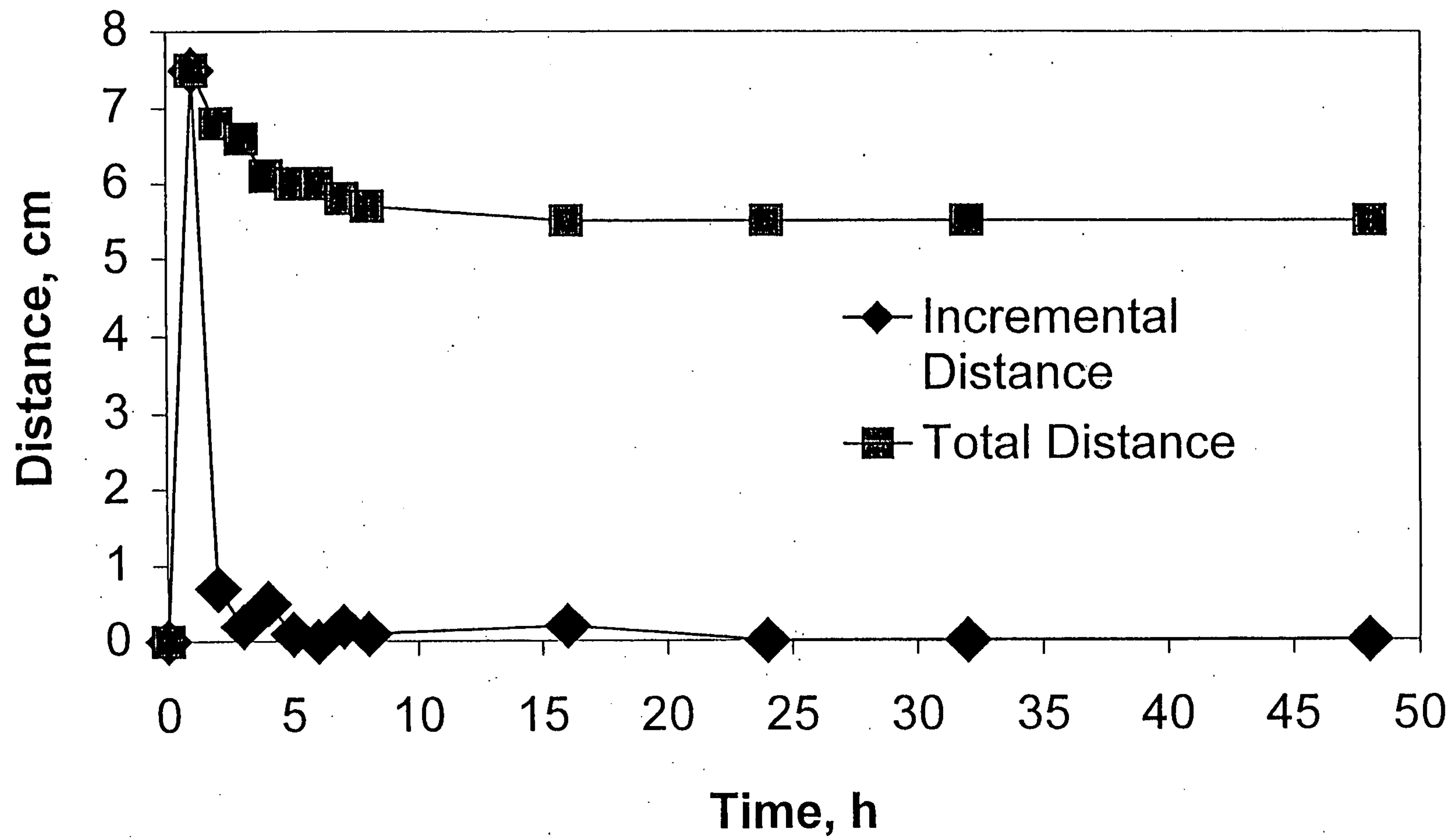

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Figure 3.3.8: K65-40-T Incremental and Total Settling Distances (H_3)

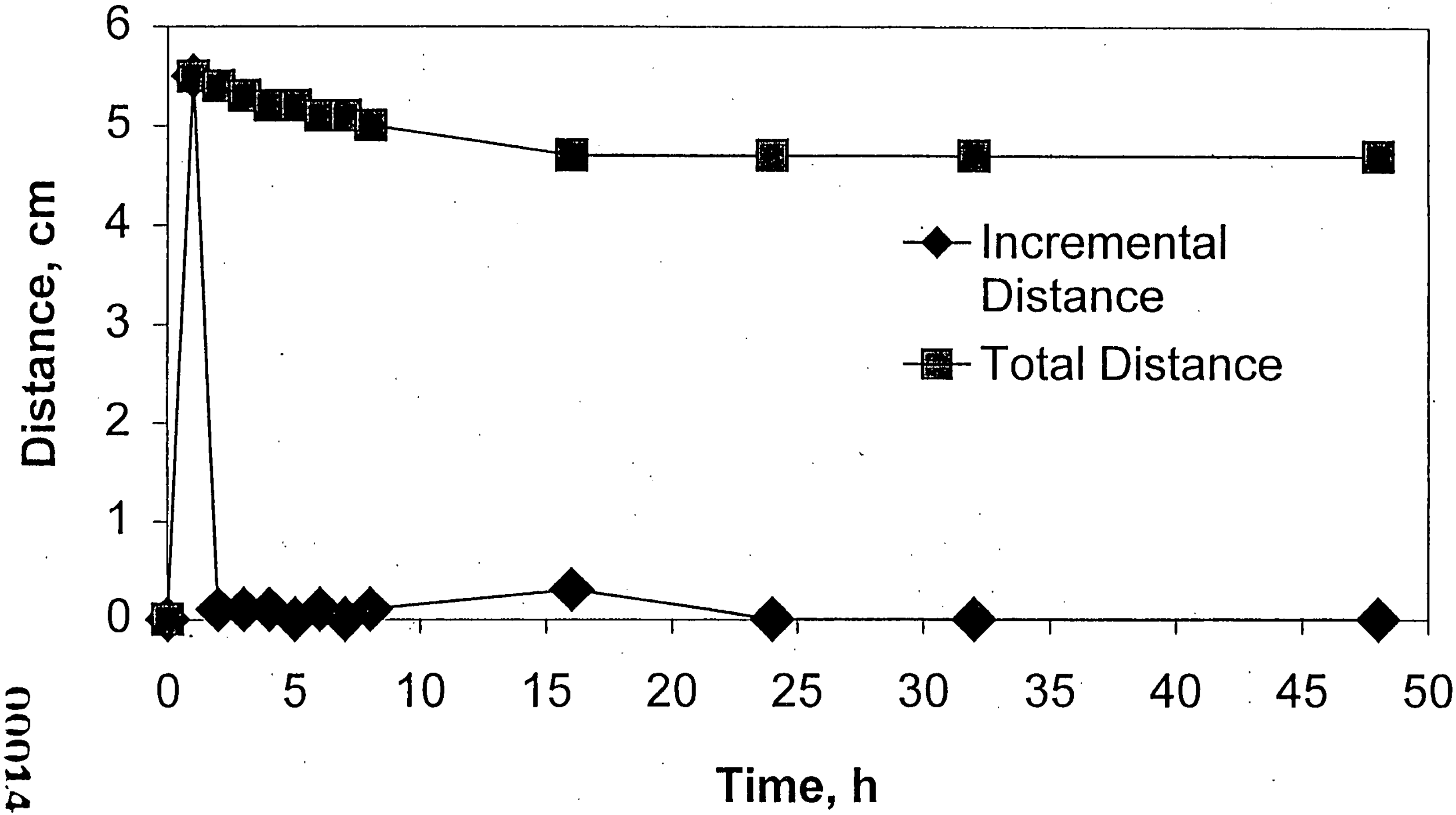

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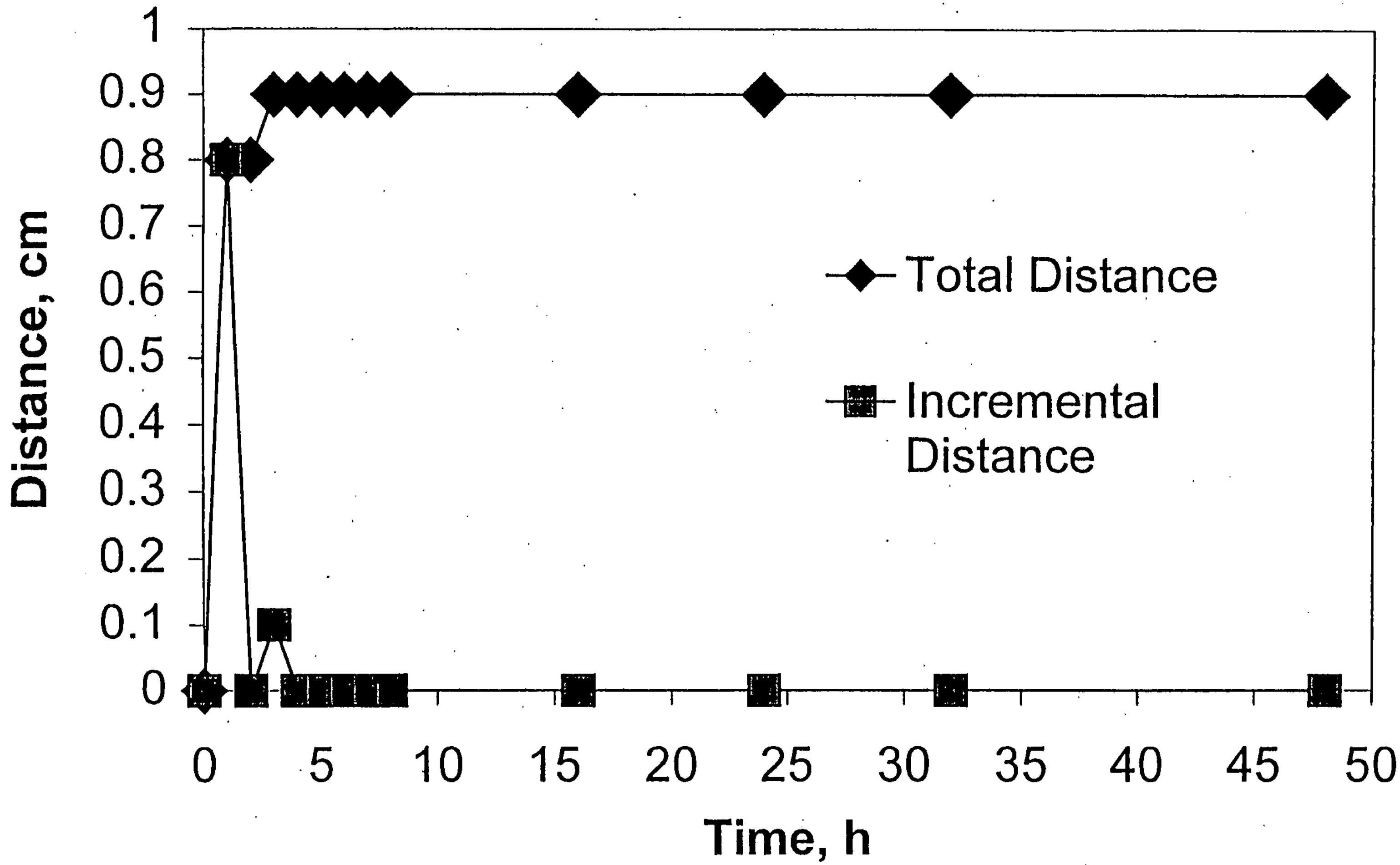
Figure 3.3.9: K65-5-F Incremental and Total Settling Distances (H_3)



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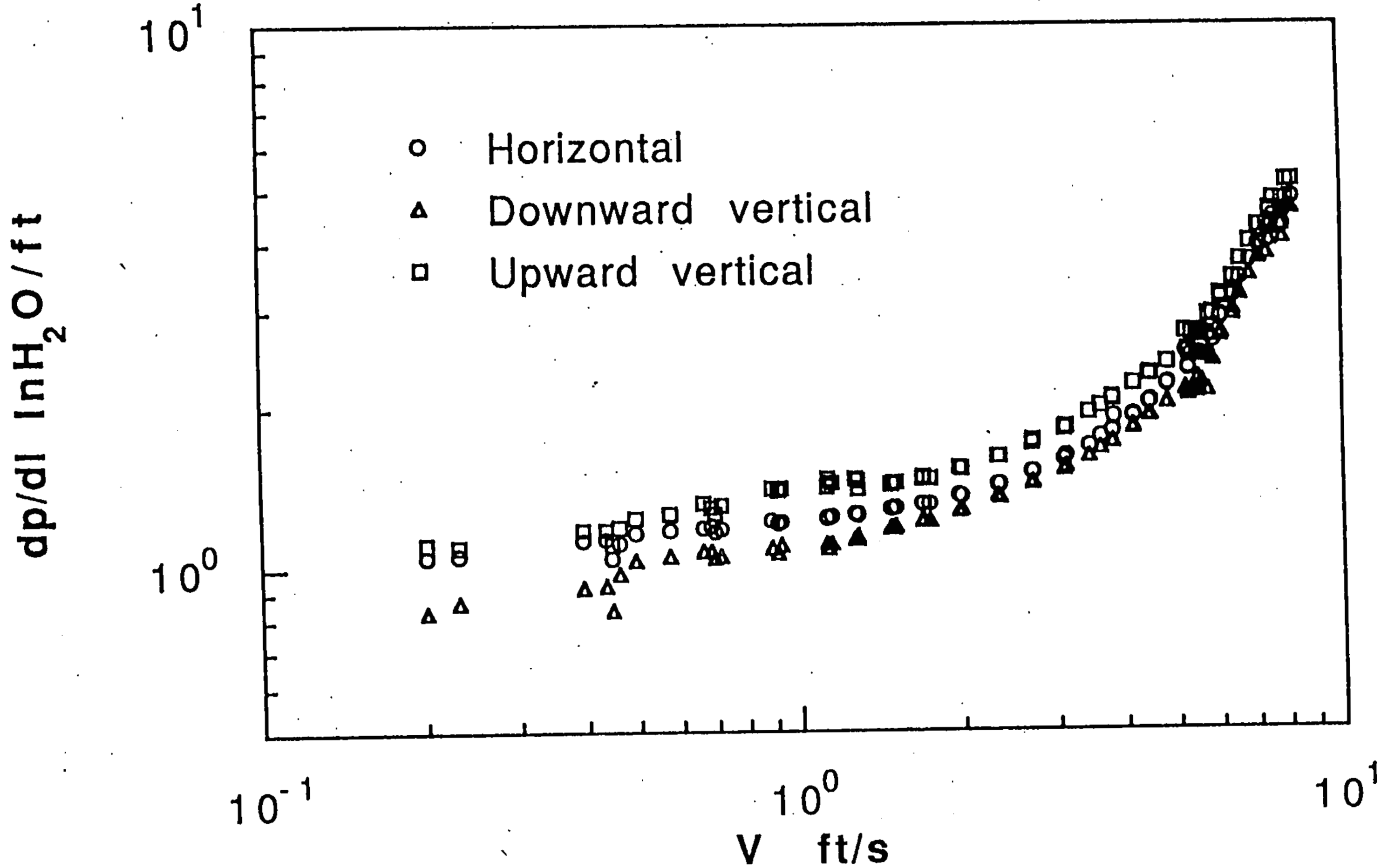

Figure 3.3.10 Pressure gradient variation in the settling test of 5% K-65 and 10% bentonite slurry

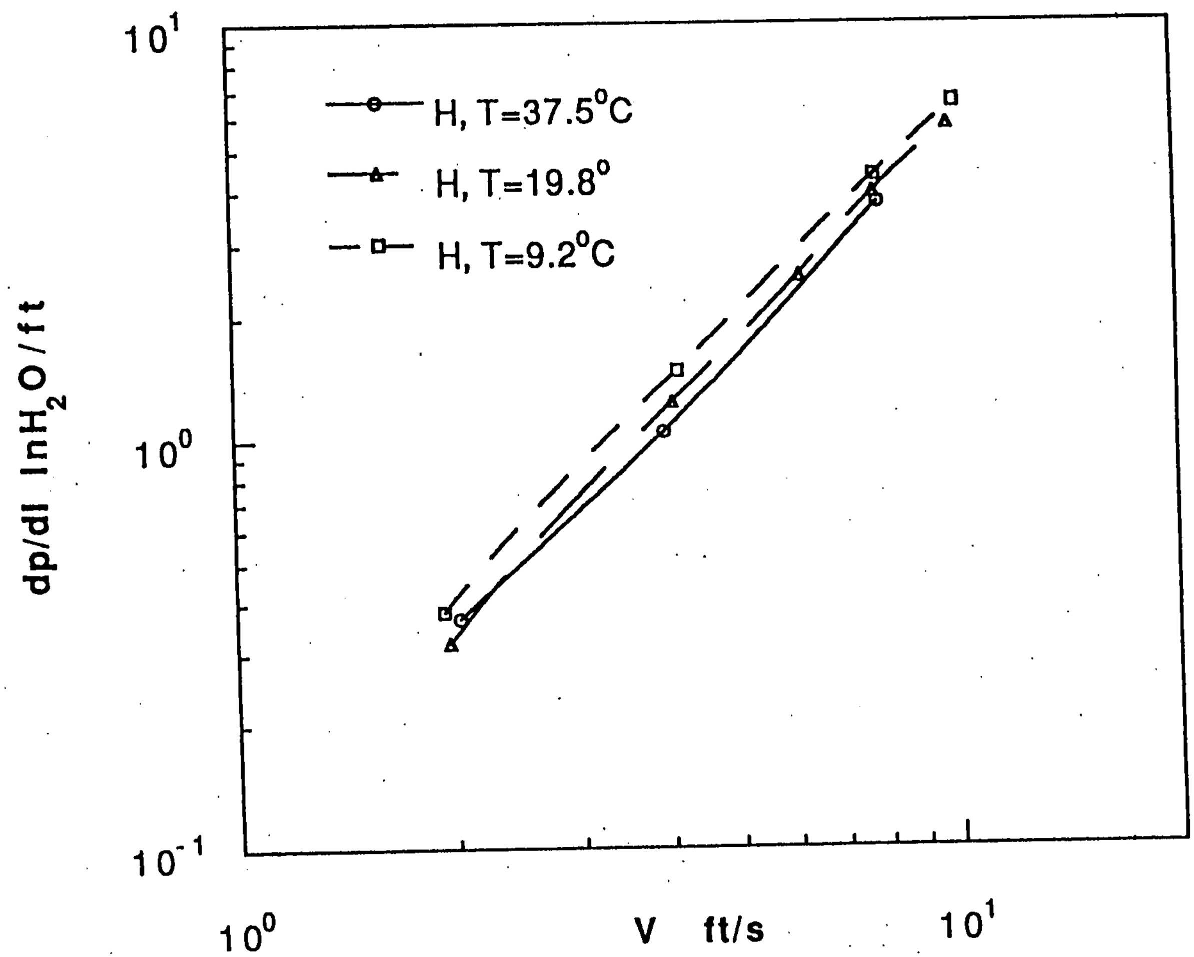

Figure 3.4.1 Pressure gradient of 25% K-65 slurry in horizontal test section.

8102

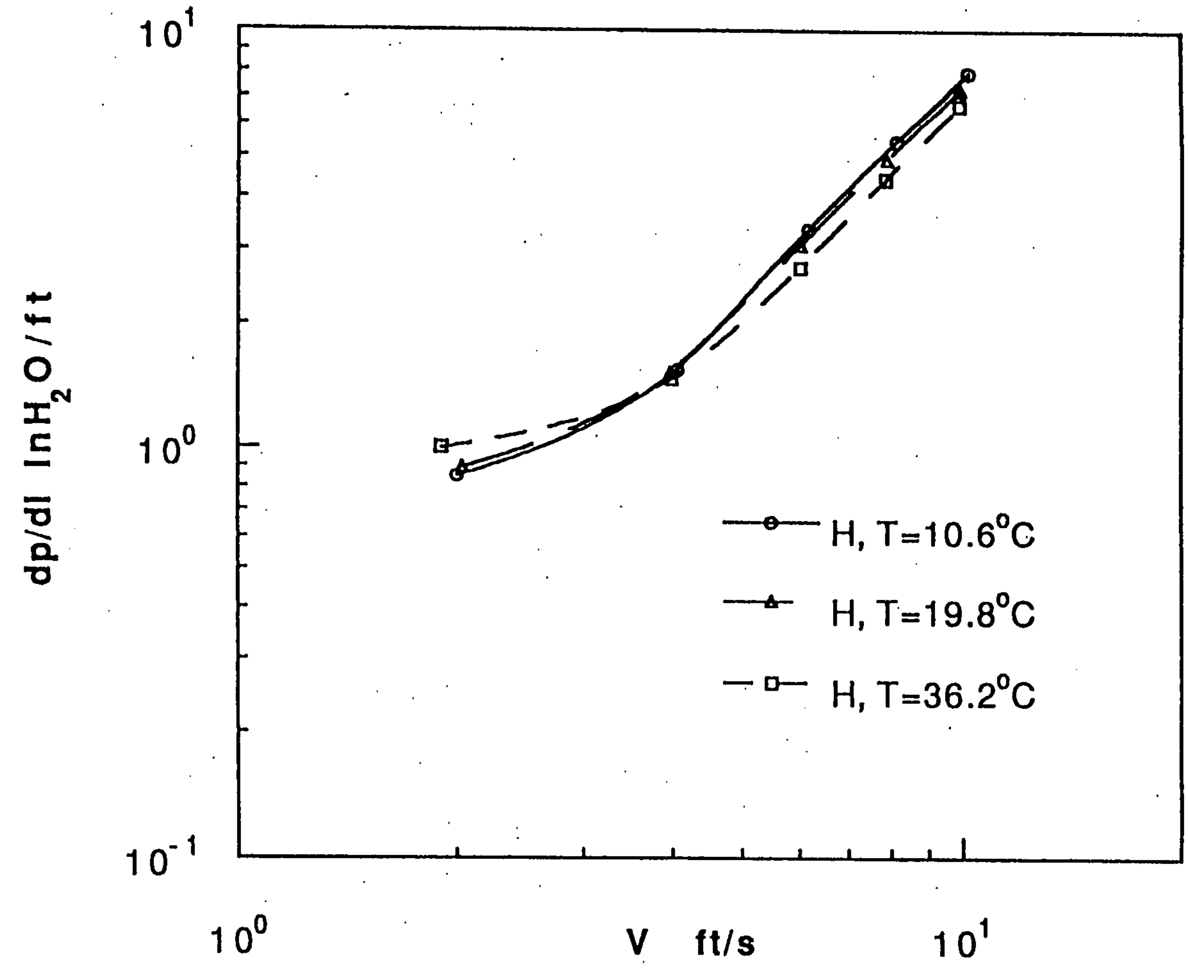

Figure 3.4.2 Pressure gradient of 25% K-65 slurry with 5% bentonite in horizontal test section.

8102

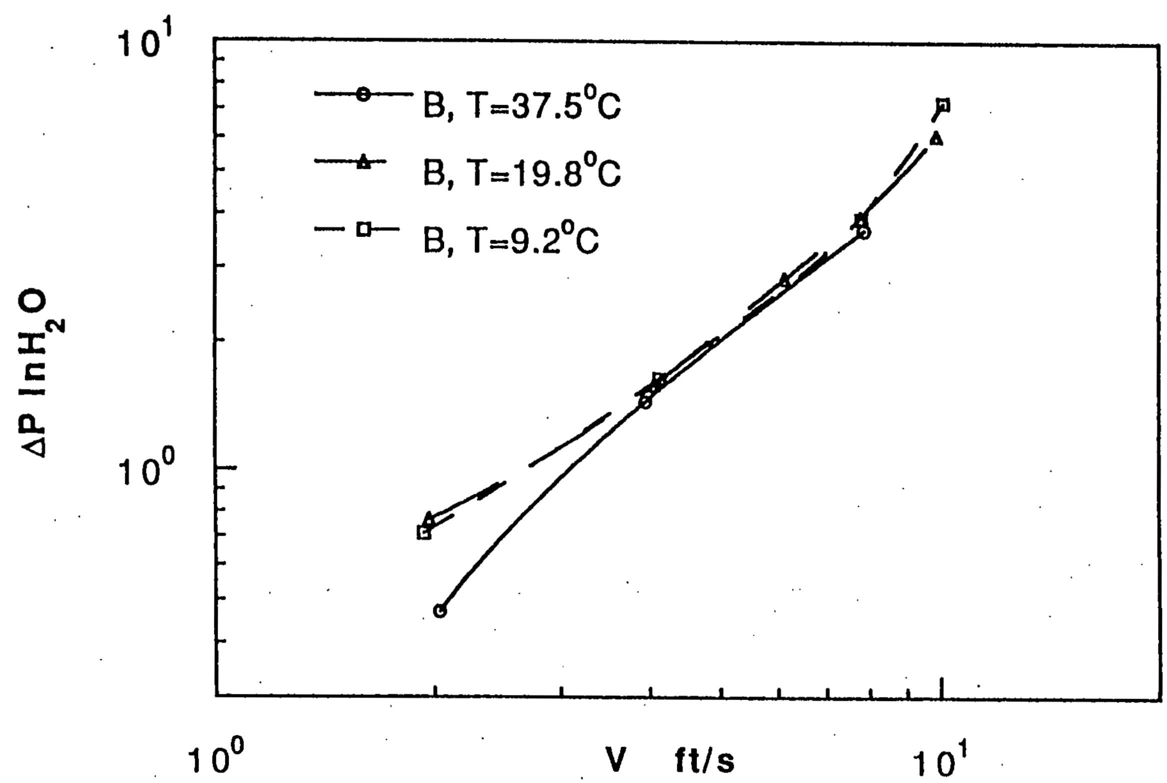

Figure 3.4.3 Pressure drop across the bend of 25% K-65 slurry.

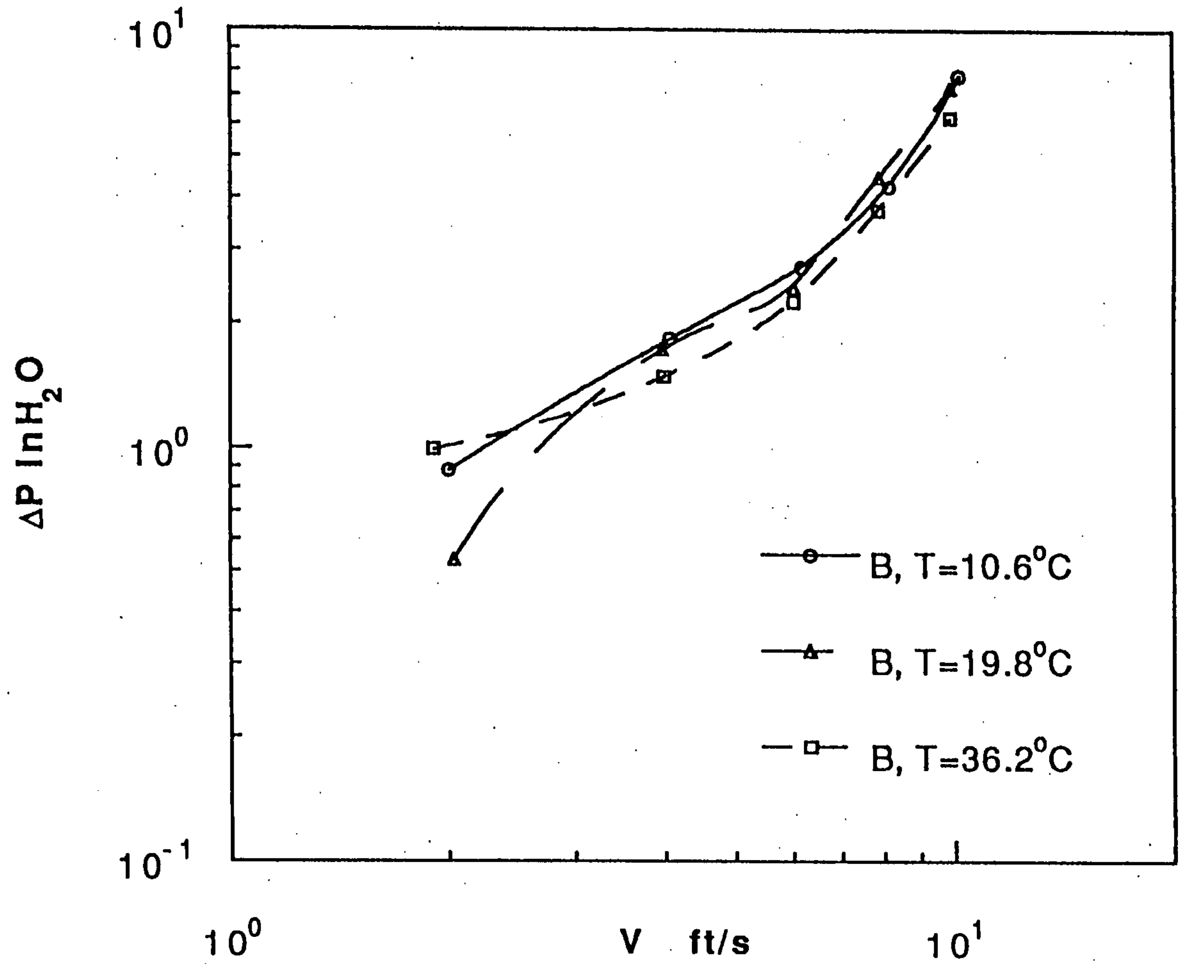

Figure 3.4.4 Pressure drop across the bend of 25% K-65 slurry with 5% bentonite.

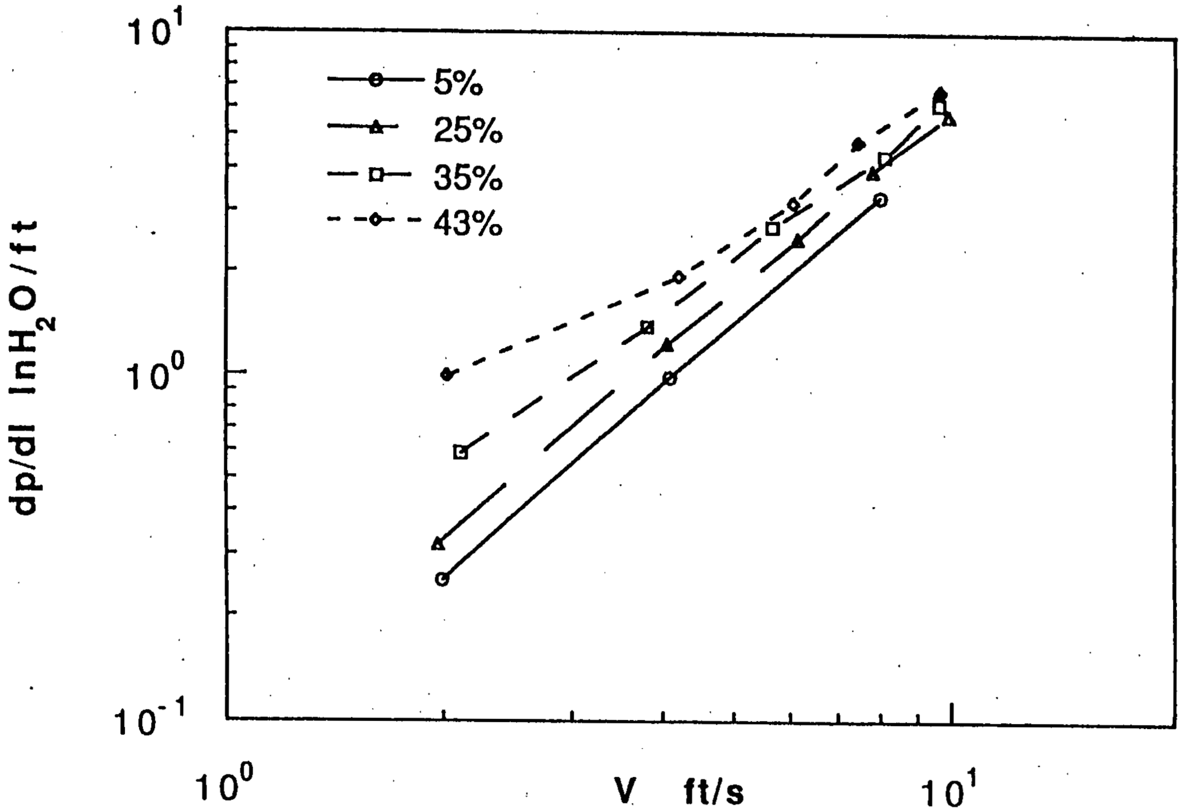

Figure 3.4.5 Concentration effect on pressure gradient of K-65 slurry without bentonite in horizontal test section.

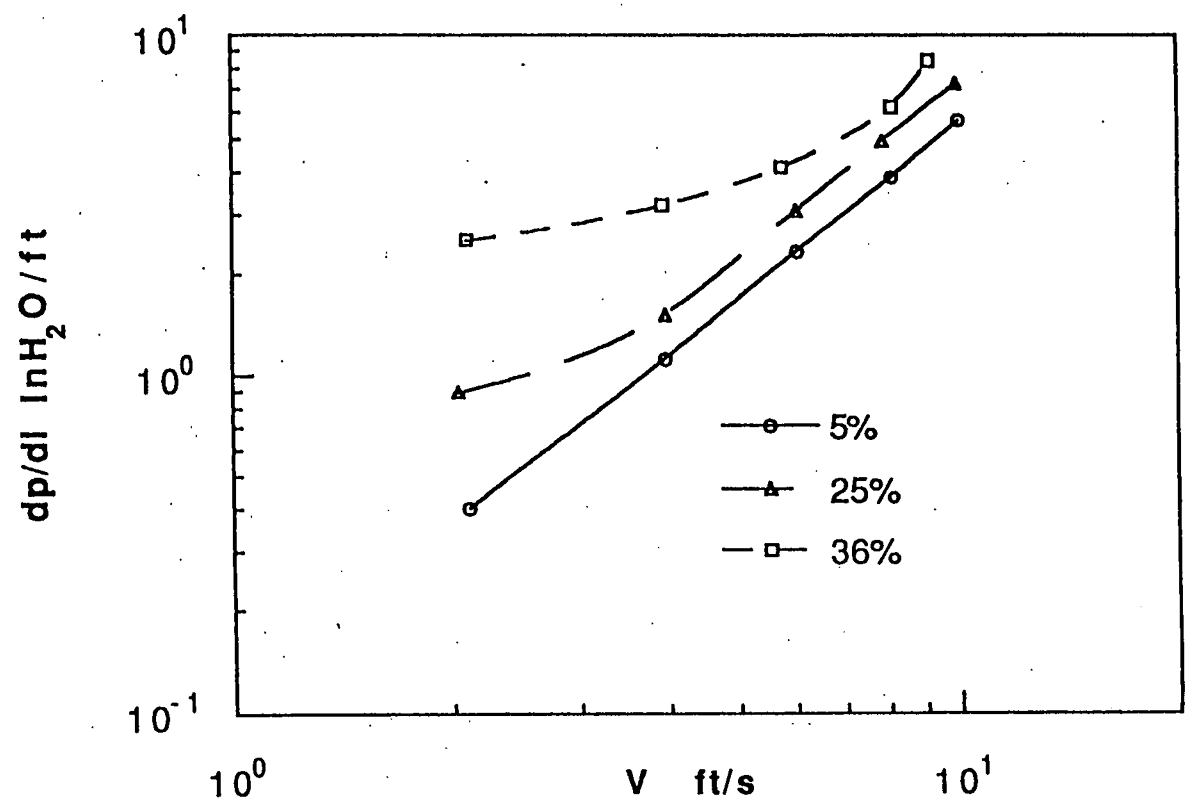

Figure 3.4.6 Concentration effect on pressure gradient of K-65 slurry with 5% bentonite in horizontal test section.

8102

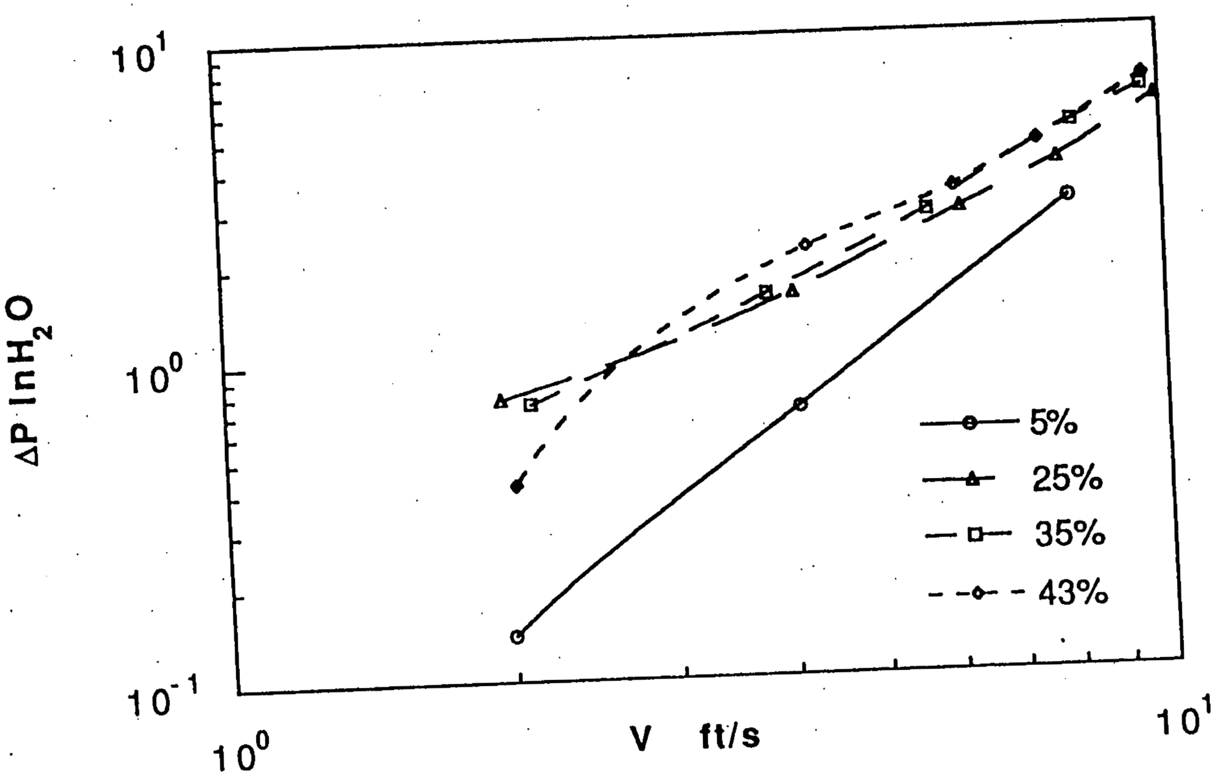

Figure 3.4.7 Concentration effect on pressure drop across the bend of K-65 slurry without bentonite.

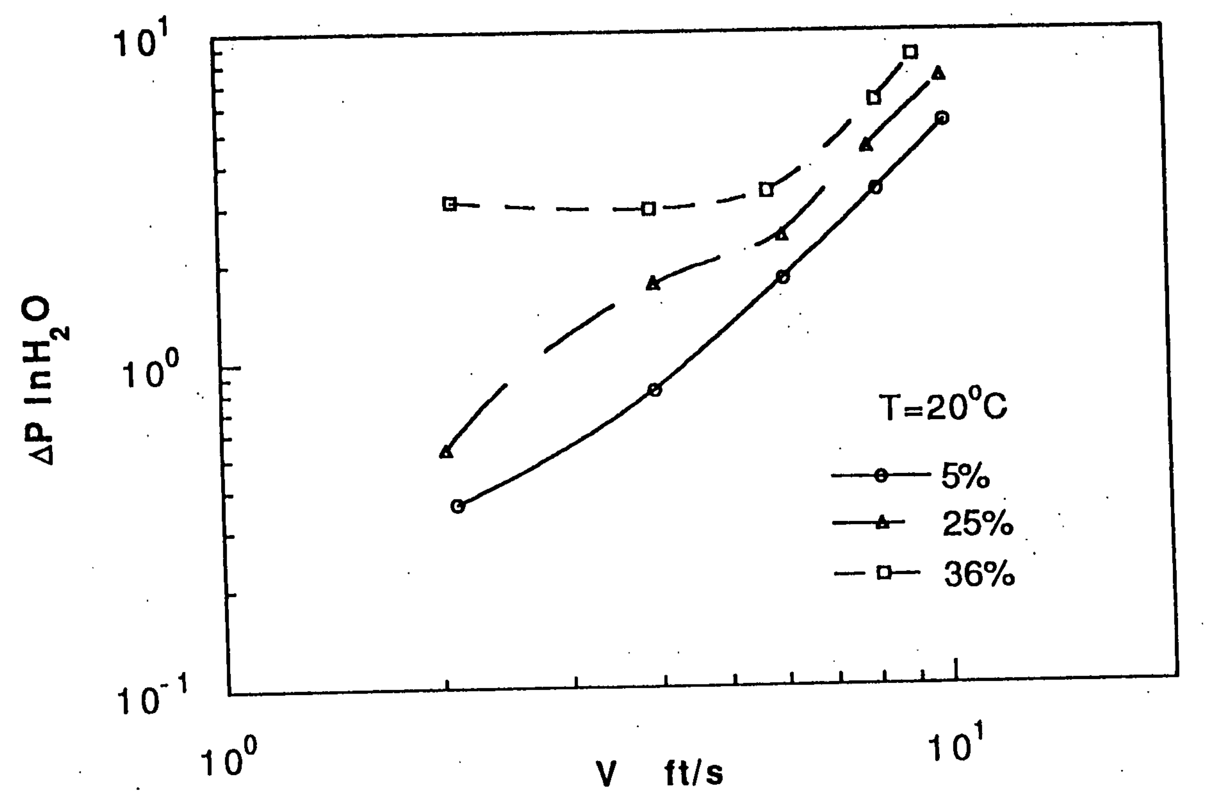

Figure 3.4.8 Concentration effect on pressure drop across the bend of K-65 slurry with 5% bentonite.

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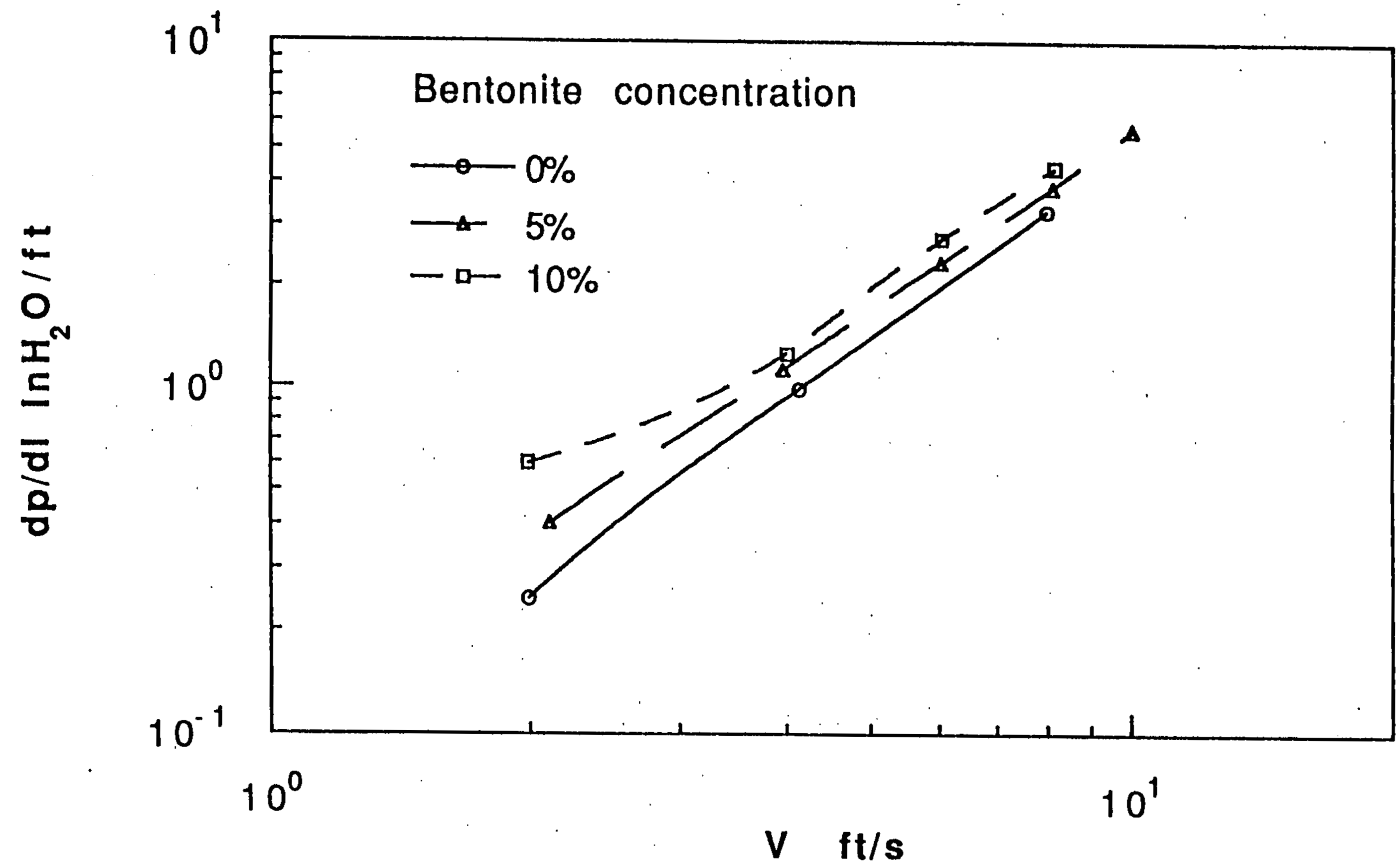

Figure 3.4.9 Bentonite concentration effect on pressure gradient of 5% K-65 slurry in horizontal test section.

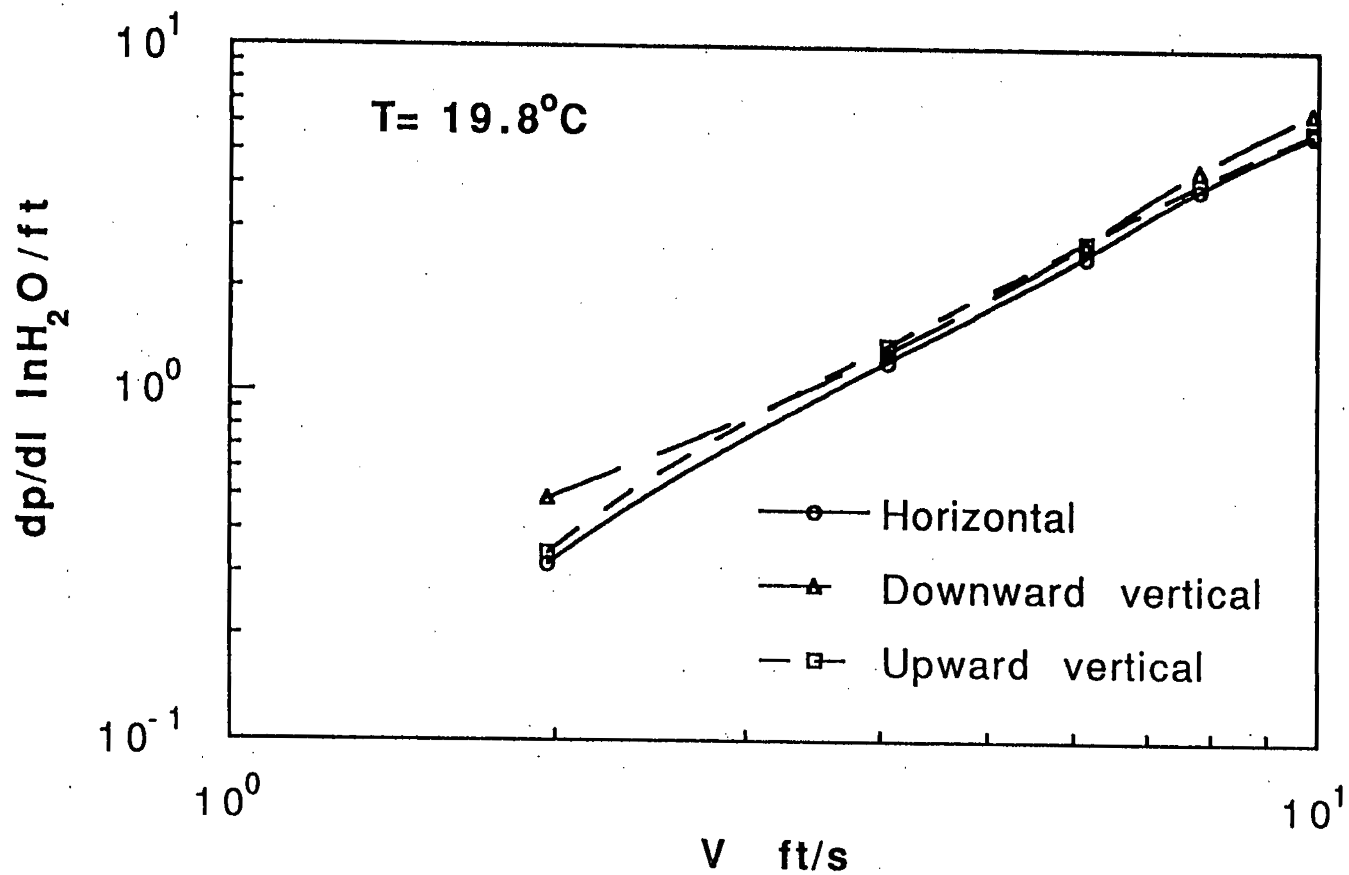

Figure 3.4.10 Flow orientation effect on pressure gradient of 25% K-65 slurry without bentonite.

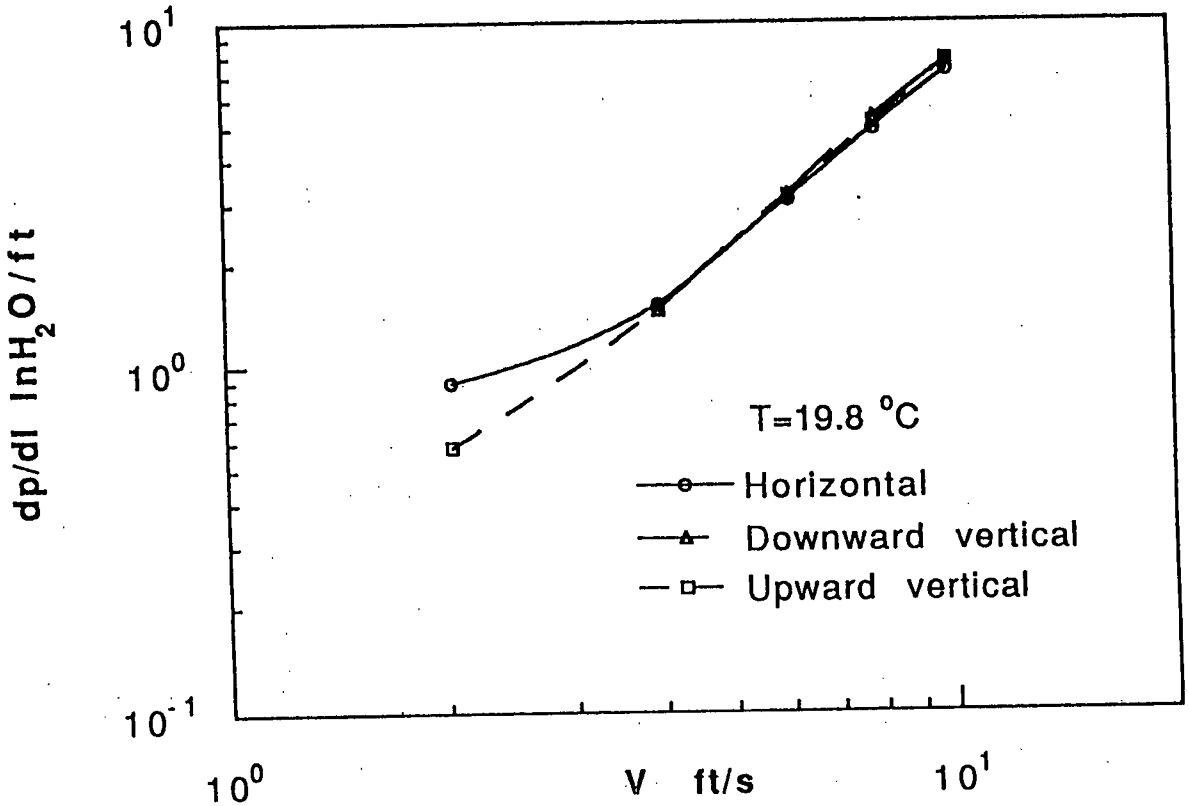

Figure 3.4.11 Flow orientation effect on pressure gradient of 25% K-65 slurry with 5% bentonite.

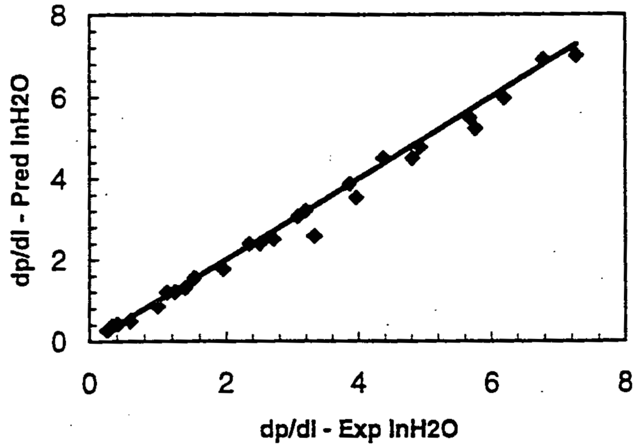

Figure 3.4.12 Comparison of experimental data and prediction for K-65 slurry without bentonite.

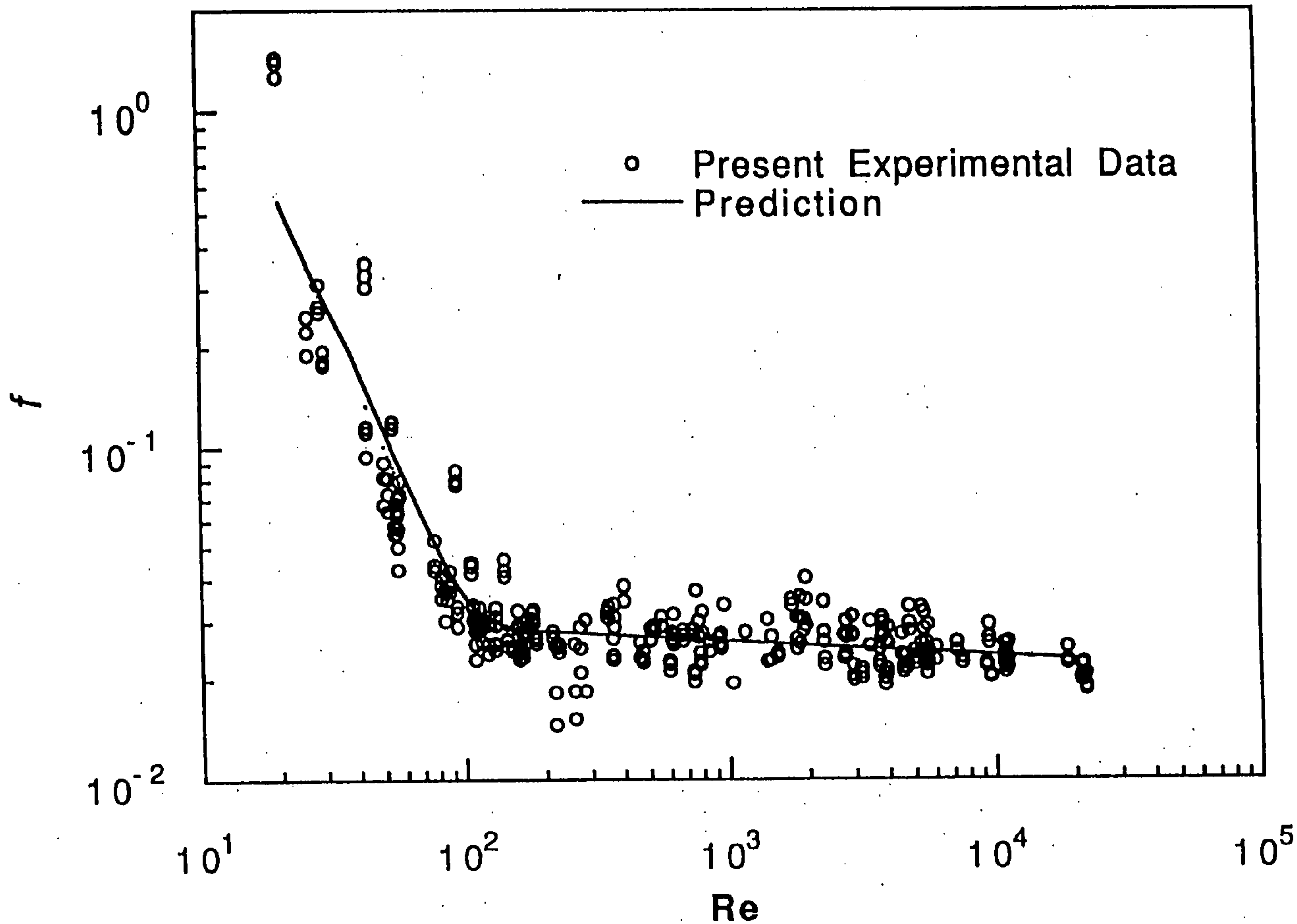

Figure 3.4.13 Experimental results and correlation of friction factor in straight section.

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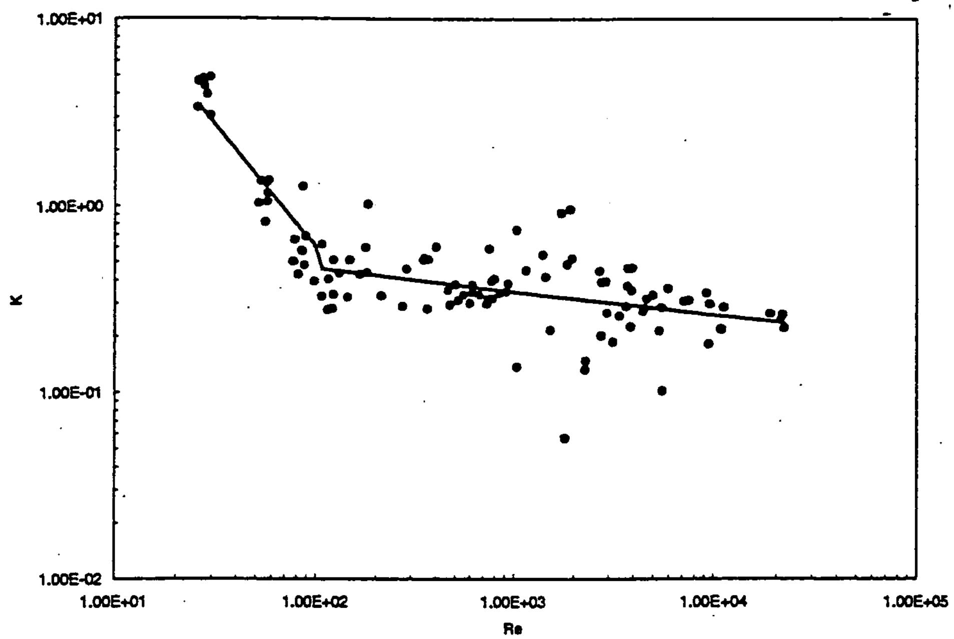

Figure 3.4.14 Experimental results and correlation of resistance factor of the bend.

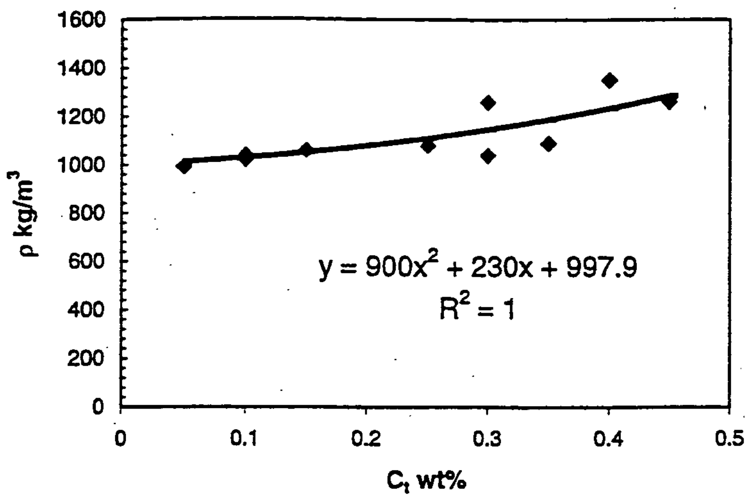

Figure 4.2.1 Density and solid concentration relationship of surrogate #1.

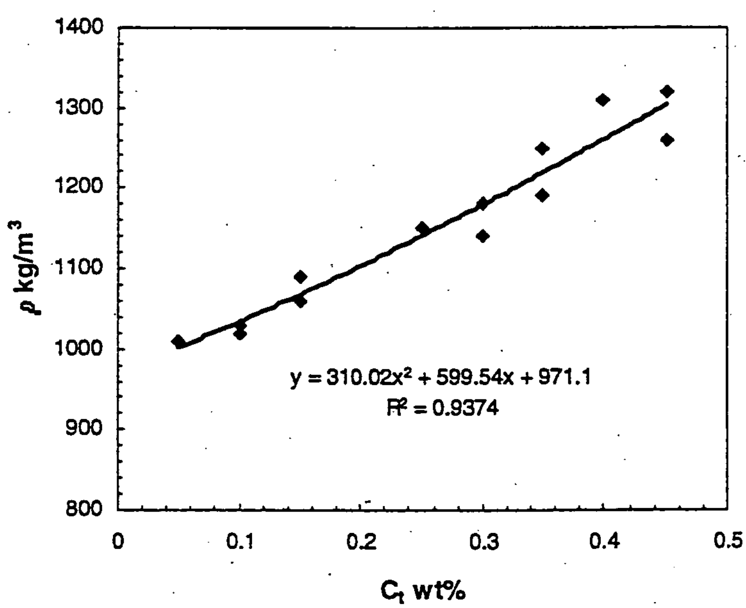

Figure 4.2.2 Density and solid concentration relationship of surrogate #2.

Figure 4.2.3: Concentration Effect on Fresh Surrogate 1 Viscosity at Room Temperature

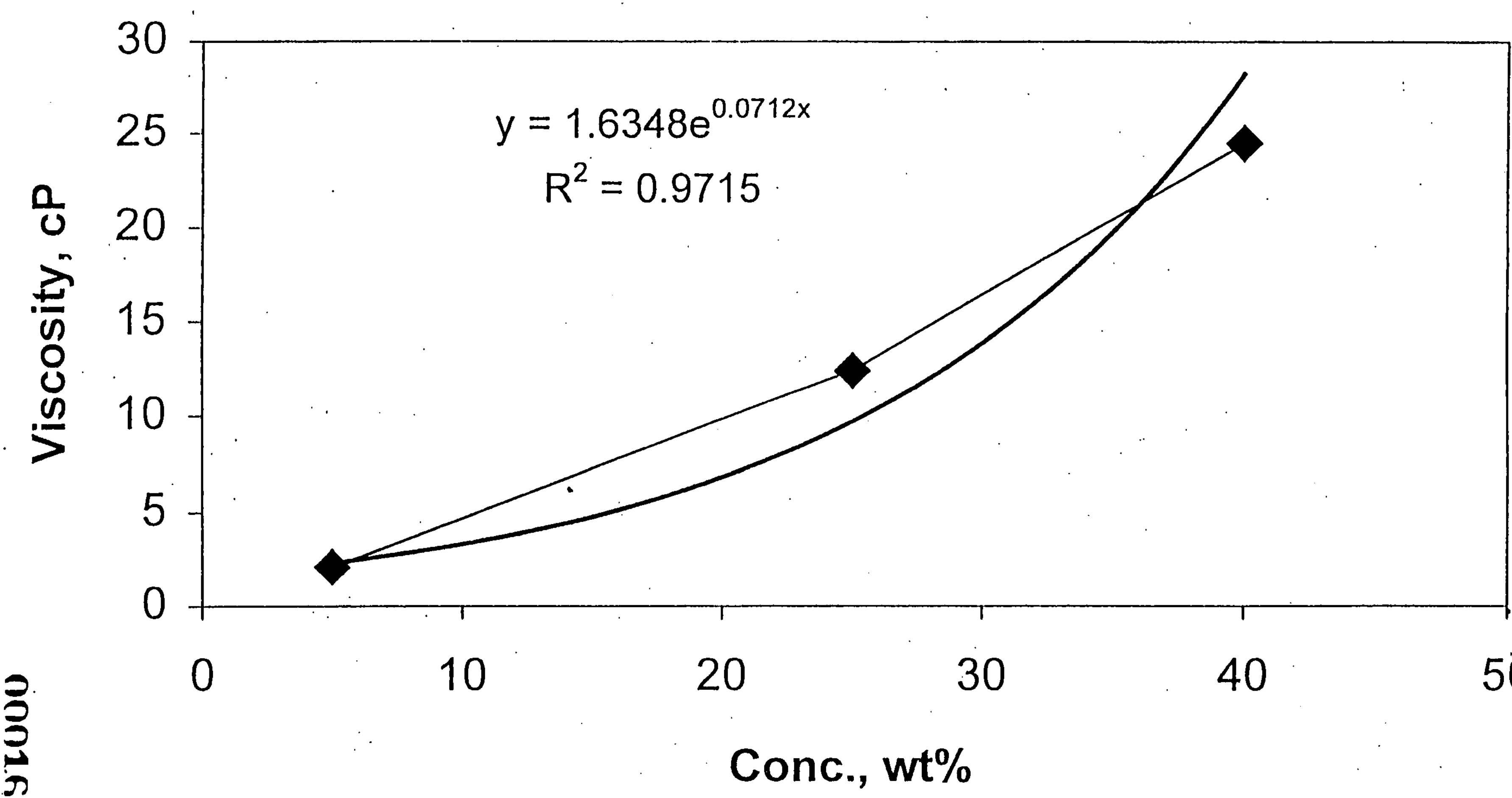

Figure 4.2.4: Concentration Effect on Fresh Surrogate 2 Viscosity at Room Temperature

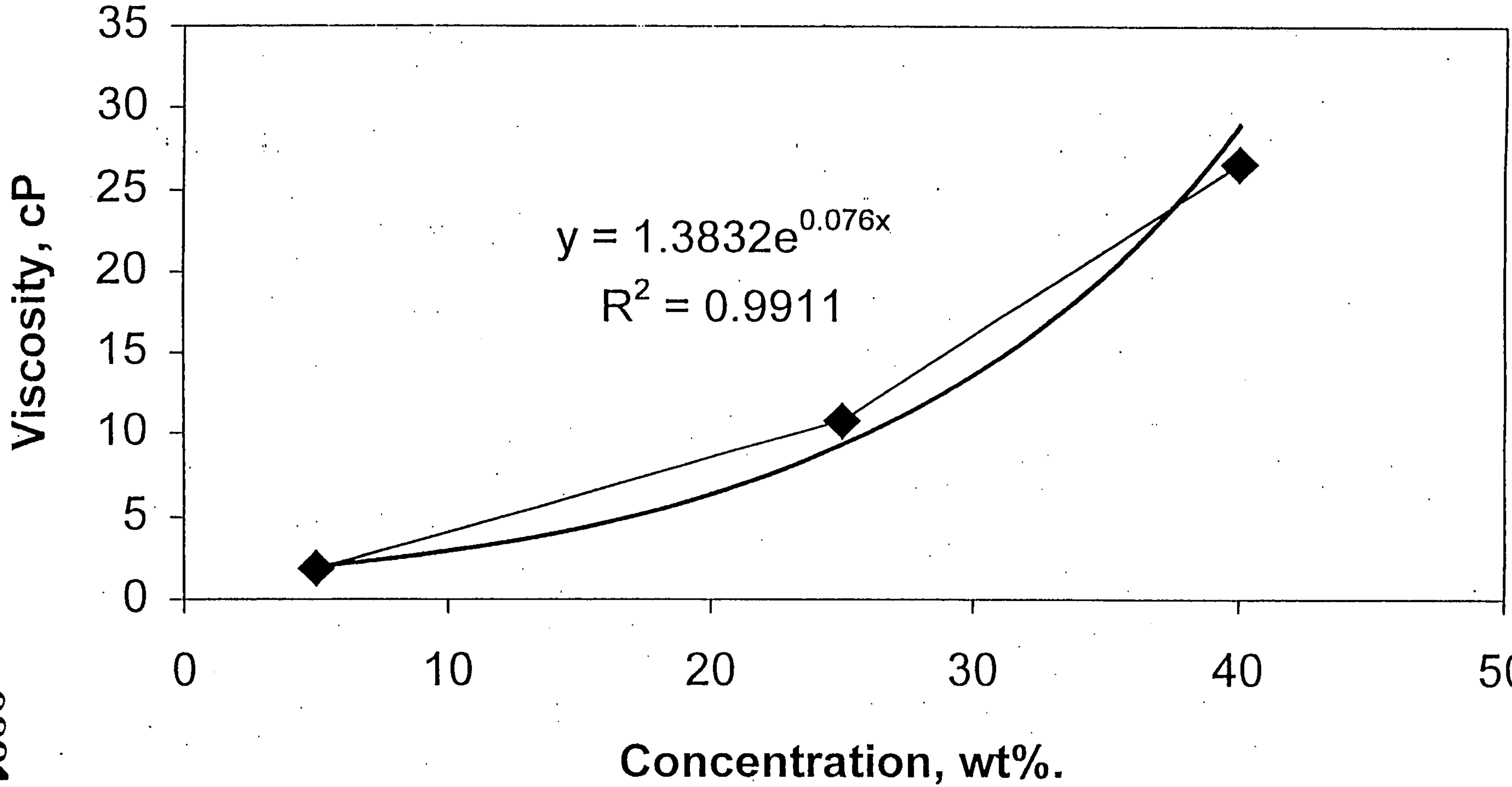

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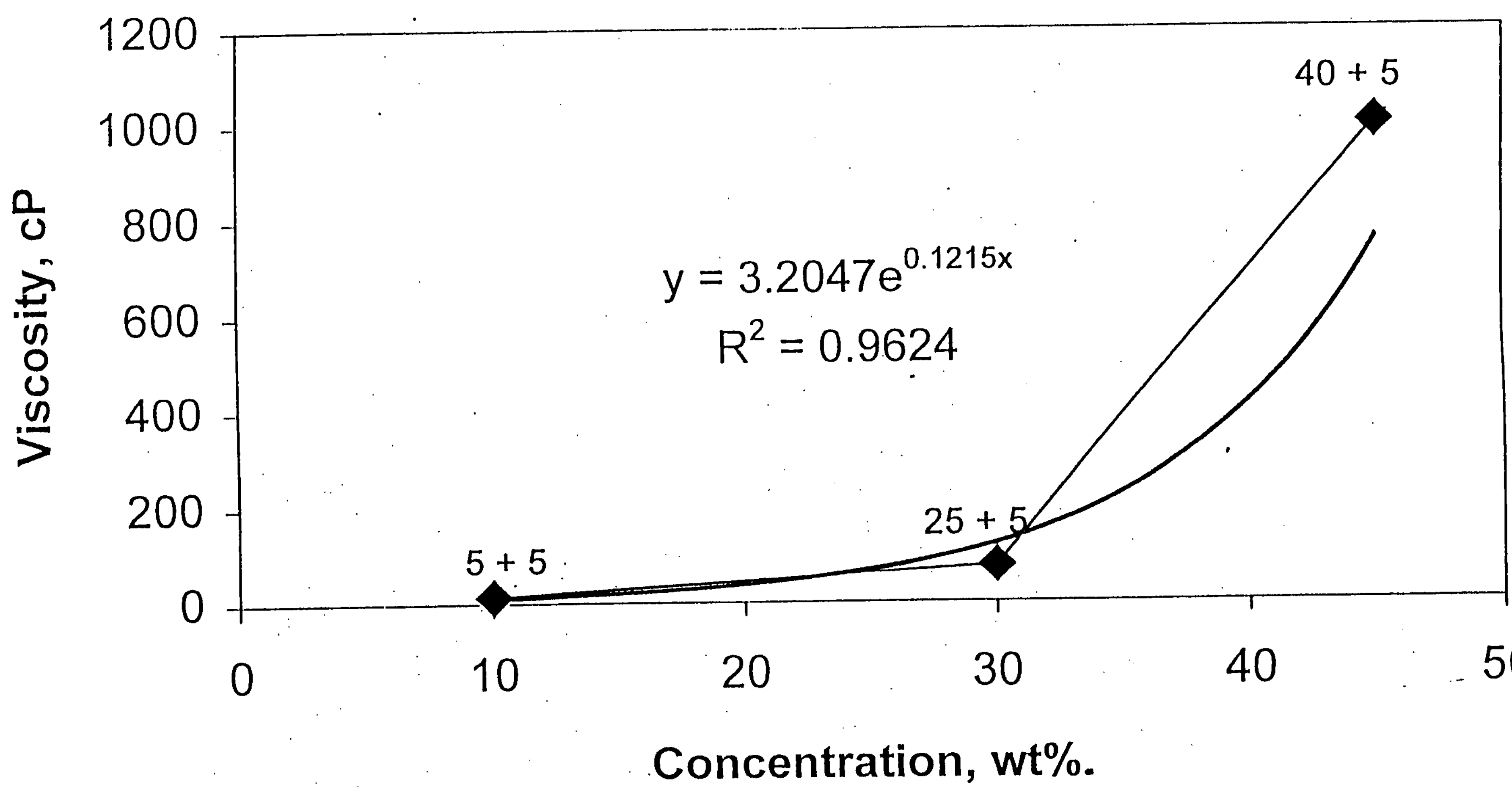
Figure 4.2.5: Concentration Effect on Fresh Surrogate 2 + Bentonite Viscosity at Room Temperature



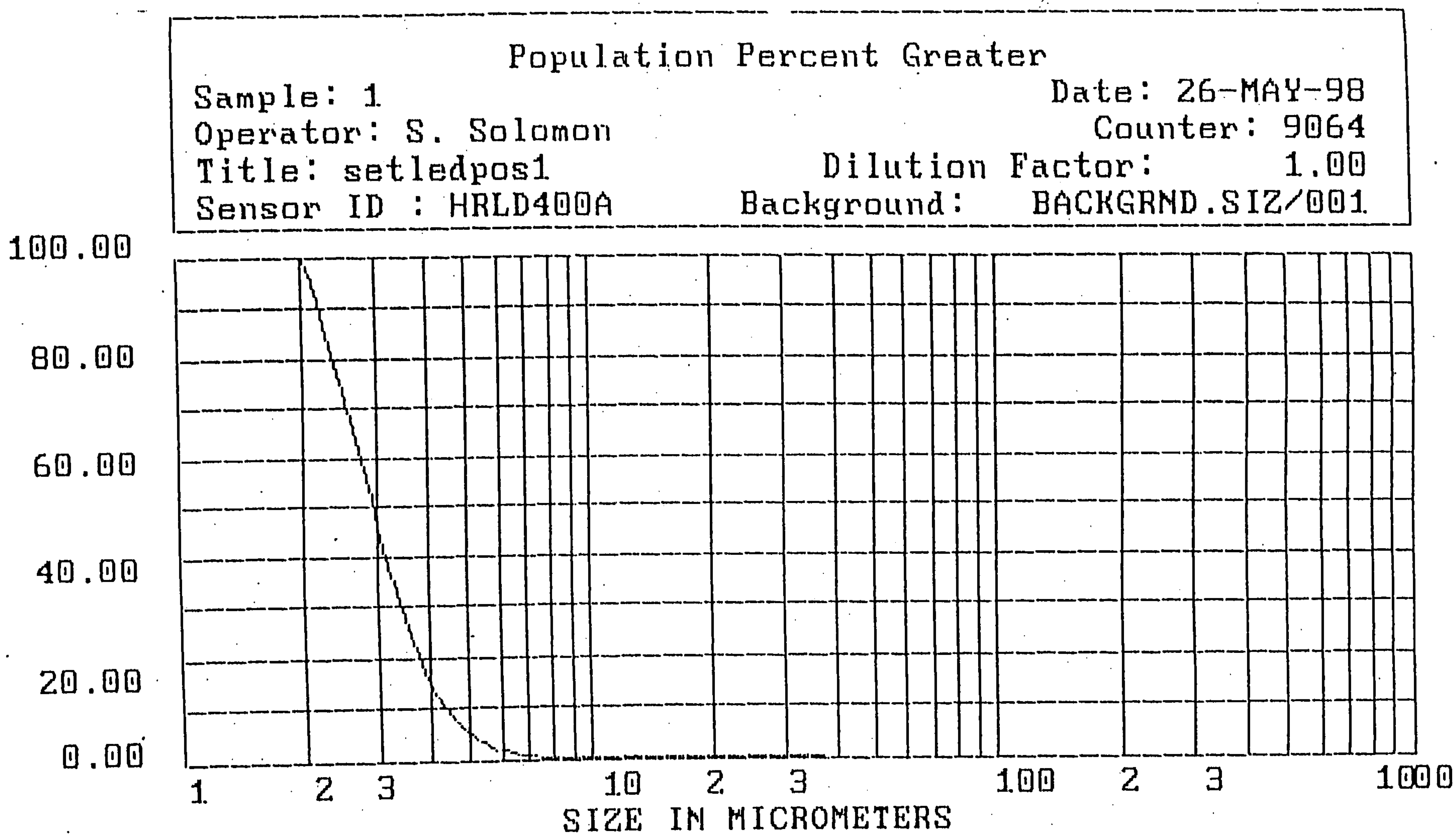


Figure 4.3.1
5% Unpumped Surrogate Without Bentonite-Supernatant of Settled Material, at 10mm Depth.

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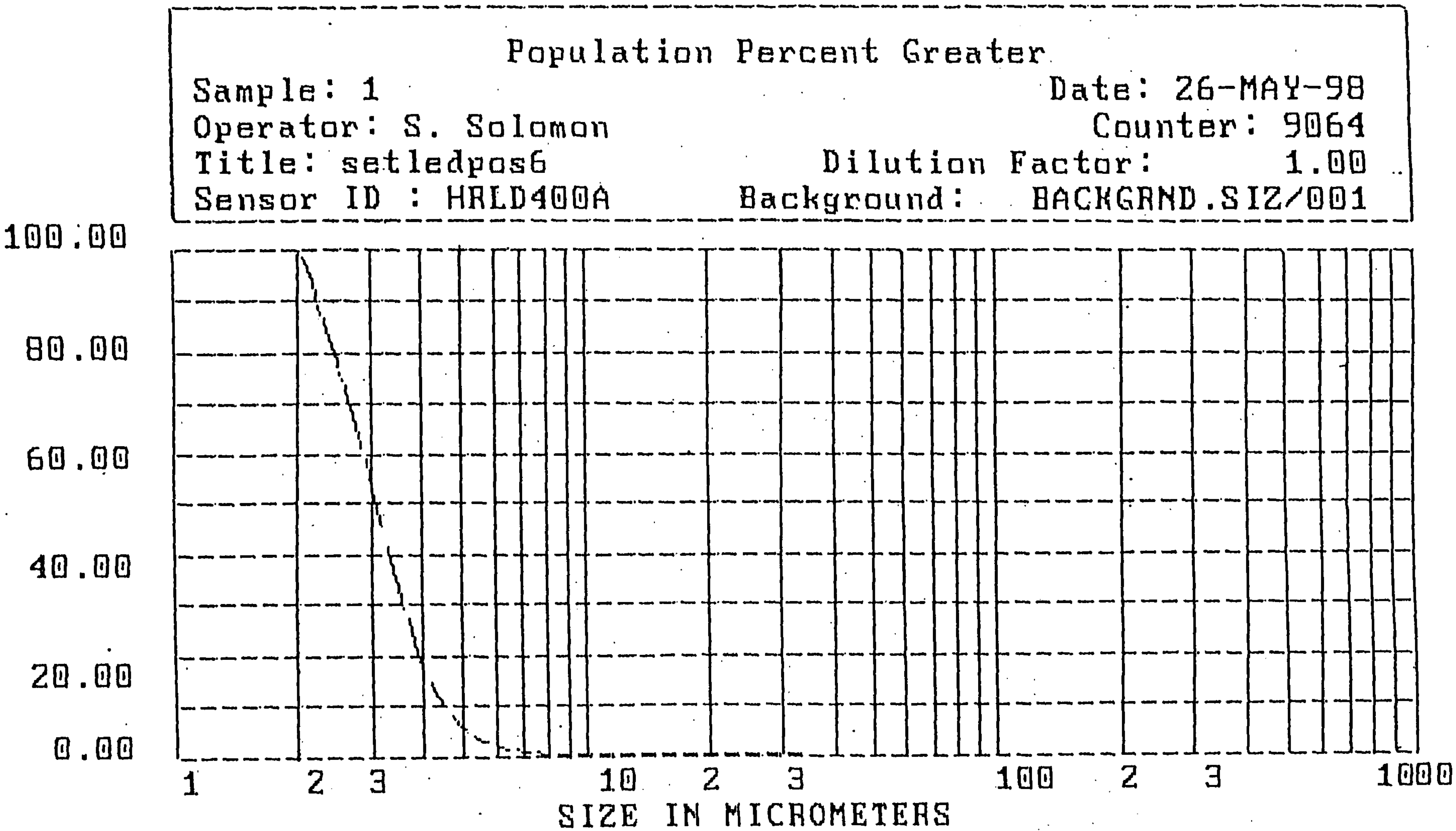

Figure 4.3.2
5% Unpumped Surrogate-Supernatant of Settled Material, at 60mm Depth.

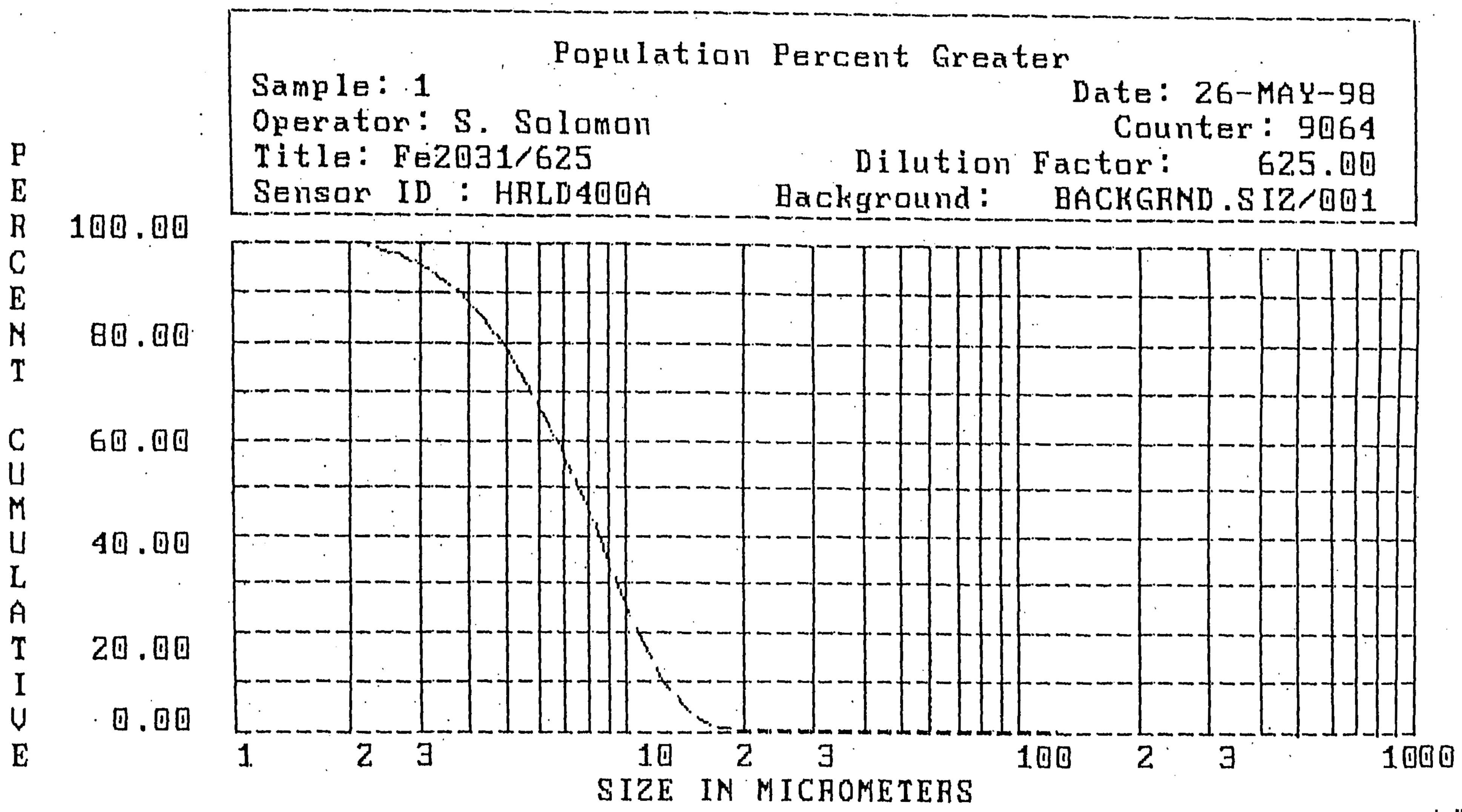

Figure 4.3.3
5% Unpumped Surrogate-Supernatant of Diluted Red Settled Layer, 1:625 Dilution 30 mm Depth.

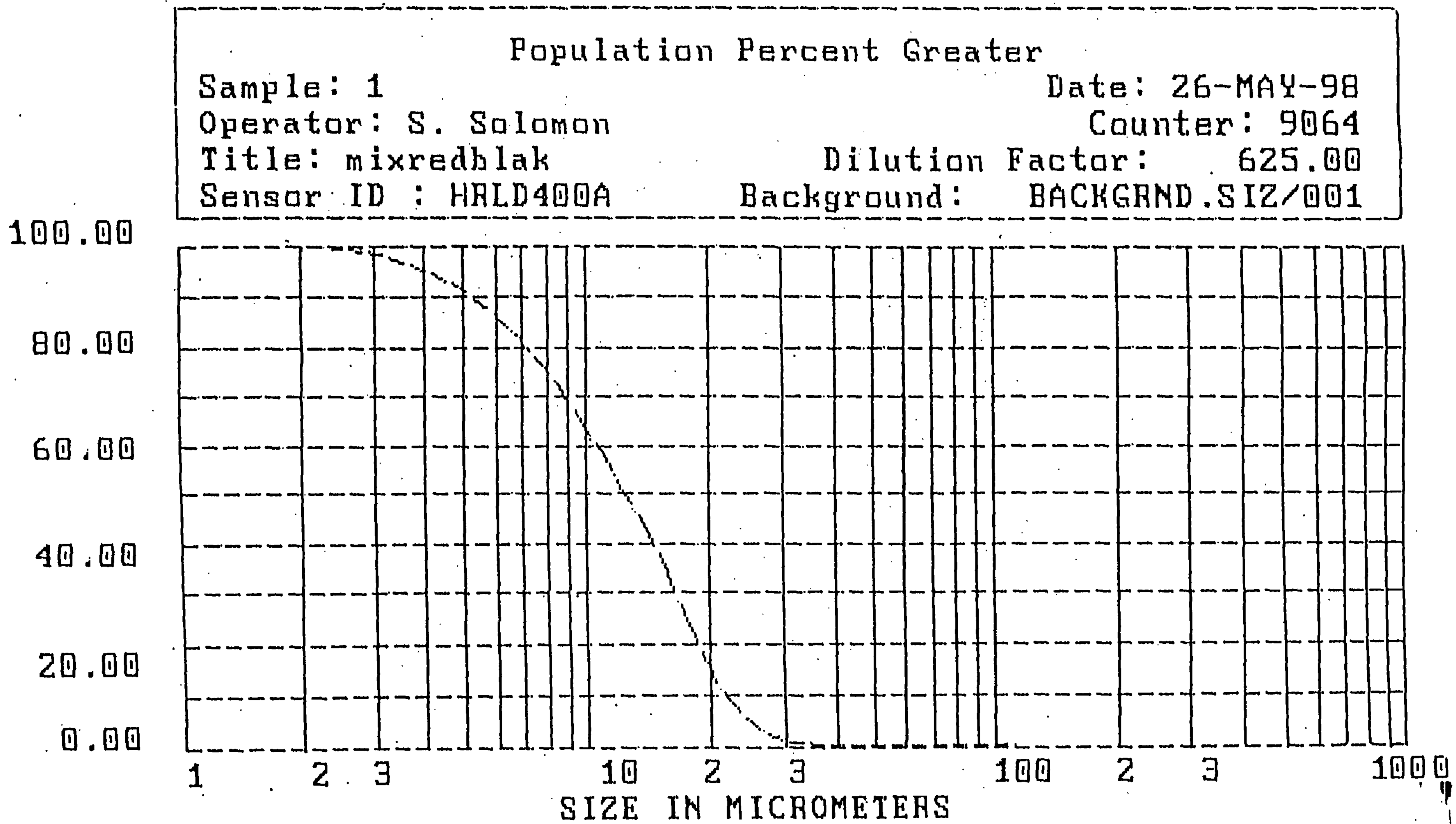

Figure 4.3.4
5% Unpumped Surrogate-Supernatant of Diluted Black Settled Layer, 1:625 Dilution.

000173

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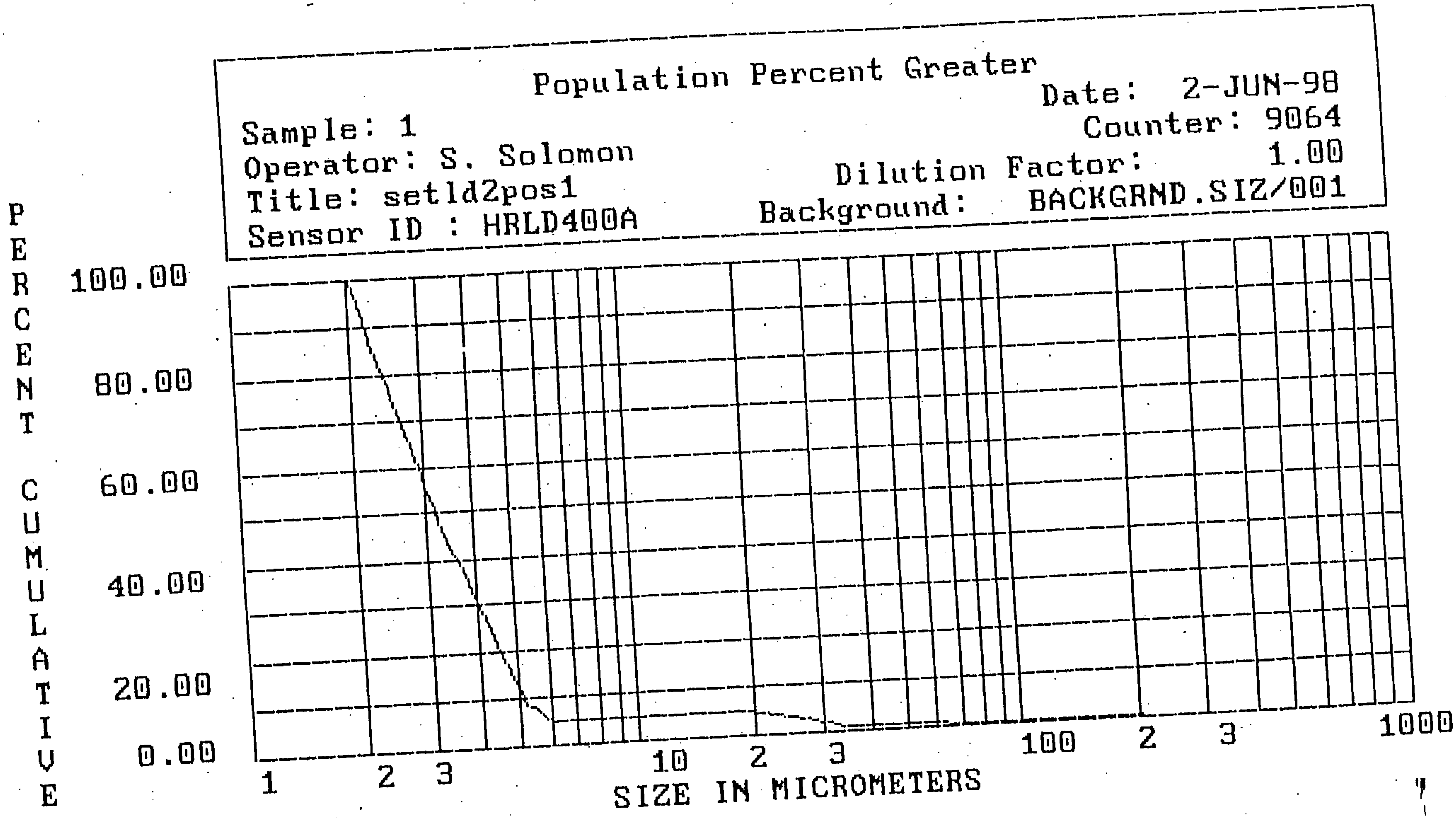

Figure 4.3.5

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

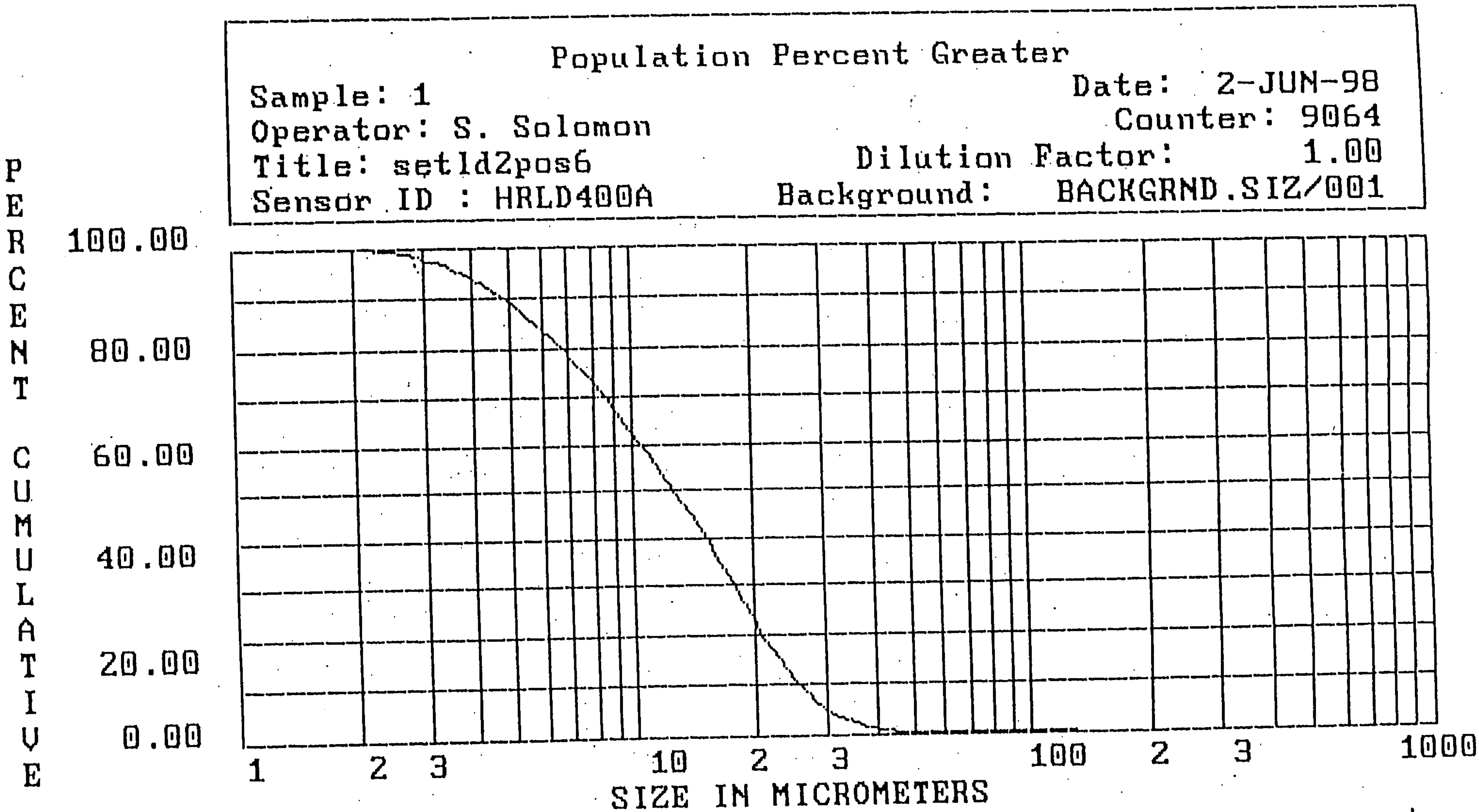

Figure 4.3.6
5% Pumped Surrogate- Sample at Top of Red Settled Material, Undiluted.

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Population Percent Greater

Sample: 1 — Date: 4-JUN-98
Operator: S. Solomon — Counter: 9064
Title: FRSTLDPOS1 — Dilution Factor: 1.00
Sensor ID : HRLD400A — Background: BACKGRND.SIZ/024

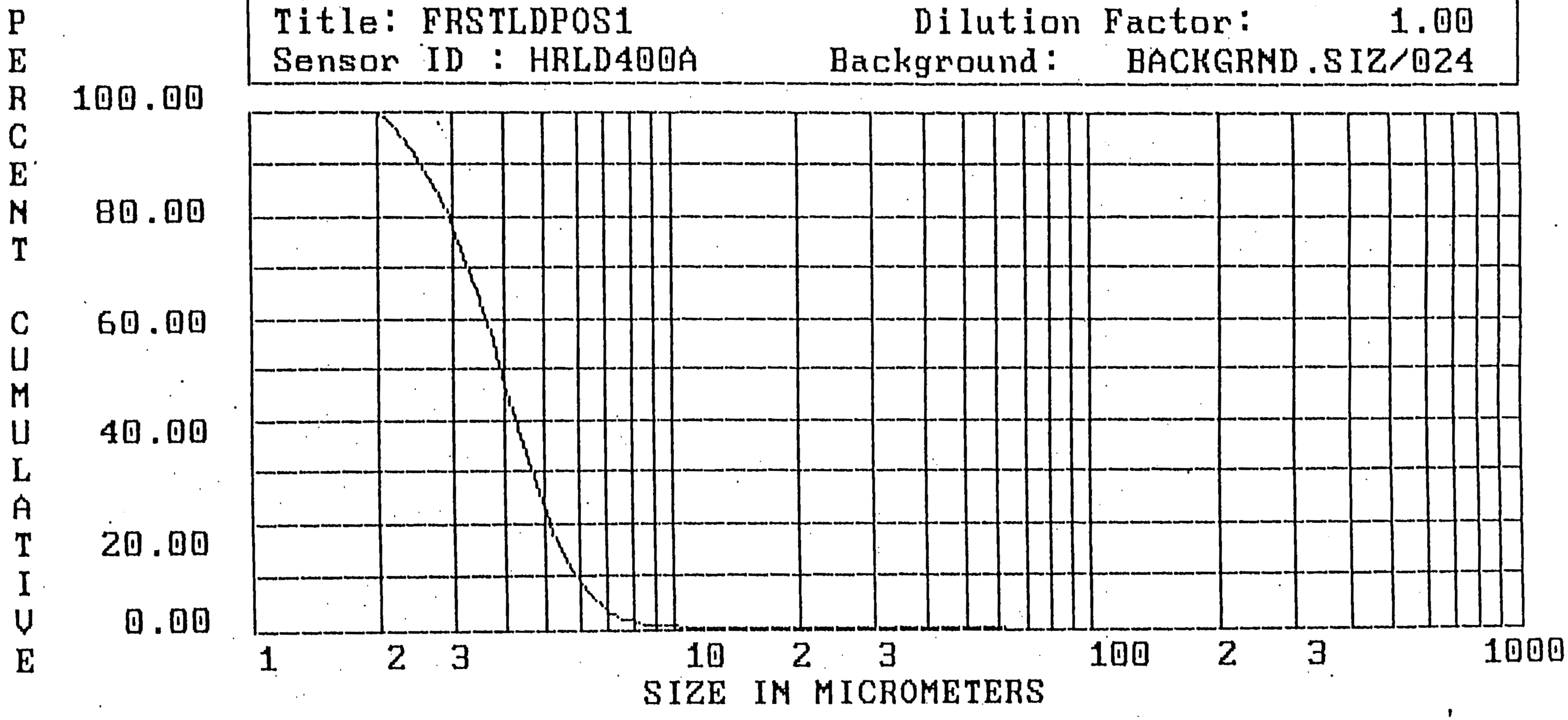

Figure 4.3.7
25% Unpumped Surrogate Without Bentonite-Supernatant of Settled Material, at 10mm Depth.

8102

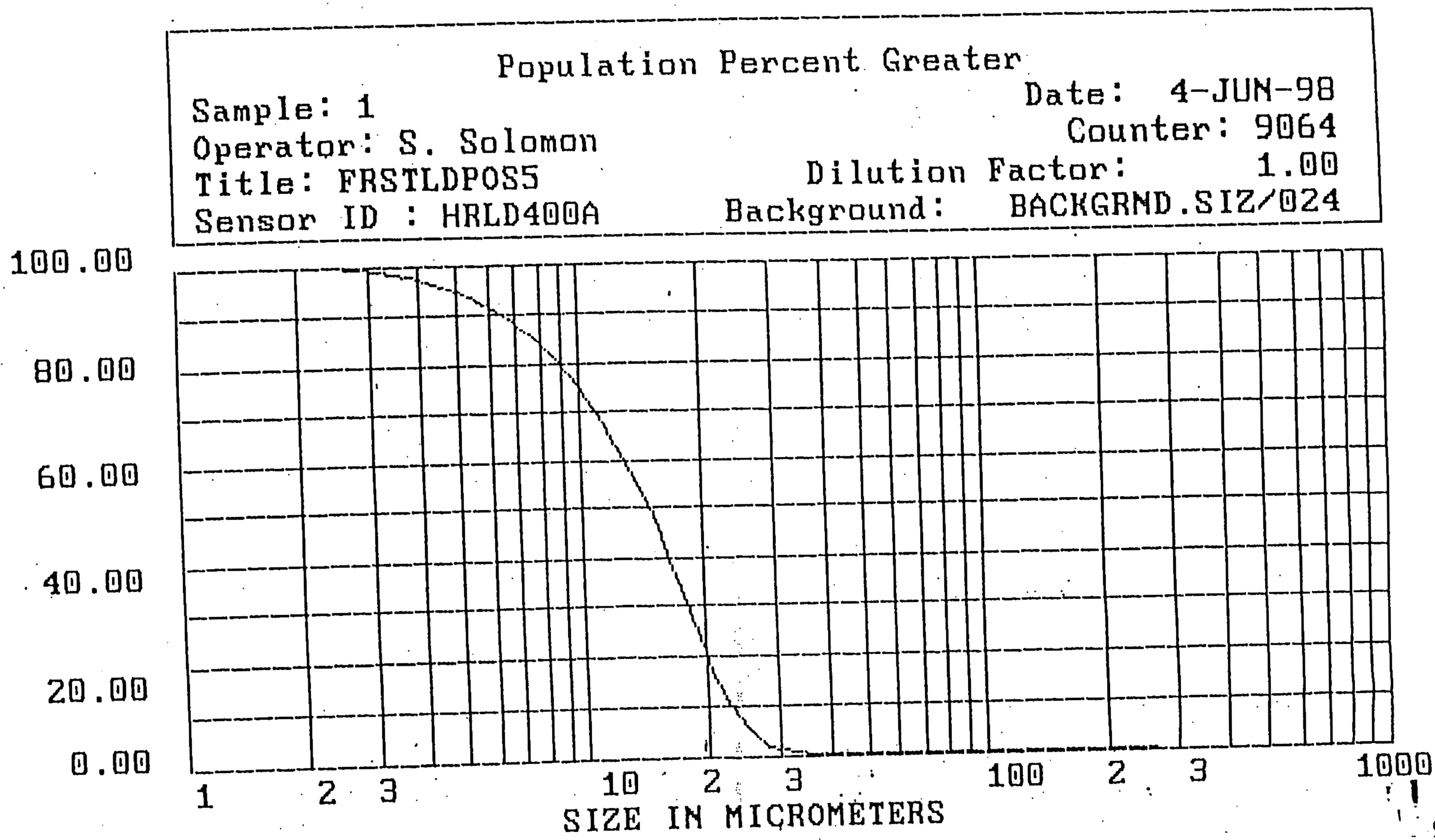

Figure 4.3.8
25% Unpumped Surrogate- Sample at Top of Red Settled Material, Undiluted

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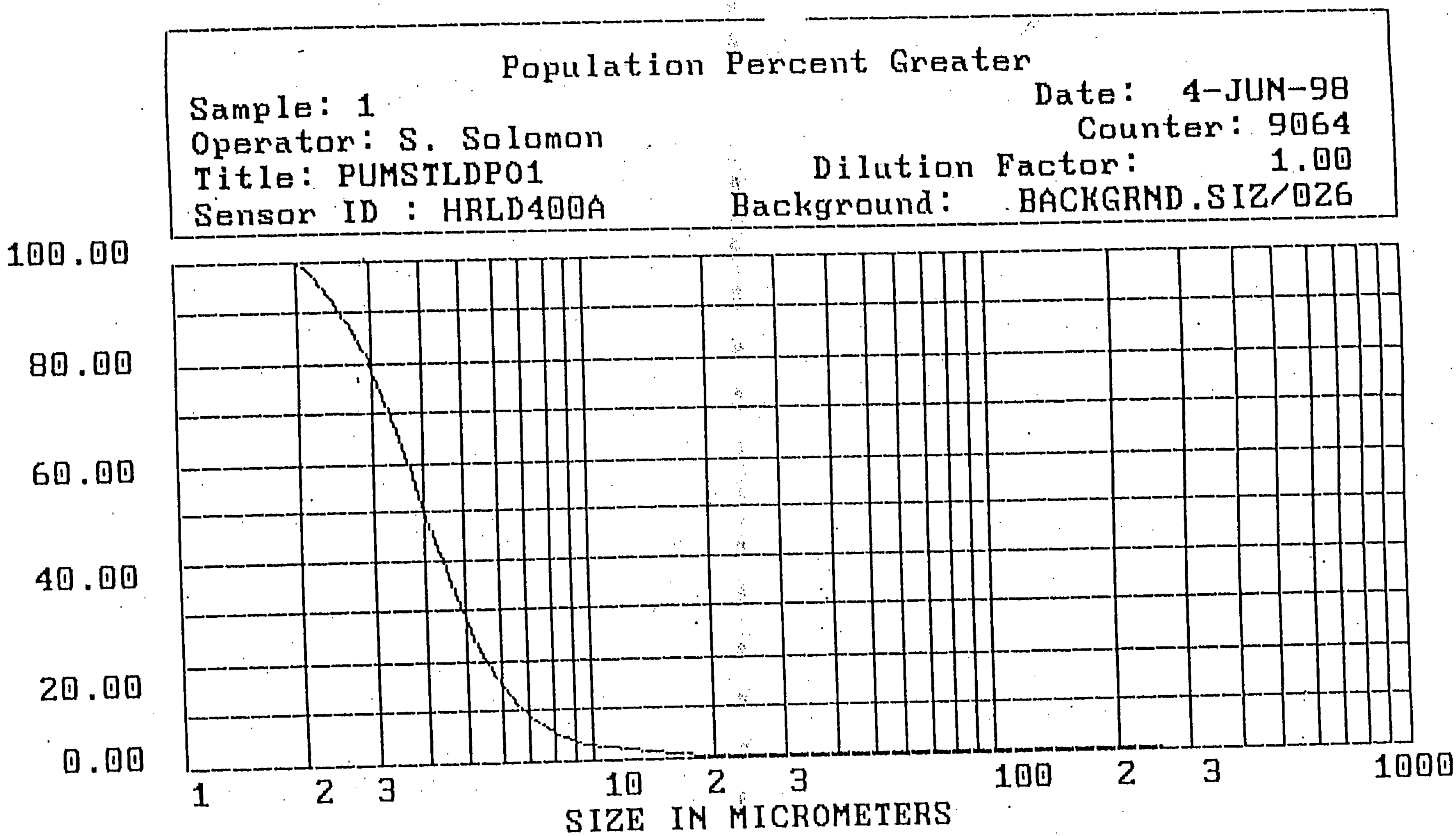

Figure 4.3.9
25% Pumped Surrogate Without Bentonite-Supernatant of Settled Material, at 10mm Depth.

8102

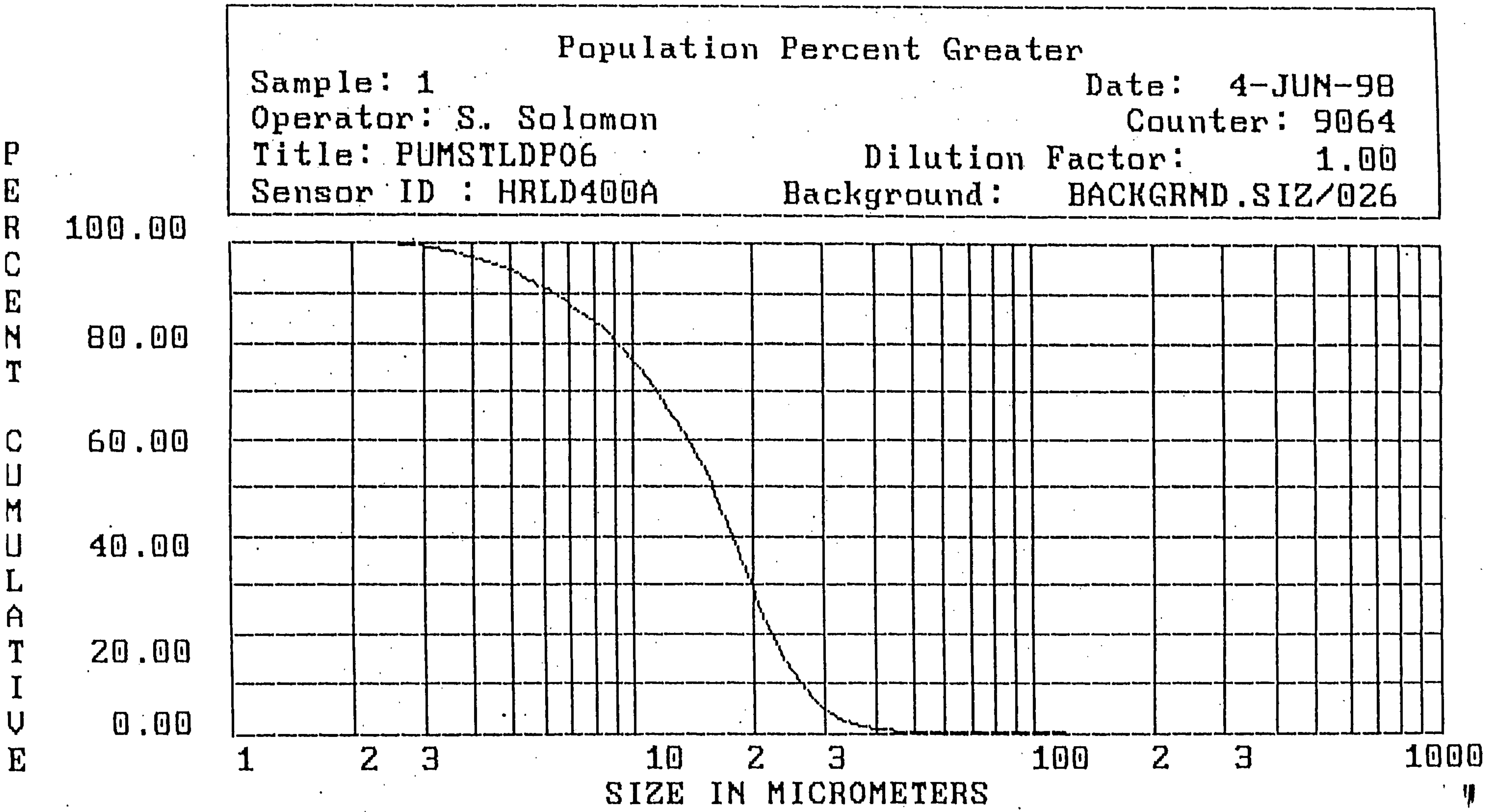

Figure 4.3.10
25% Pumped Surrogate- Sample at Top of Red Settled Material, Undiluted.

8102

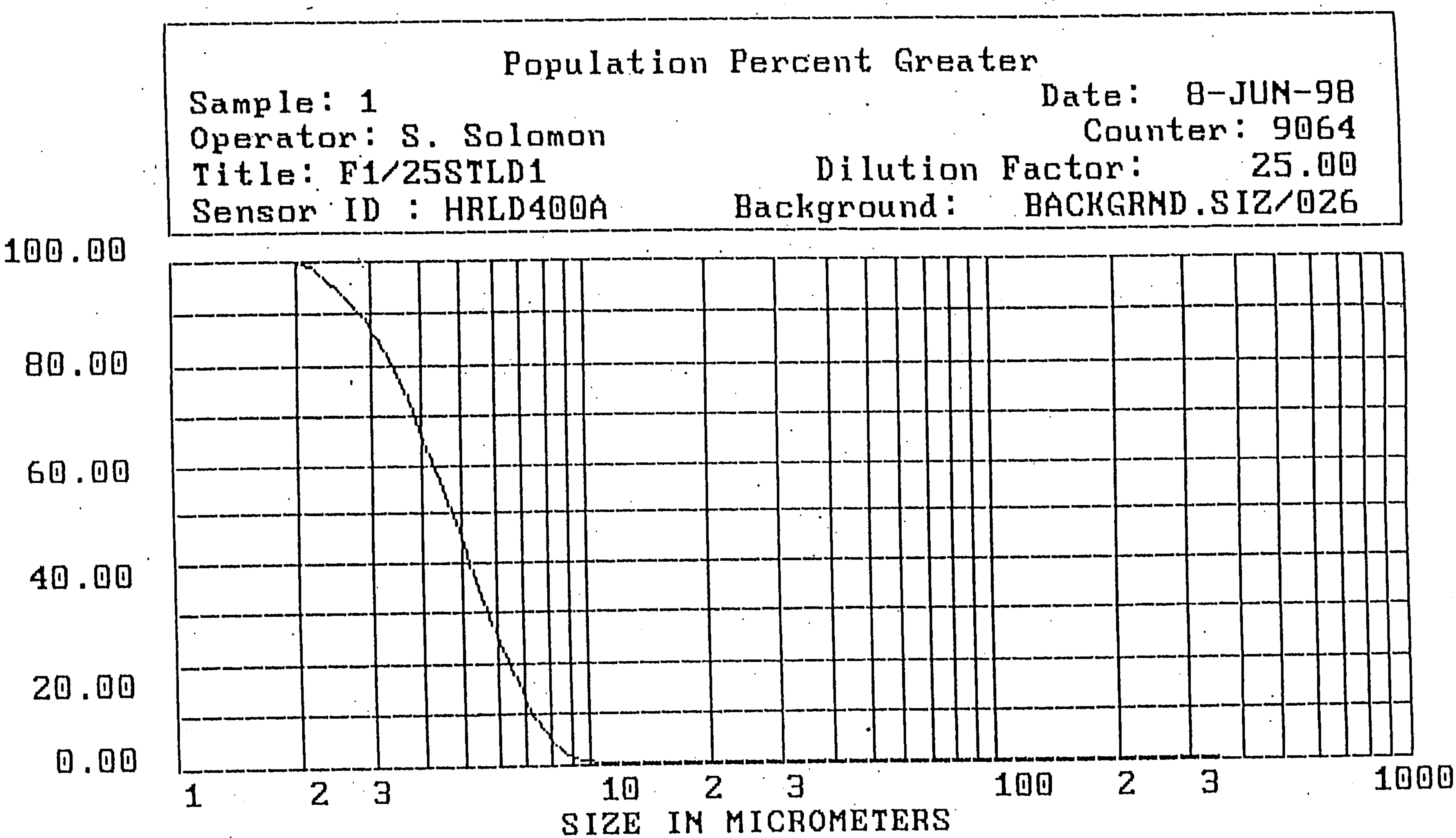

Figure 4.3.11
5% Unpumped Surrogate With 5% Bentonite-Supernatant of Settled Material, at 10mm Depth, Diluted 1:25.

8102

Population Percent Greater

Sample: 1 | Date: 8-JUN-98
Operator: S. Solomon | Counter: 9064
Title: P1/25STLD1 | Dilution Factor: 25.00
Sensor ID : HRLD400A | Background: BACKGRND.SIZ/028

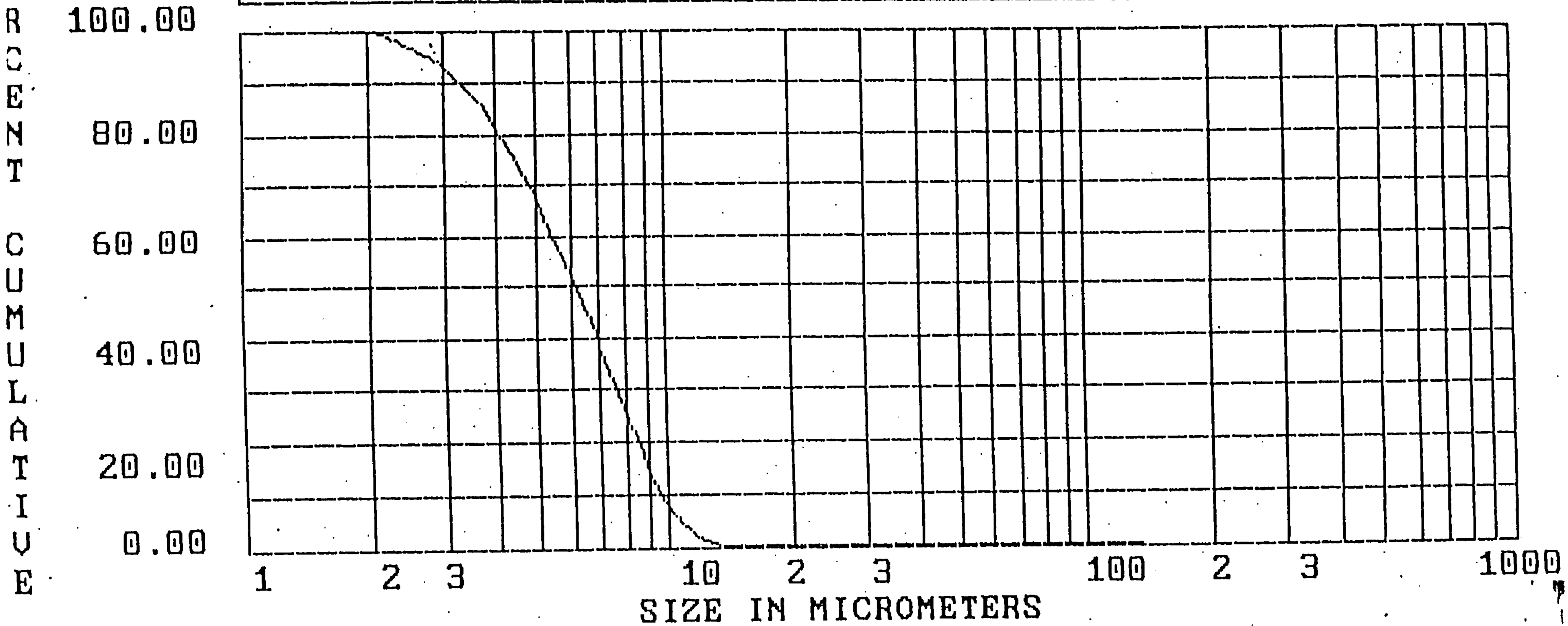

Figure 4.3.12
5% Pumped Surrogate With 5% Bentonite-Supernatant of Settled Material, at 10mm Depth, Diluted 1:25.

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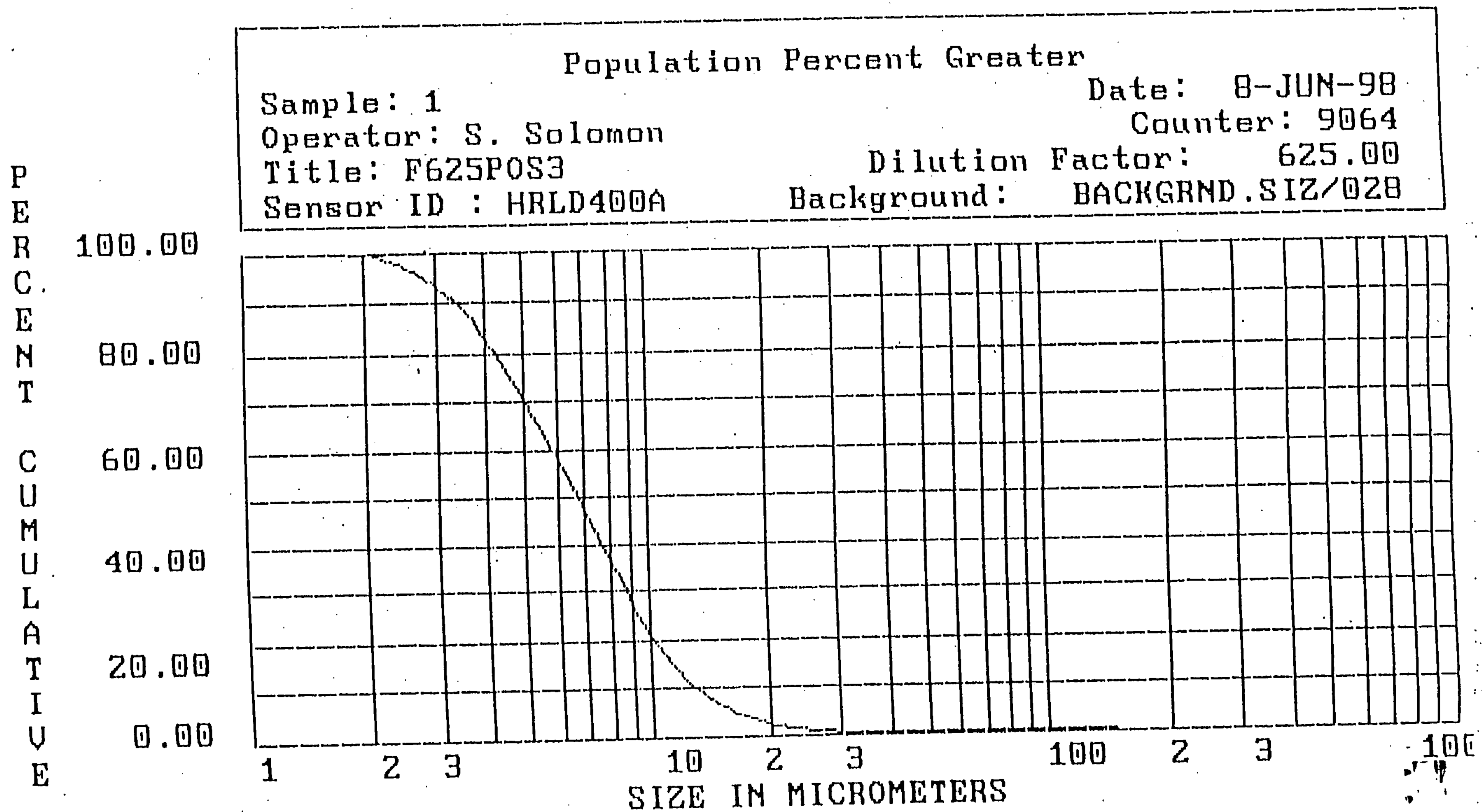

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Figure 4.3.13
25% Unpumped Surrogate With 5% Bentonite-Supernatant of Settled Material, at 10mm Depth Diluted 1:625.

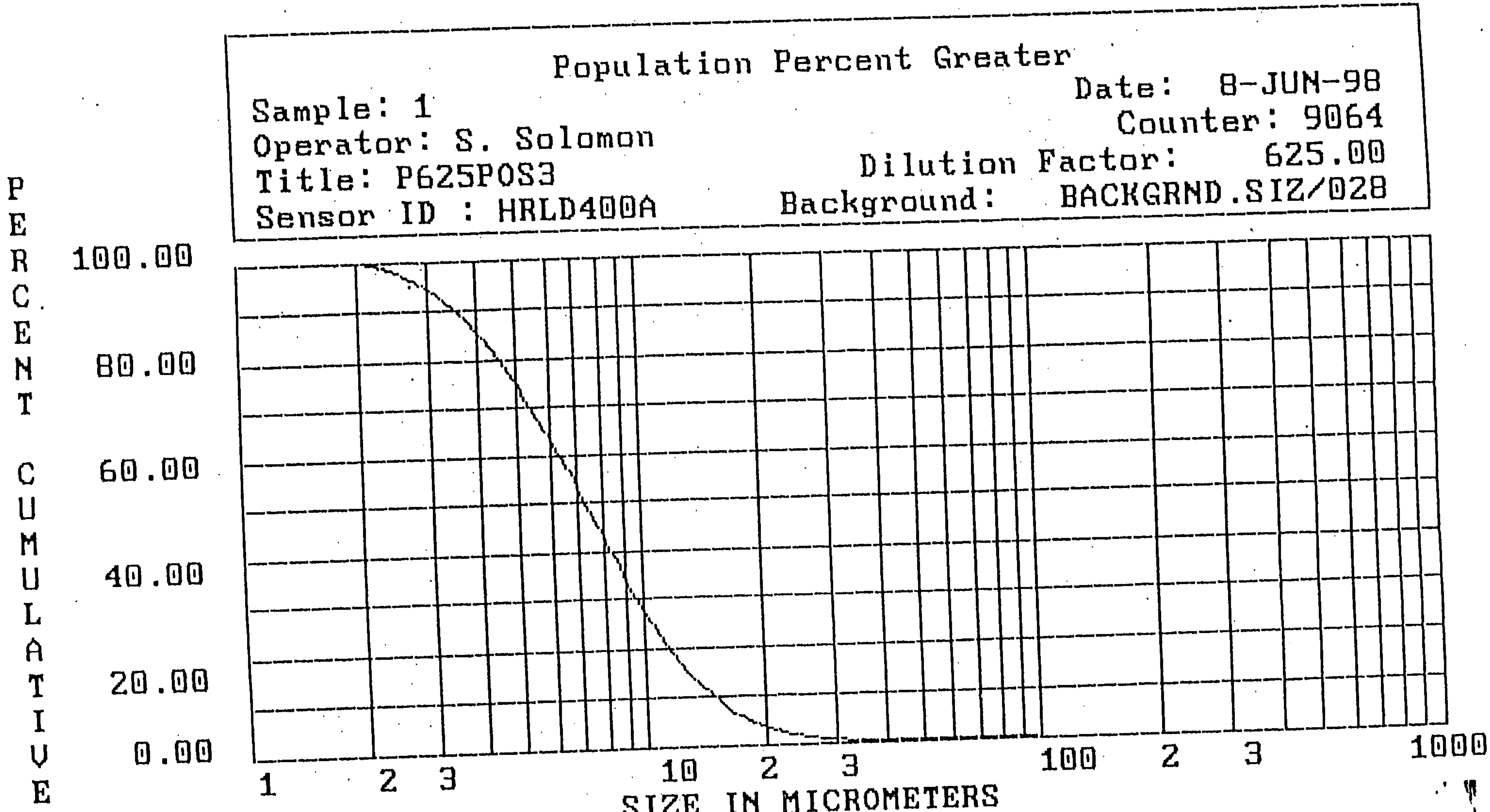

Figure 4.3.14
25% Pumped Surrogate With 5% Bentonite-Supernatant of Settled Material, at 10mm Depth, Diluted 1:625

8102

Figure 4.4.1: SURR1-5-F Incremental and Total Settling Distances

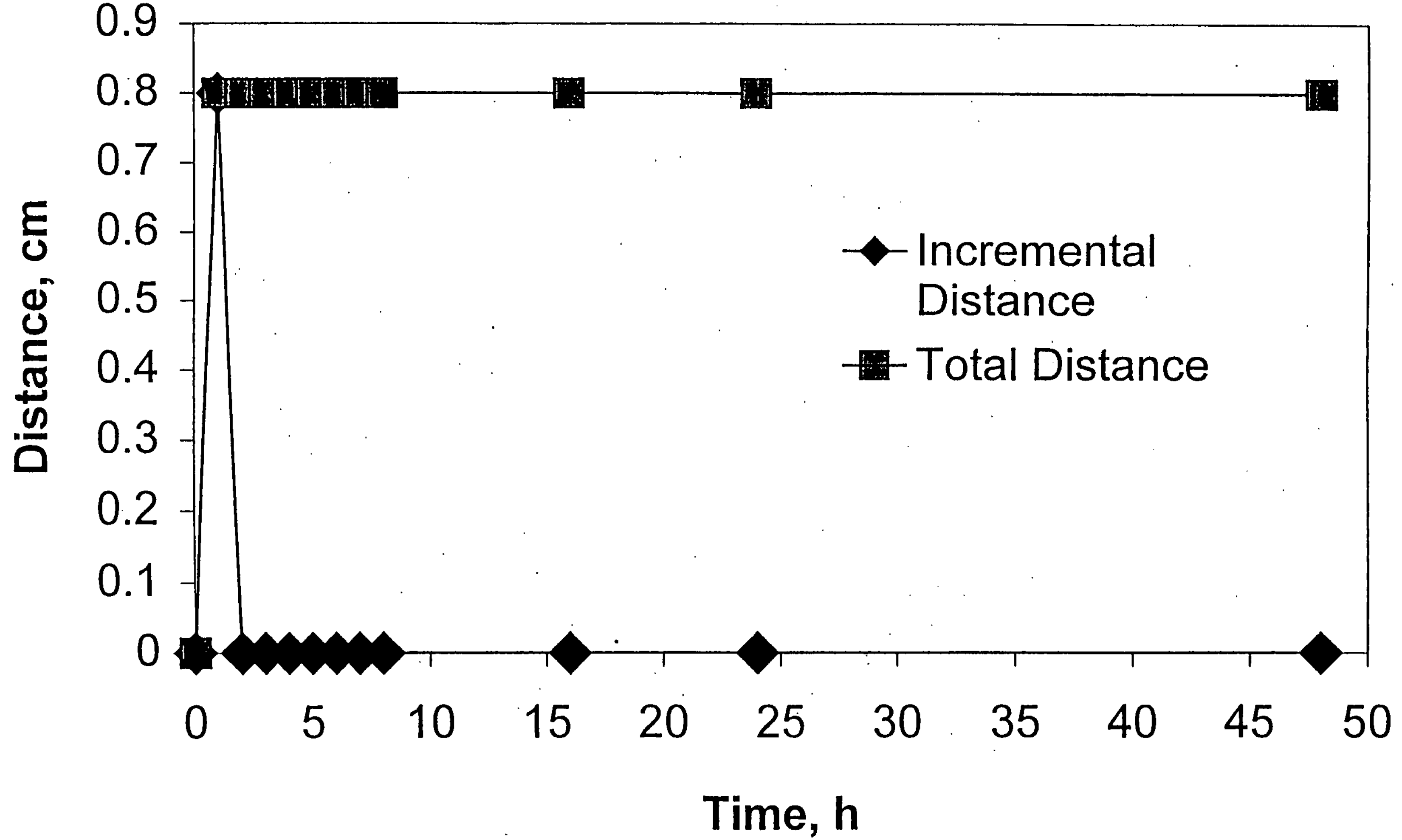

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Figure 4.4.2: SURR1-5-T Incremental and Total Settling Distances

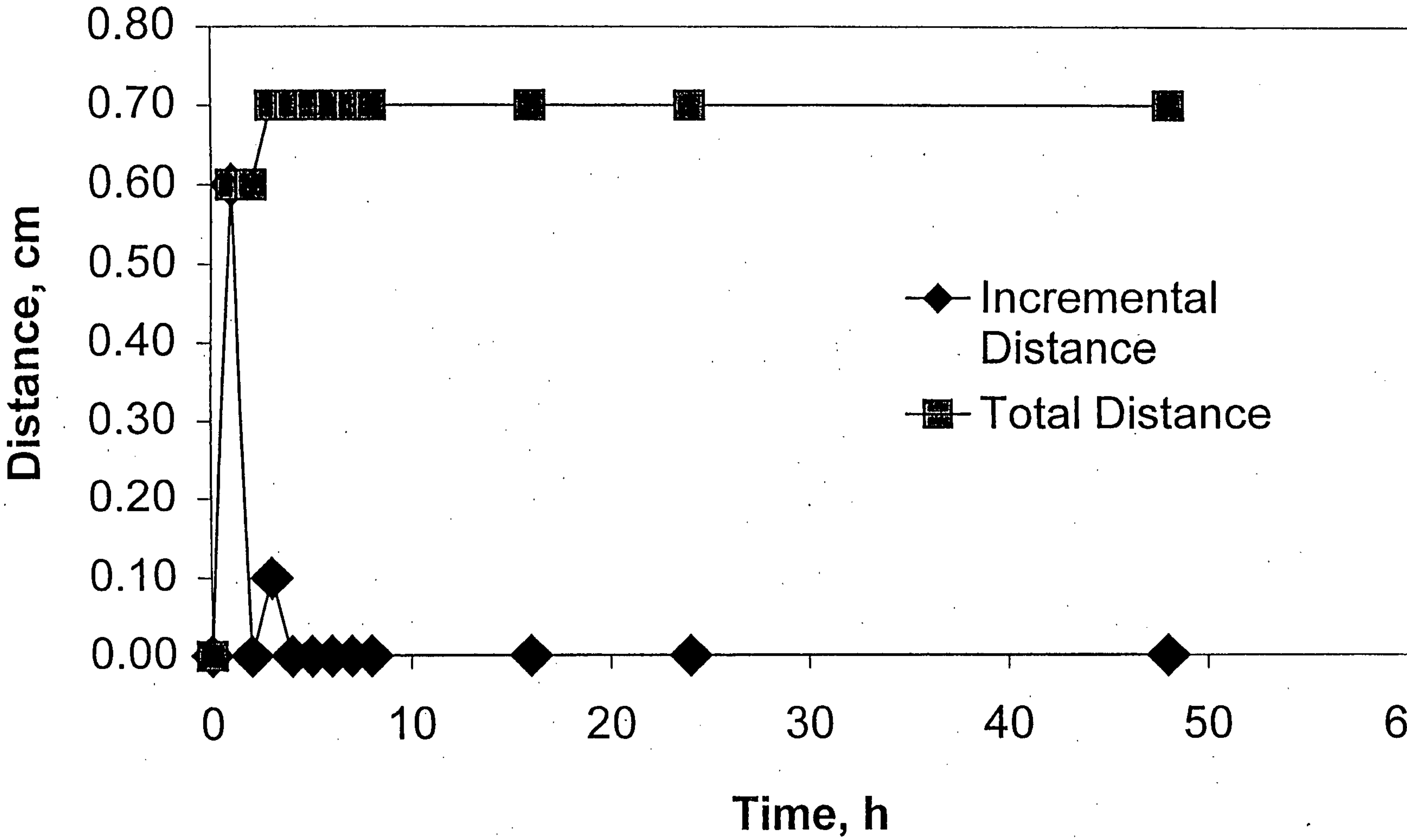

Figure 4.4.3: SURR1-25-F Incremental and Total Settling Distances

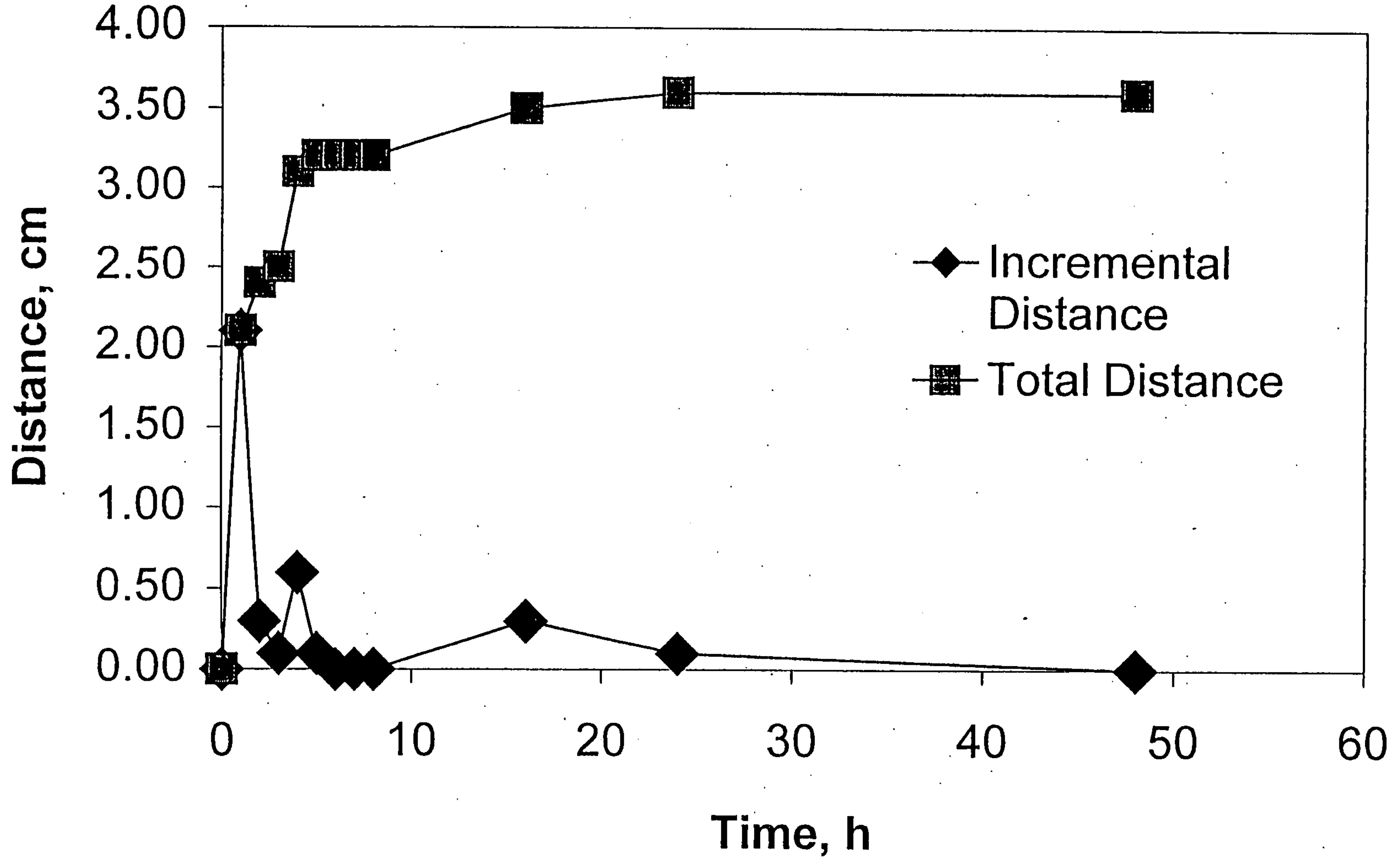

Figure 4.4.4: SURR1-25-T Incremental and Total Settling Distances

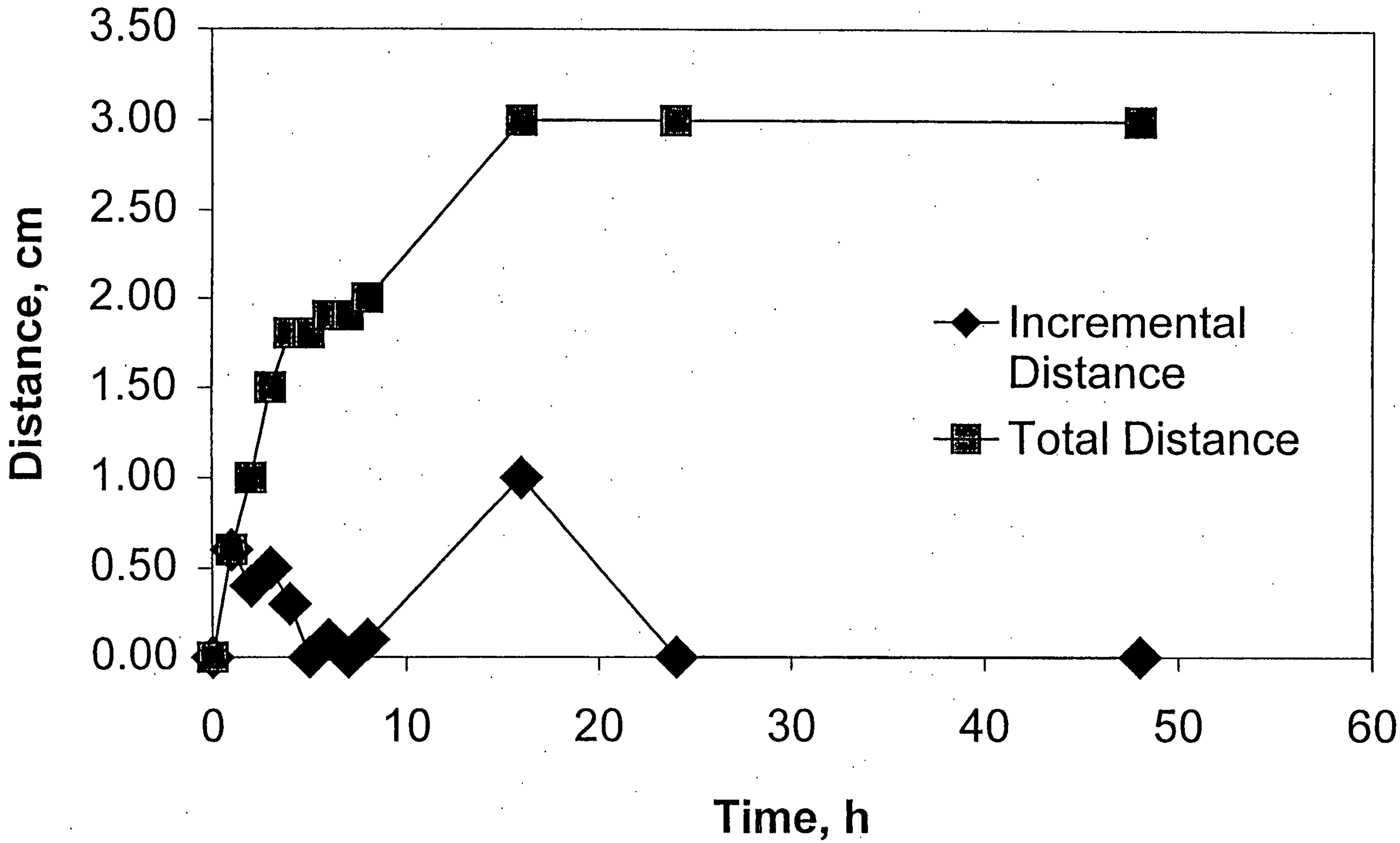

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Figure 4.4.5: SURR1-40-F Incremental and Total Settling Distances

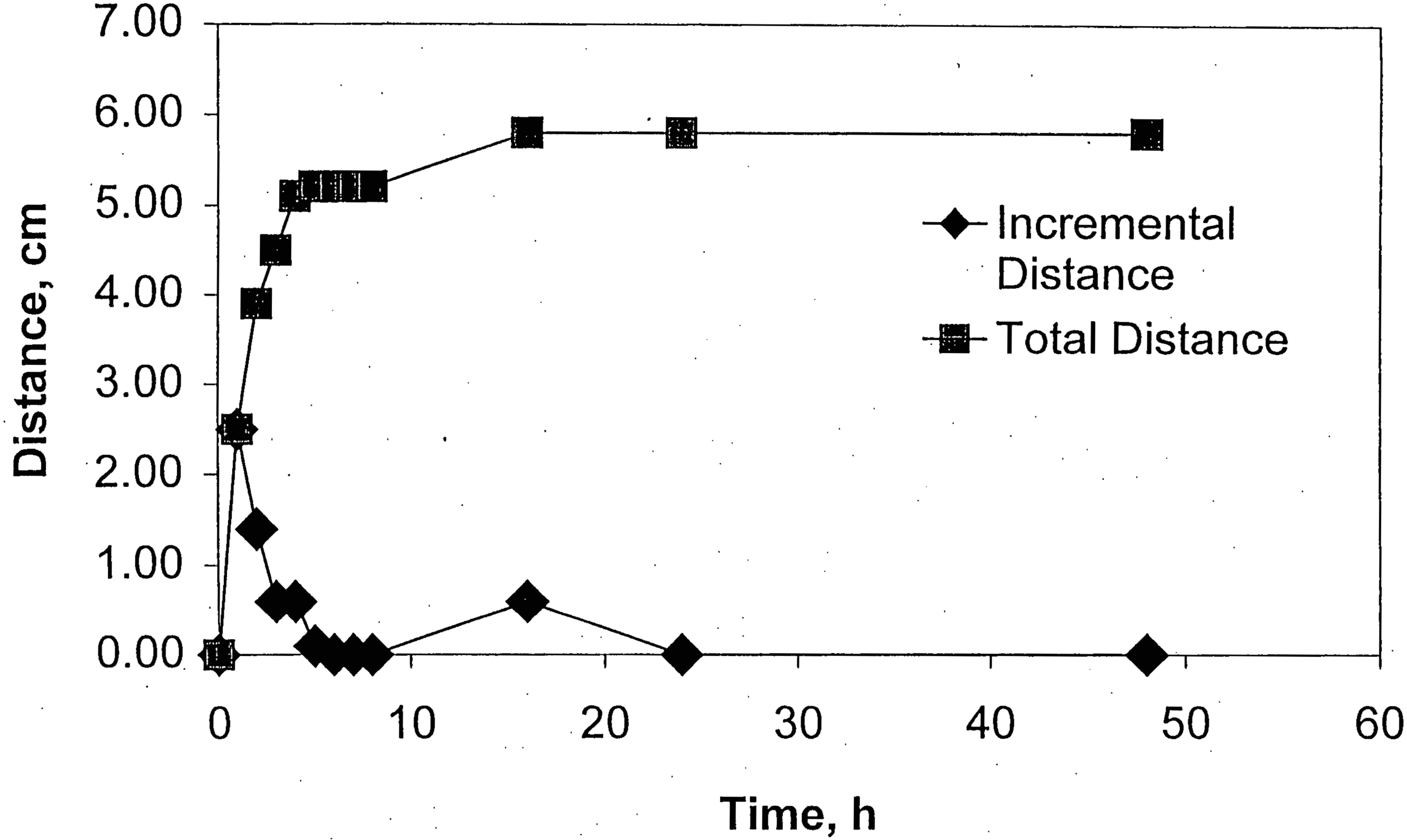

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Figure 4.4.6: SURR1-40-T Incremental and Total Settling Distances

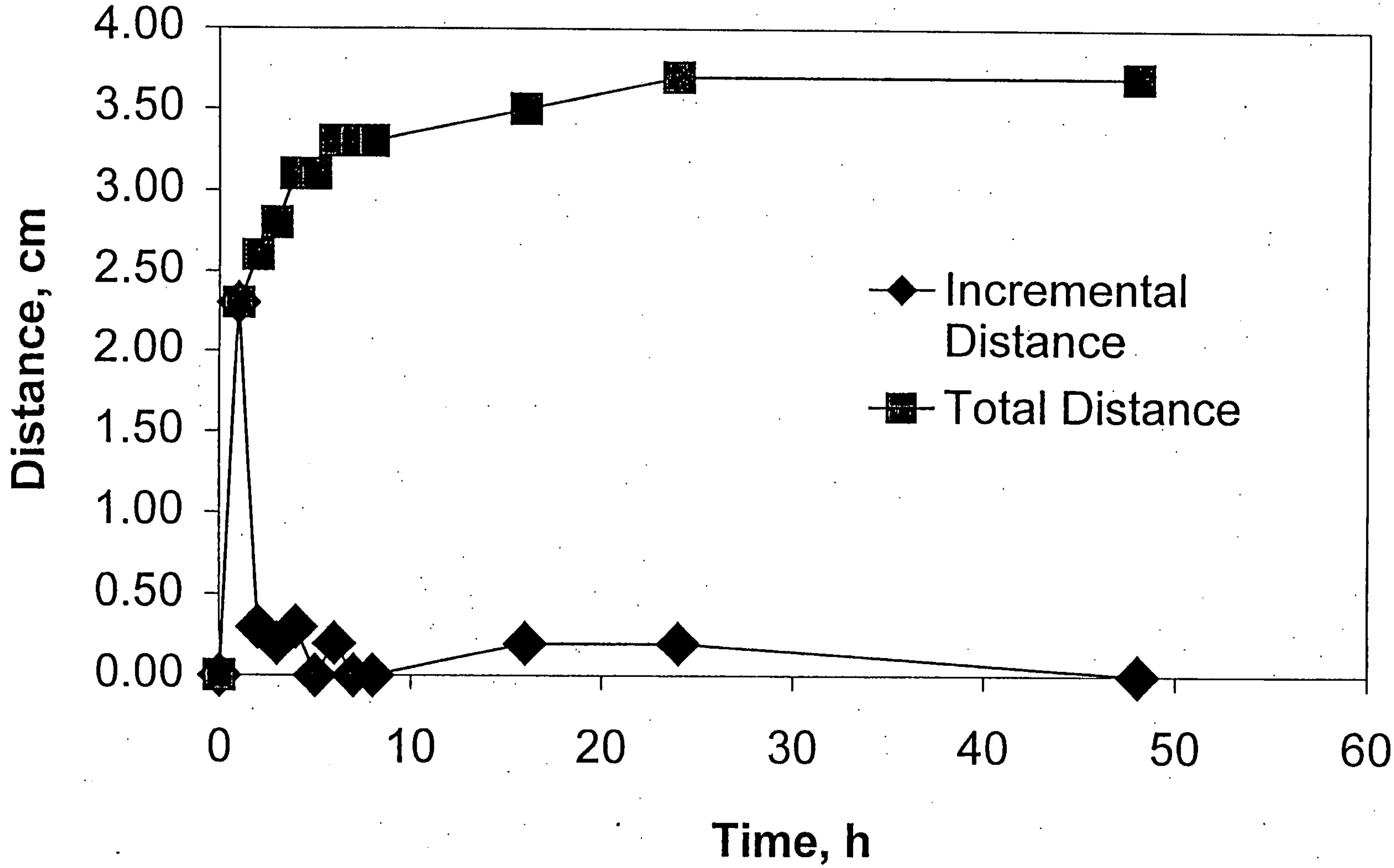

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Figure 4.4.7: SURR2-5-F Incremental and Total Settling Distances (H_3)

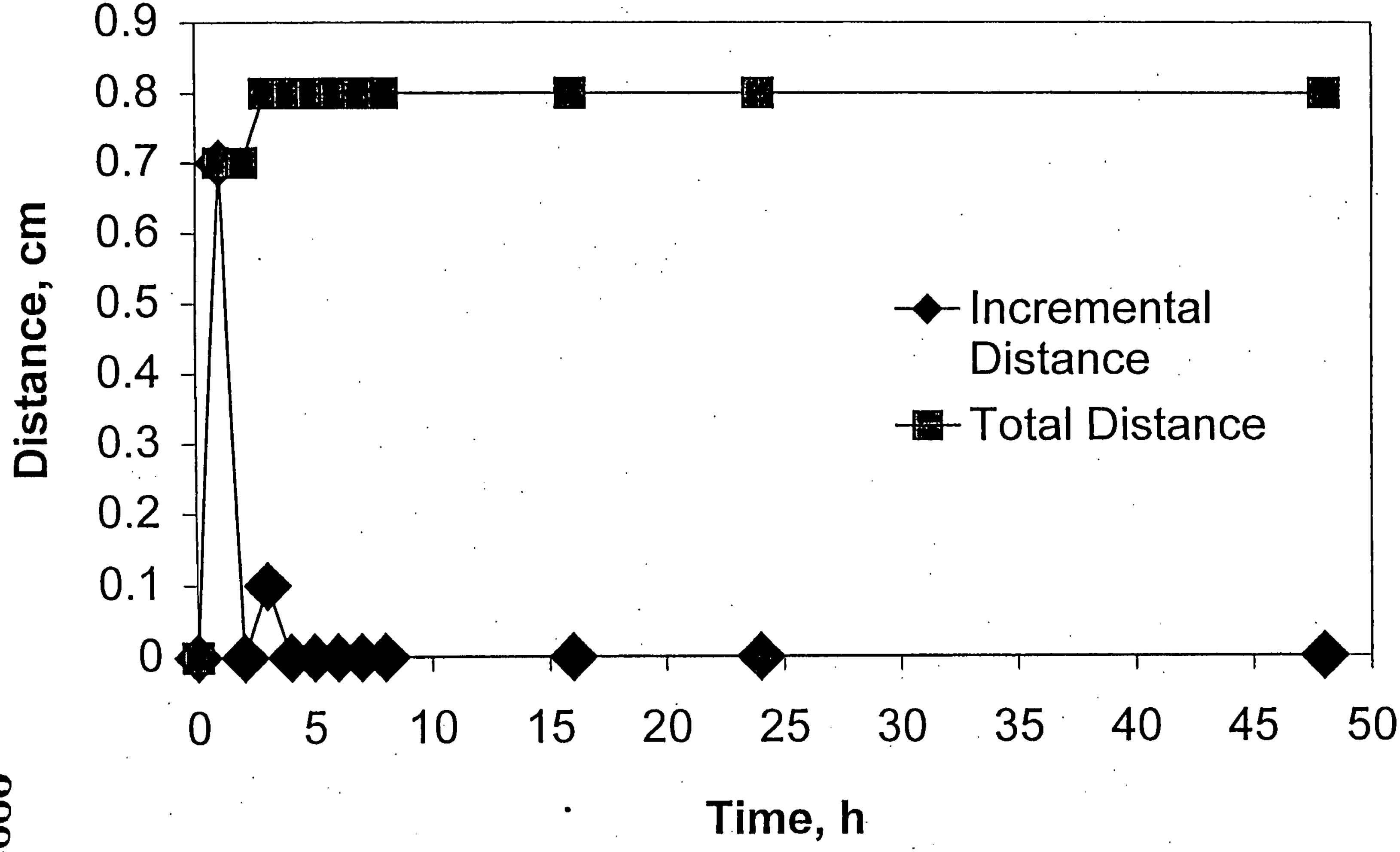

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Figure 4.4.8: SURR2-25-F Incremental and Total Settling Distances (H_3)

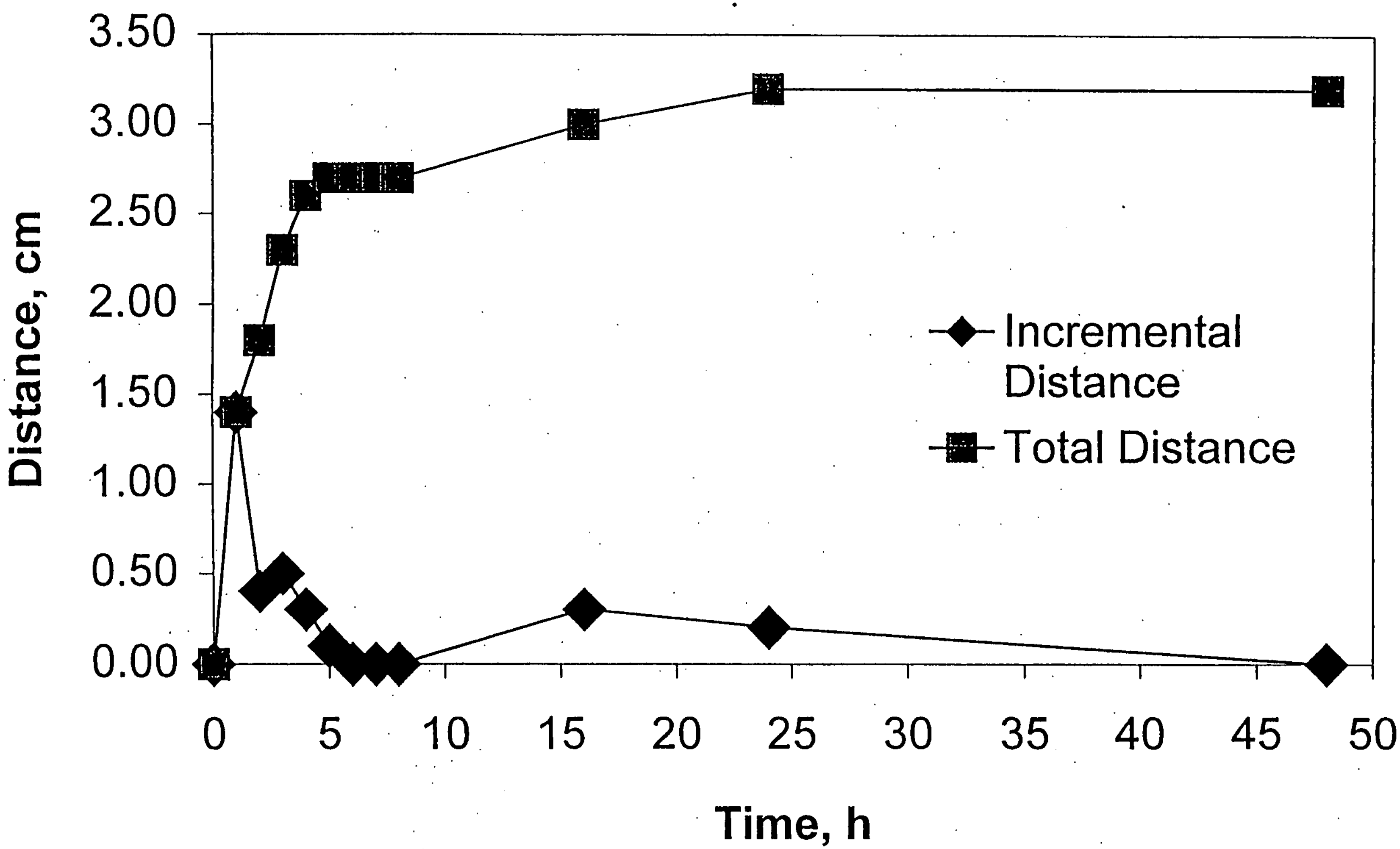

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Figure 4.4.9: SURR2-40-F Incremental and Total Settling Distances (H_3)

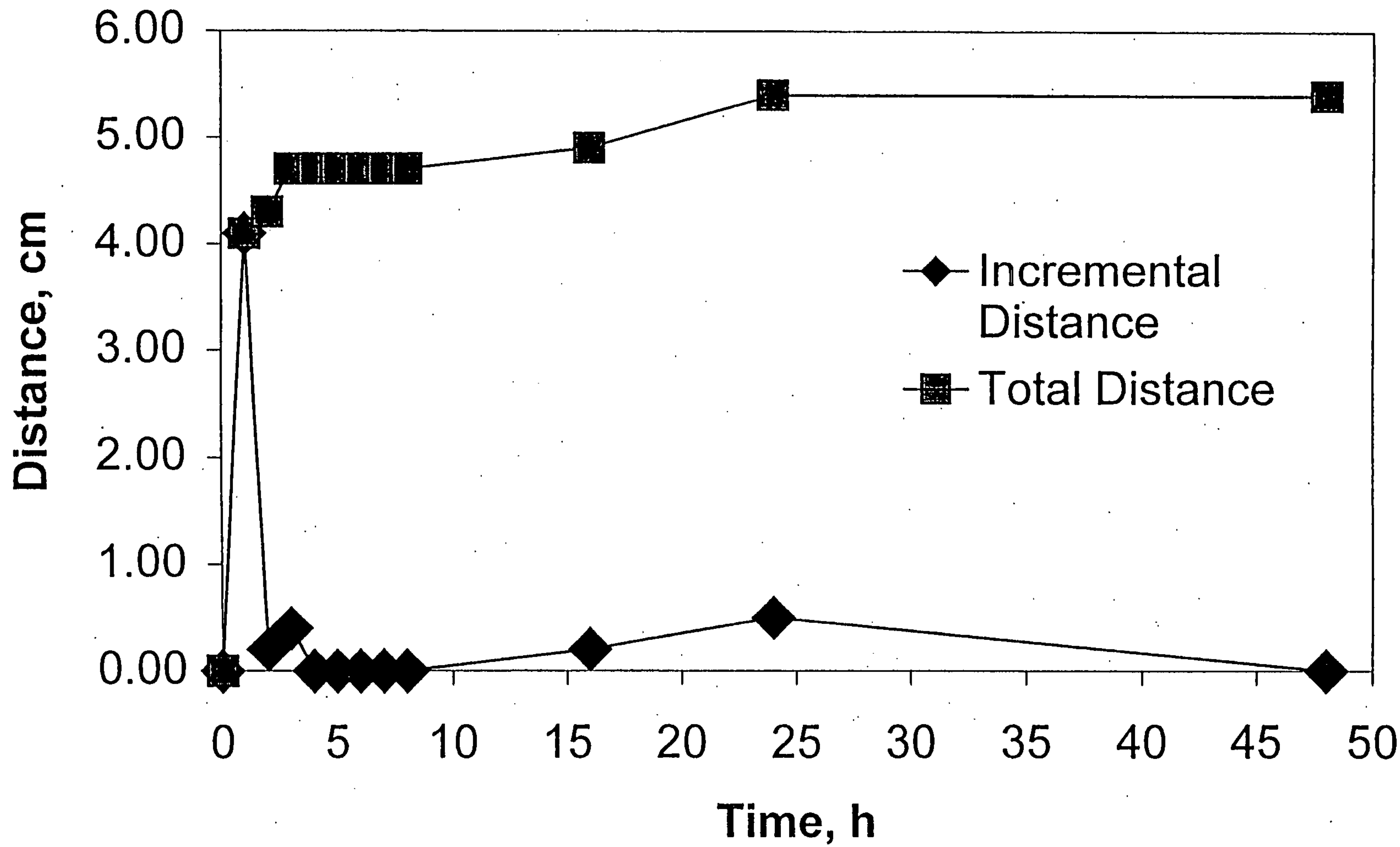

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Table 4.4.10: SURR2-5-5-F Incremental and Total Settling Distances (H_3)

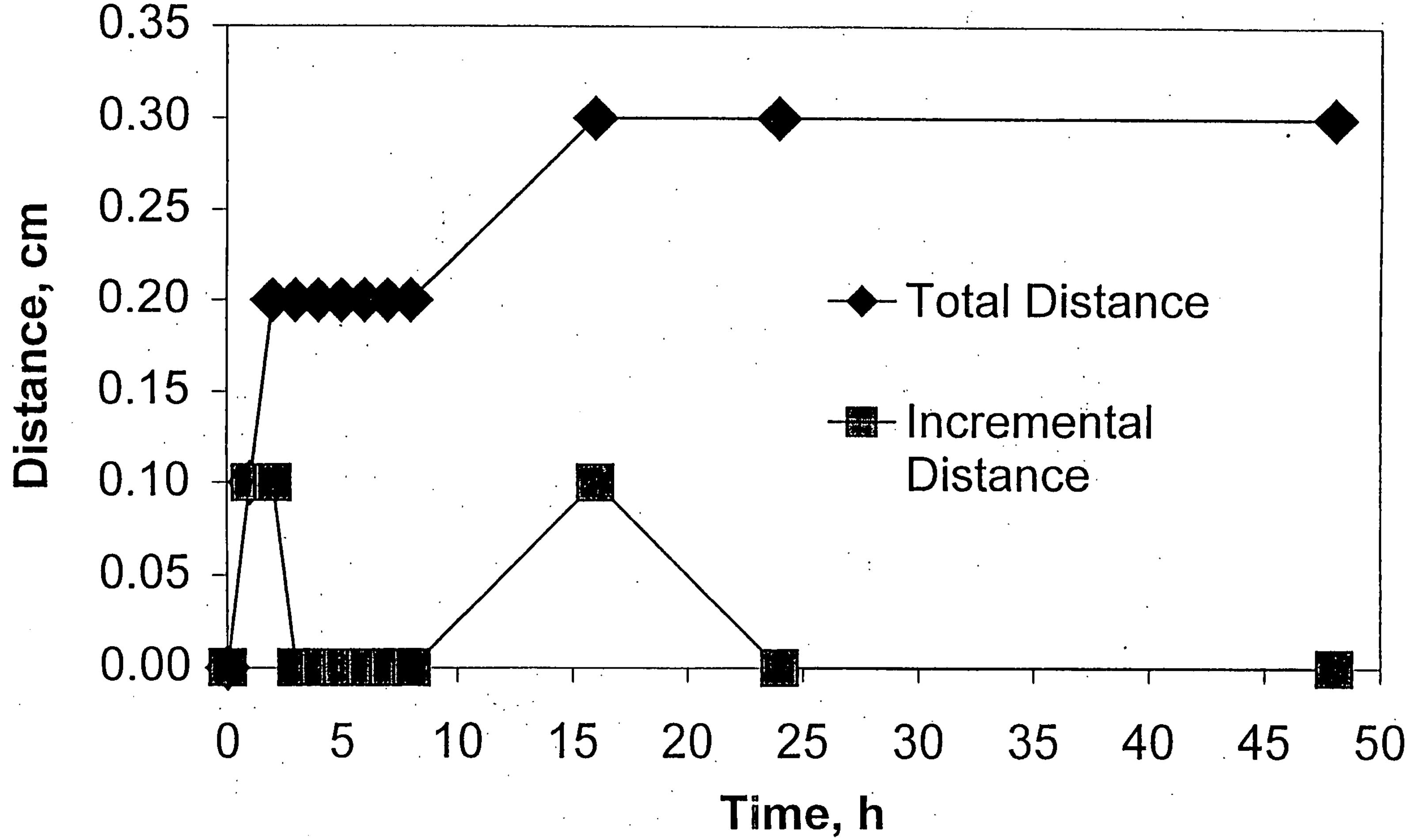

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Figure 4.4.11: SURR2-25-5-F Incremental and Total Settling Distances (H_3)

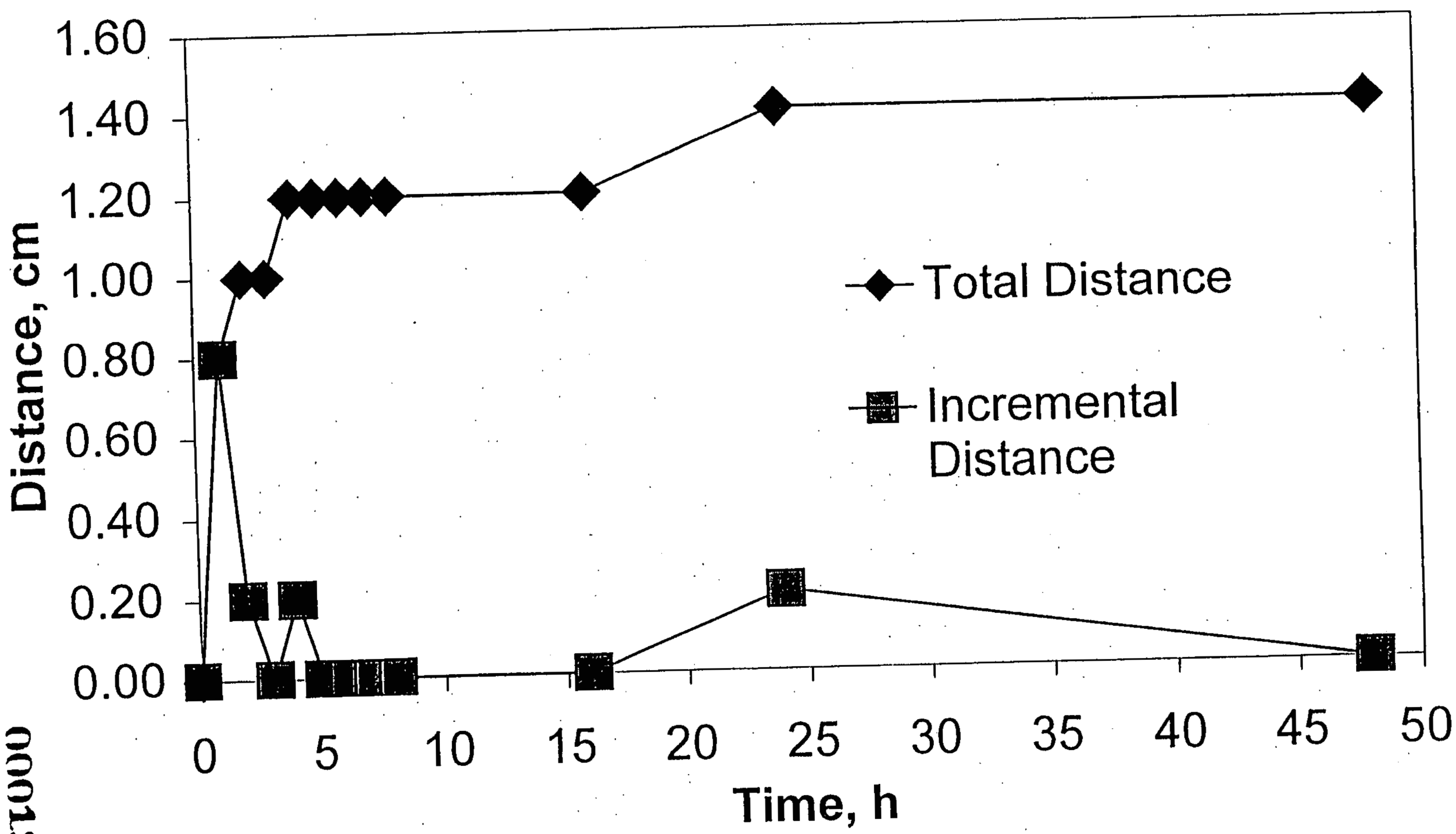

Figure 4.4.12: SURR2-40-5-F Incremental and Total Settling Distances (H_3)

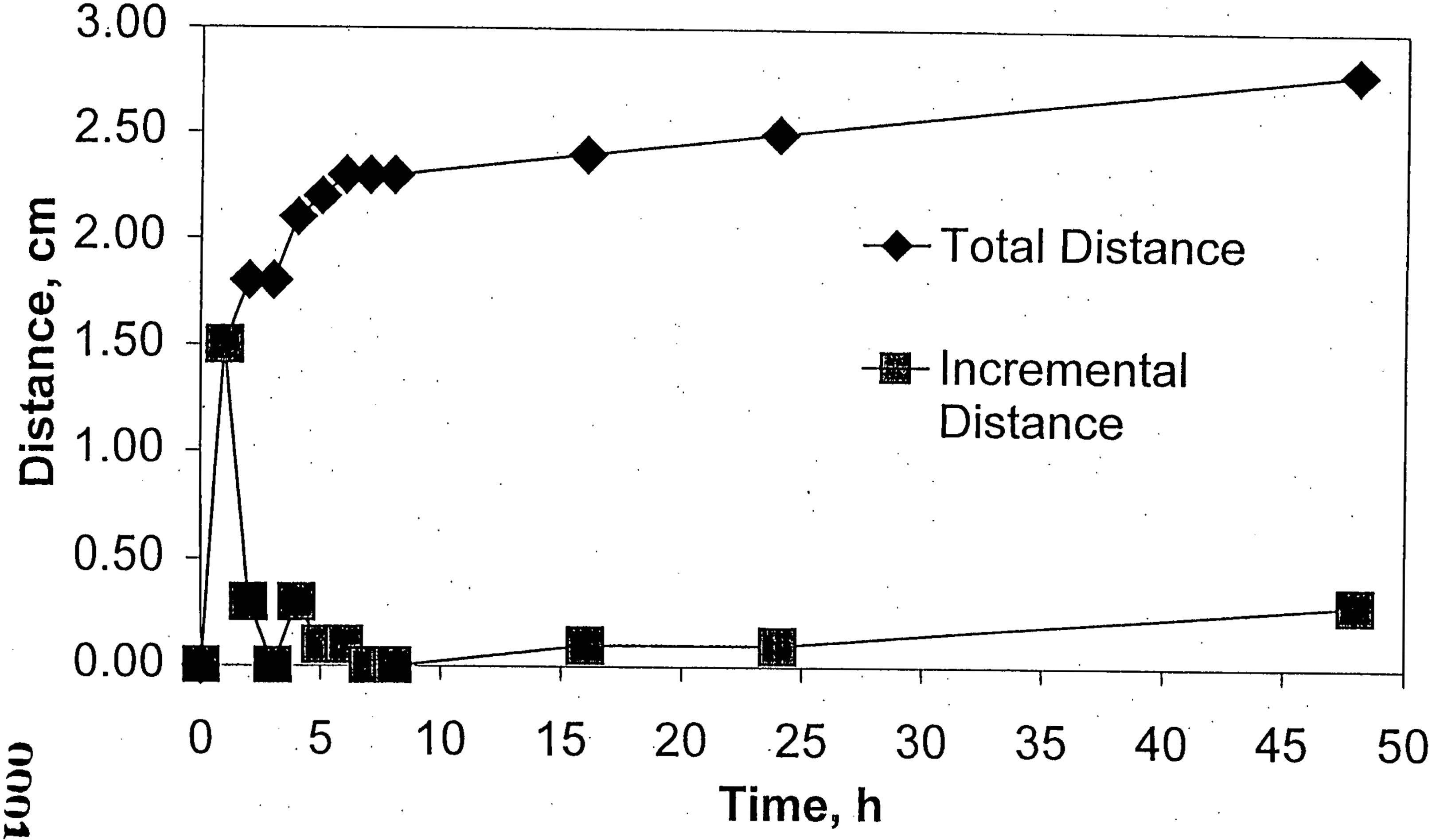

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Figure 4.4.13: SURR2-5-5-T Incremental and Total Settling Distances (H_3)

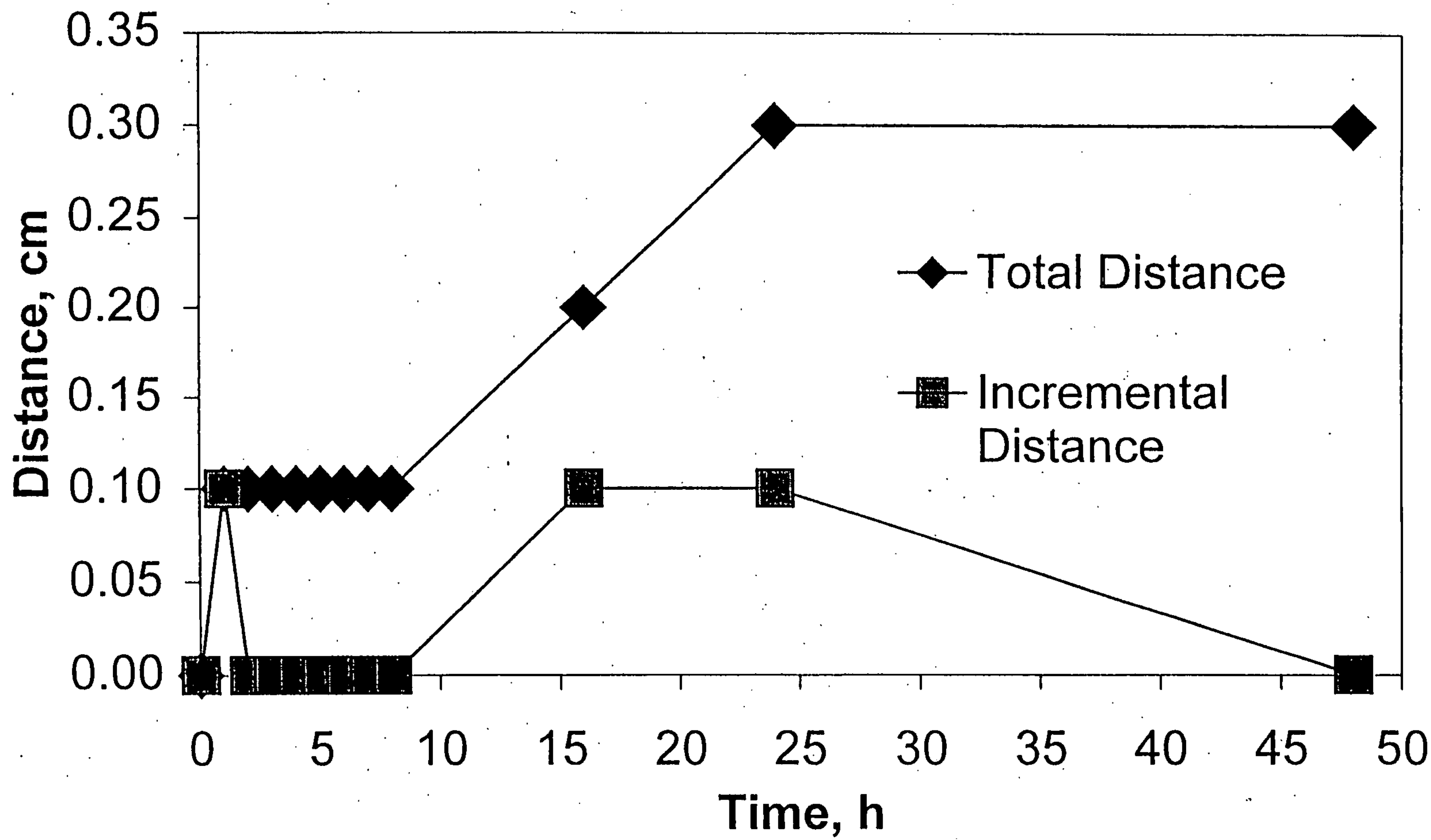

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Figure 4.4.14: SURR2-25-5-T Incremental and Total Settling Distances (H_3)

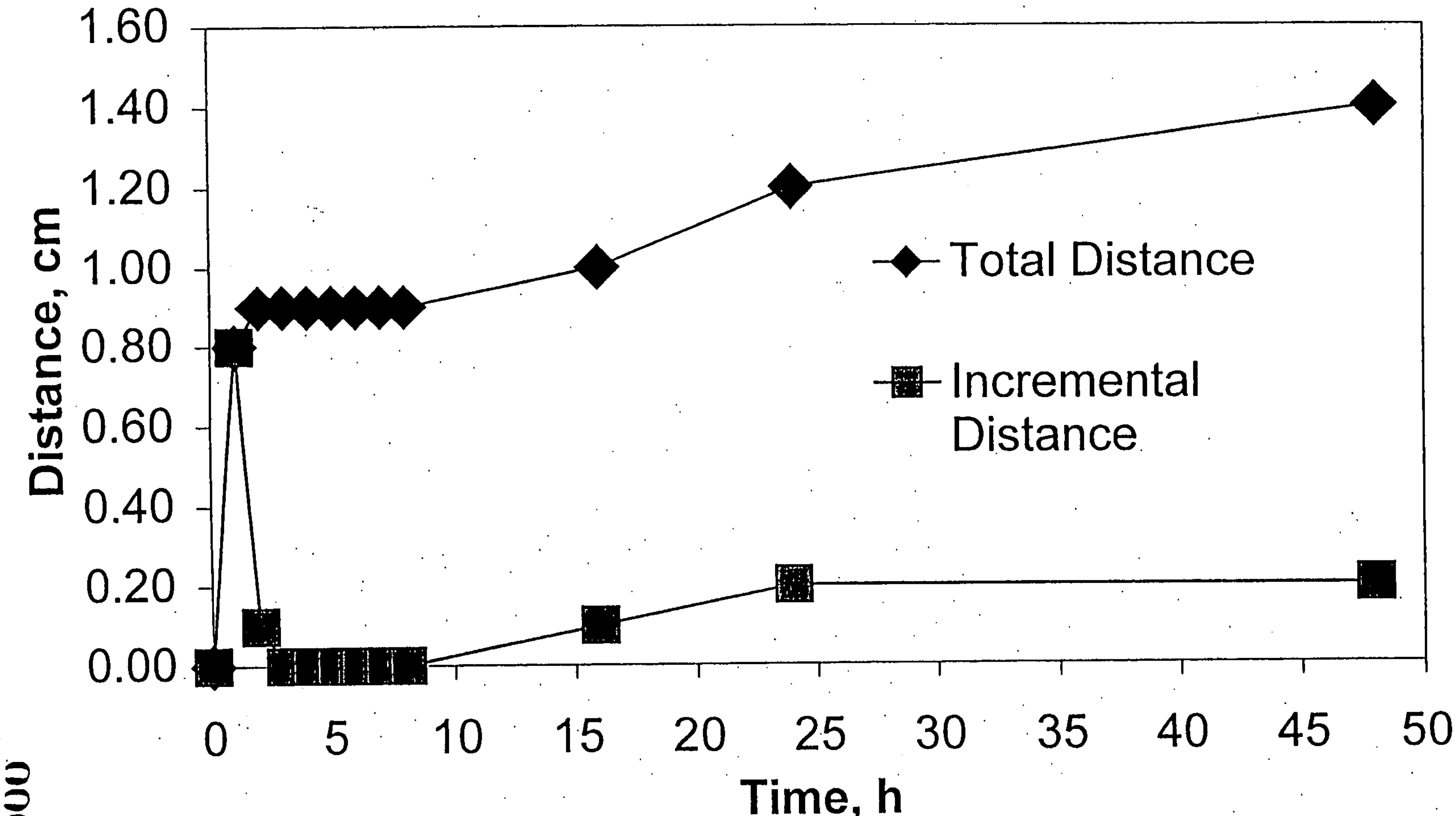
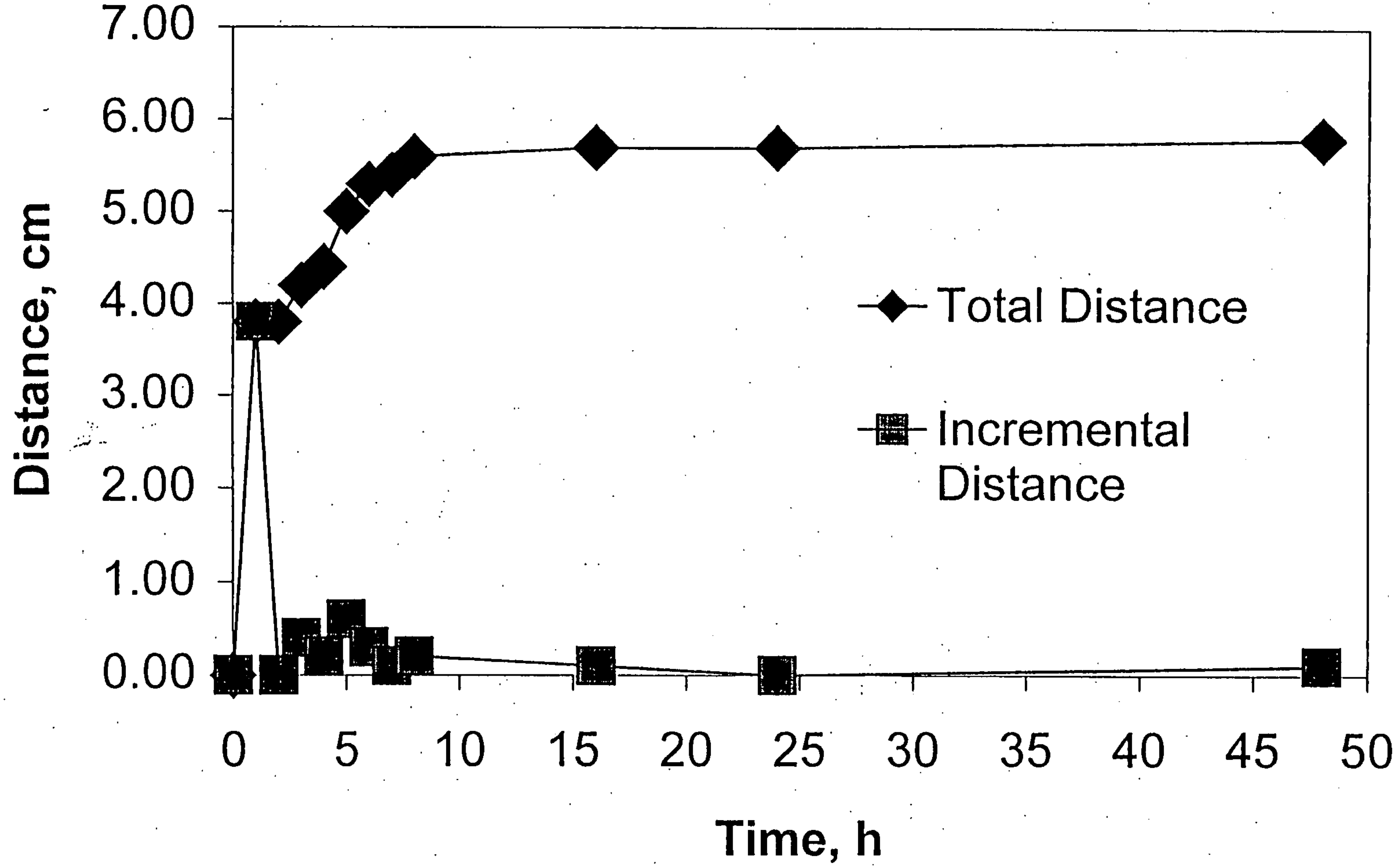


Figure 4.4.15: SURR2-40-5-T Incremental and Total Settling Distances (H_3)



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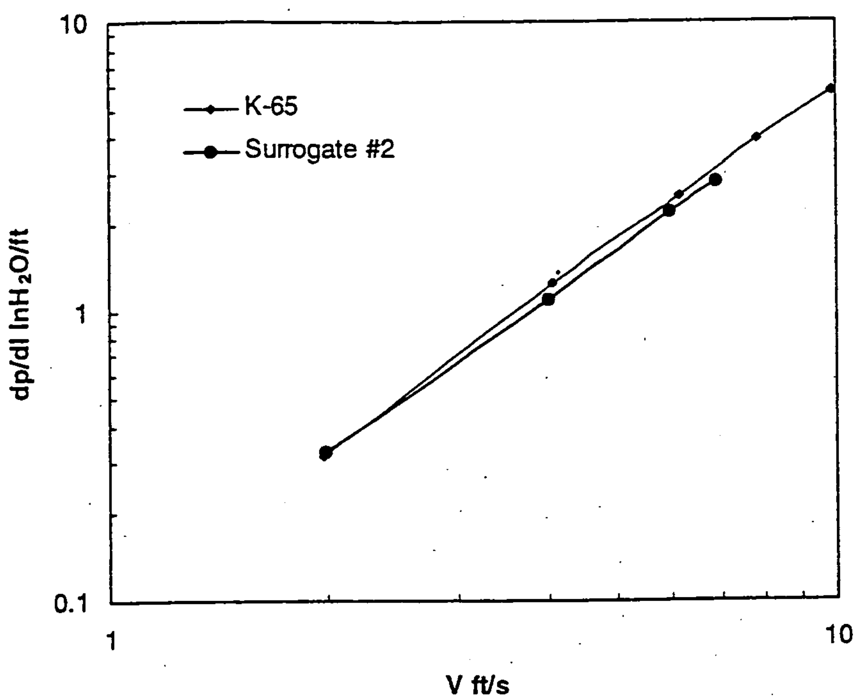

Figure 4.5.1 Comparison of pressure gradients of 25% slurries of K-65 and surrogate #2 without bentonite.

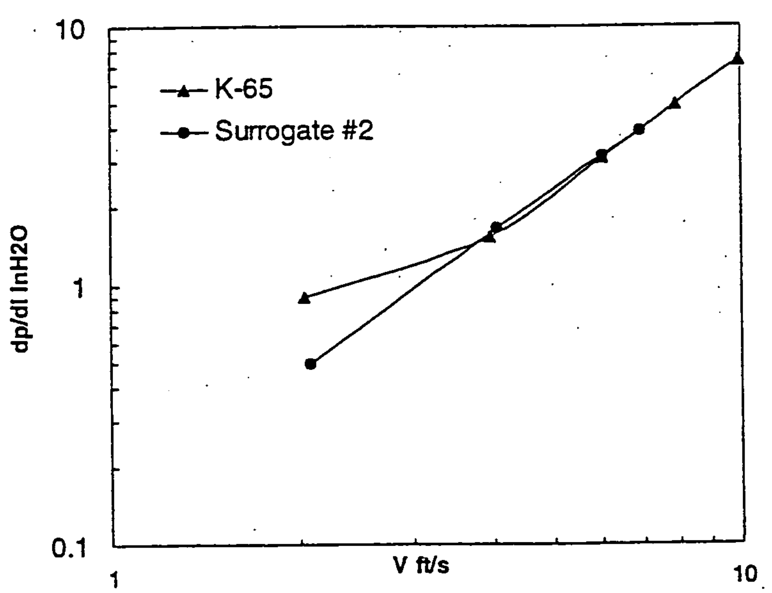

Figure 4.5.2 Comparison of pressure gradients of 25% slurries of K-65 and surrogate #2 with 5% bentonite.