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Testing Solids Settling Apparatuses for Design and Operation of Wet-Weather Flow Solids-Liquid Separation Processes

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Testing Solids Settling Apparatuses for Design and Operation of Wet-Weather Flow Solids-Liquid Separation Processes

by

Thomas P. O'Connor, David Fischer and Richard Field
Water Supply and Water Resources Division
National Risk Management Research Laboratory
Edison, New Jersey 08837
U.S.A.

John Cigana, Benoît Gagné and Martin Couture
John Meunier Inc.
Saint-Laurent, Quebec H4S 2B3
Canada

CRADA No. 136-96

Project Officer
Richard Field
Urban Watershed Management Branch
Water Supply & Water Resources Division
National Risk Management Research Laboratory
Edison, NJ 08837

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This study was a side-by-side comparison of two settling column tests: one traditional and one new. The newer apparatus was developed by the Centre d'Enseignement et de Recherche pour la Gestion des Ressources Naturelles et de l'Environnement (CERGRENE) of France and uses several small columns to sequentially measure particle-settling velocities. The new apparatus was compared with a larger, more traditional column, which has been widely used in the past as a research and academic tool, but it is difficult to transport and set up in a field location due to its size. The newer settling testing method was thought to be more amenable to field use because of ease of transport and sampling and the limited number of samples generated.

The study was conducted in three phases: fabrication and preliminary testing, laboratory testing, and field testing. Equipment for the two testing methods was fabricated and laboratory tested and preliminary evaluations were made. Laboratory tests were conducted with two well characterized settling media, microsand and clay soil in order to measure suspended solid (SS) concentrations and develop settling distributions of known substances in the columns prior to testing actual WWF which exhibits variable SS concentrations and settling distributions. Field tests were conducted at a combined sewer control structure to compare the performance of the two columns when filled with combined sewage.

A summary of the performance as measured by predicted percent removal of both columns for 15 laboratory tests and 3 field tests is presented, as well as a comparison of the advantages and disadvantages of the two methods. The newer testing method (CERGRENE) did not perform up to the anticipated theoretical expectations of the method. The report ends with conclusions and recommendations regarding the two specific methods and settleability test in general.

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Abbreviations

Centre d'Enseignement et de Recherche pour la Gestion des Ressources Naturelles et de l'Environnement	CERGRENE
Combined Sewer Overflow	CSO
Cooperative Research and Development Agreement	CRADA
Dry Weather Flow	DWF
Environmental Protection Agency	EPA
Quality Assurance	QA
Relative Percent Difference	RPD
Relative Standard Deviation	RSD
Standard Deviation	s
Suspended Solids	SS
Total Solids	TS
Urban Watershed Management Branch	UWMB
U.S. Environmental Protection Agency	EPA
United States Infrastructure, Inc.	USI
Volatile Suspended Solids	VSS
Wastewater Treatment Plant	WWTP
Wet Weather Flow	WWF

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1. INTRODUCTION

Background

This final report pertains to the laboratory and field evaluations of a side-by-side comparison of two settling column tests: one traditional and one new. The newer apparatus was developed by the Centre d'Enseignement et de Recherche pour la Gestion des Ressources Naturelles et de l'Environnement (CERGRENE) of France and uses several small columns to sequentially measure particle-settling velocities. This method was adapted for North American application by John Meunier, Inc. of Montreal, Quebec, Canada. Particle-settling-velocity distribution and pollutant content measurements made with the apparatus are intended to be used for wet-weather flow (WWF) treatment process selection and design, and for evaluation of preliminary or existing process operations that depend on solids-liquid separation.

The U.S. Environmental Protection Agency (EPA) National Risk Management Research Laboratory's Water Supply and Water Resources Division, Urban Watershed Management Branch (UWMB) in Edison, New Jersey, and John Meunier Inc. in Montreal, Quebec, Canada, established a Cooperative Research and Development Agreement (CRADA) (136-96) to develop settling columns suitable for obtaining particle-settling-velocity distribution data for WWF. This CRADA compared the new apparatus with a larger, more traditional column, and detailed the advantages and disadvantages of each method, quality assurance (QA) procedures, expected results, and the limitations for both settling-velocity-distribution tests for WWF. John Meunier, Inc. and the UWMB were jointly responsible for the fabrication, testing, and field evaluation of both technologies compared.

The traditional column has been widely used in the past as a research and academic tool, but it is difficult to transport and set up in a field location due to its size. The newer settling testing method was thought to be more amenable to field use because of ease of transport and sampling and the limited number of samples generated. The comparison attempted to predict whether these tests can capture the solids in WWF, particularly the rapidly settling particles, and whether both systems provide similar design information. Measurements of suspended solids (SS) for several settling times were used to compare the methods. A summary of each column's performance as measured by percent removal for 15 laboratory bench-scale and 3 field experiments is presented.

This study was performed in three phases (a flow chart Figure 1-1 also shows project development):

- **Phase I:** Preliminary screening - In phase I, different types of particles were tested to select the best media to be used in the benchtop laboratory studies and to assist in determining sampling and analysis procedures, experimental parameters, and number of samples required. Aspects of this phase were performed independently by both parties (UWMB and John Meunier, Inc.). Procedures were then adjusted to allow for any difficulties encountered.
- **Phase II:** Laboratory bench-scale experiments - The official QA-approved experimental runs of the side-by-side analysis of the two settling characterization methods were conducted in the laboratory of John Meunier, Inc. by both parties.
- **Phase III:** Field study - The side-by-side comparative study was continued at an offsite location (Perth Amboy Sewage treatment plant, Perth Amboy, New Jersey) predominantly by UWMB.

Chapters 3 and 5 cover most of the experimental results for Phases II and III, respectively.

Chapters 1 and 2 provide background information, Phase I findings, and experimental design for Phase II and III. In addition to the distinct phases of the experiment, there was some additional laboratory testing performed between phases II and III which is covered in Chapter 4. Chapter 6 discusses conclusions and specific recommendations.

This side-by-side comparison was intended to determine the limitations and advantages (e.g., cost, setup requirements, correlation to actual settling [in a primary sedimentation tank]) of each approach. Onsite settling column sampling better represents settling velocities than offsite (laboratory) testing because sample storage and transport prior to the settling test may change the naturally occurring matrix of settleable material. The field settling samples were delivered immediately to the UWMB laboratories and analyzed for various solids parameters. The Perth Amboy Sewage treatment plant was approved by both parties for the sampling of combined sewer overflow (CSO).

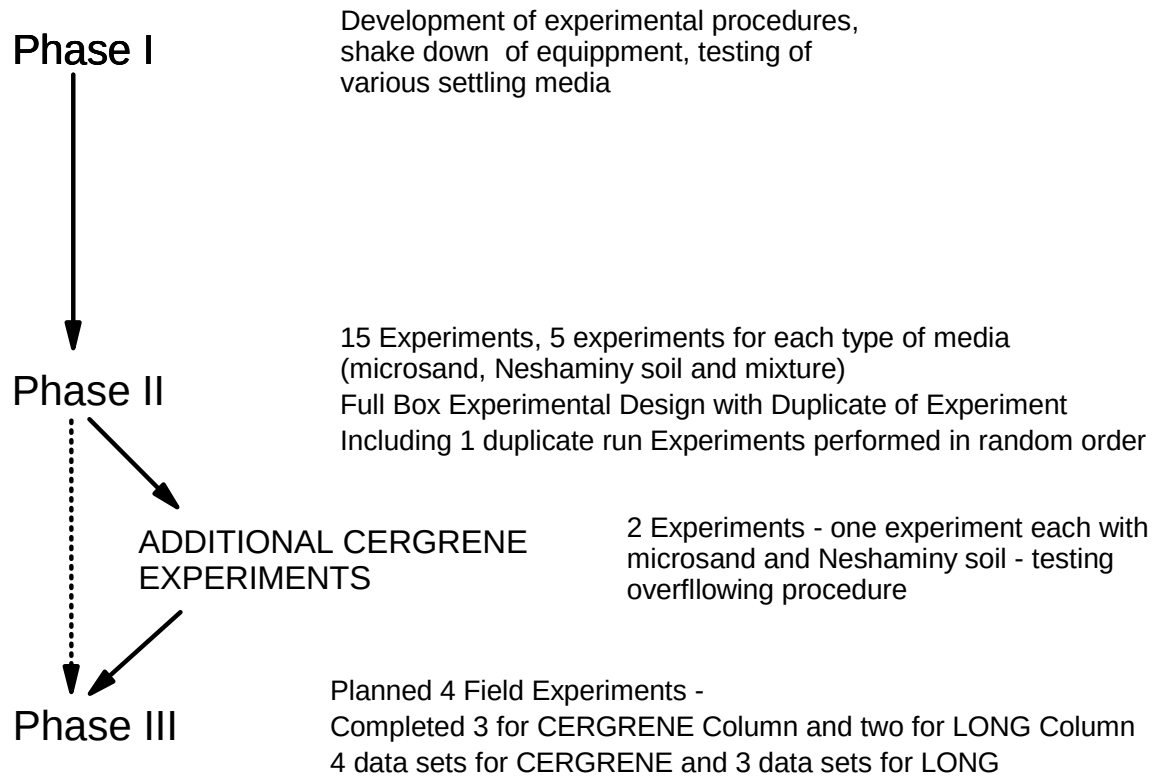

Figure 1-1 Flowchart of Project

Objectives

The monitoring and analysis needed for proper selection, application, assessment, design, and evaluation of WWF treatment are expensive, time consuming, and complex; however, reliable data collection may save even more costly construction costs by eliminating unnecessary facilities and/or additional controls. The particle-settling-velocity distributions of WWF samples as related to total solids (TS), SS, and associated pollutant content are essential for proper assessment of high-rate settling and solids-liquid separation technologies.

The objective of this study was to compare sampling and analytical procedures of two settling column techniques used to characterize the settling velocity of SS in WWF. The results

were intended to aid engineers in obtaining pertinent WWF pollution-abatement facility selection and design data by analyzing particle-settling-velocity distribution and the settleable solids and SS fractions.

Low cost, expedient methods to obtain facility-design data or settling-velocity distributions are necessary because WWF characteristics are highly site specific. In order to test the viability of the newly developed CERGRENE columns, a comparison to a settling method with a precedent was needed. Thus, a traditional column settling method was used.

Combined Sewer Overflows

CSO are a mixture of storm drainage and municipal-industrial wastewater discharged from combined sewers typically when the flow capacity of a sewer system is exceeded during rainstorms. The EPA National Combined Sewer Overflow Control Policy (59 Federal Register 18688) (CSO Policy) guidance "Combined Sewer Overflow - Guidance for Nine Minimum Controls" (EPA, 1995) requires:

- Maximization of flow to the publically owned treatment works (POTW) for treatment
- Control of solid and floatable materials in CSOs

and "Combined Sewer Overflow - Guidance for Long-Term Control Plan" (EPA, 1995) further requires:

- Characterization, monitoring, and modeling activities as the basis for selection and design of effective CSO controls
- Evaluation of alternatives that will enable the permittee, in consultation with the National Pollutant Discharge Elimination System (NPDES) permitting authority, water quality standard (WQS) authority, and the public, to select CSO controls that will meet Clean Water Act (CWA) requirements
- Cost/performance considerations to demonstrate the relationships among a comprehensive set of reasonable control alternatives
- Maximization of treatment at the existing POTW for WWFs

The CSO Policy recommends control/treatment without defining the need for analysis of the flow characteristics and constituents to obtain design information. Determining certain flow characteristics and constituents will optimize the selection and design of unit processes for various degrees of established physical treatment technologies, e.g., vortex separation, screening, sedimentation, flocculation-clarification, dissolved air flotation, and filtration, and assist in the assessment of newer technologies, e.g., microcarrier coagulation-sedimentation processes. Site specific, storm-event evaluations are needed for designing CSO treatment facilities, as CSO differs from dry-weather flow (DWF). Combined sewer overflow settleable solids build-up and characteristics in the sewer system are a function of the length of the antecedent dry-weather period, sewer slope and cross-sectional area, drainage area (catchment) size, flowrate, and drainage area soil characteristics, etc., whereas DWF SS characteristics (barring industrial sources) are similar from place to place. Furthermore, settleable solids and SS concentrations can vary with time during storm events and from storm to storm.

Studies have identified urban stormwater runoff as a major contributor to the degradation of many urban lakes, streams, and rivers. Industrial and commercial parking lots, material storage areas, and vehicular service stations are the most significant contributors of a variety of pollutants to WWF. Chebbo et al. (1990) found that the fine particles which make up the majority of SS are also the principal vector of pollution in stormwater during wet weather. Fine particles (< 50 **:**m) found in stormwater can achieve settling velocities of 2.5 m/h (0.07 cm/s) or more (Chebbo et al.,

1990); 70 to 80% will deposit within 15 min and more than 97% after 1 h.

Settling Columns

The traditional method for determining settling-velocity distributions is a batch test that uses a large column equipped with vertically spaced side ports or syphon tubes to obtain samples for solids analysis. Camp (1945) published settling curves using Stoke's Law based on particle settling. Eckenfelder (1966) described the use of a large column as a design aid for sedimentation processes and for analysis of flocculation. There is substantial variability associated with this method (referred to as the Long column in the remainder of the document).

Currently, only one method for measuring gravity separation is accepted by Standard Methods (SM 2540.F.b; 19th Edition), called "settleable solids". A sample is pipetted from the center of a column of at least 20 cm in depth after 1 h of quiescent batch settling to directly determine the nonsettleable solids. The settleable solids are then determined by subtracting the nonsettleable solids concentration from the initial SS concentration. However, this method neither determines particle-settling velocity nor enables calculations for settling-velocity-distribution curves. This gravimetric method only measures the initial and final SS concentration after 1 h. There are no quality control limits or QA data for the method.

Traditional Long Column

The typical traditional Long column is a relatively large apparatus (Camp, 1945; Eckenfelder, 1966; Dalrymple et al., 1975; in addition to being described elsewhere), standing 1.8 to 2.5 m (6 to 8 ft) high with a diameter of 20 to 30 cm (8 to 12 in.) and side withdrawal ports evenly spaced along the column depth. The height of the column simulates the effective settling depth which occurs in a sedimentation tank typically having constructed depths exceeding 2.5 m (8 ft). The Long column requires an extensive laboratory layout and is not readily adapted for use in field situations. Depending on specific dimensions, between 40 and 80 L (10 and 20 gal) are required to fill the column. The initial water height in the column is measured. The samples, withdrawn from the side ports sequentially from top to bottom at predetermined time intervals, require further SS analysis. After each set of samples is collected, the depth of the water in the column is measured.

The most notable difficulty with the Long column method is the inability to develop a homogeneous initial SS concentration at the initial sampling time, t_0, due to the heavy particles in WWF. This is partially caused by keeping the large volume in the Long column well mixed prior to sampling and the time required to withdraw samples from all ports sequentially. Various methods have been used to pre-mix the sample before the column test begins, e.g., plunger plates. Pisano et al. (1984) went to the extent of mounting the Long column on a device that allowed horizontal and vertical axial rotation in an attempt to achieve a better estimate of SS concentration at t_0. It is almost impossible to have a homogeneously mixed sample using the Long column for WWF, which may result in predictions of lower than actual SS concentrations.

CERGRENE Columns

CERGRENE (Chadirat et al., 1997) developed a new design that uses several small columns to analyze the particle-settling velocities. Instead of sampling various fractions with a single sampling device, the CERGRENE protocol uses different settling columns. The CERGRENE settling columns, like the Long column, are designed to estimate SS concentrations of the WWF in the original sewage matrix.

The new CERGRENE columns have a shorter time to fill (< 10 s) which should provide an aliquot that better represents the completely mixed contents at the initial sample time, t_0. It is thought that the CERGRENE column may account for a wider range of settling solids which may result in establishing better design parameters for WWF. The CERGRENE column was designed

for field as well as laboratory use. Settling-velocity-distribution samples taken in the field should give a truer representation of the settling velocities of the combined sewage. This should also provide a better representation for design purposes than samples transported to the lab or stored in the lab for longer periods of time, due to less time allowed for agglomeration.

Other Columns

Other settling-velocity-distribution methods developed in Europe are:

- Brombach or German (Michelbach and Wöhrle ,1993; Pisano and Brombach, 1996);
- Norwegian Institute for Water Research (NIVA) (Lygren and Damhaug, 1986; Walker et al., 1993); and
- University of Aston, U.K. (Tyack et al., 1993)

These methods were specifically designed for the relatively high concentration of heavier particles in storm-generated flows, and accordingly, may offer several benefits over the Long column for field analysis. They require fewer analyses, yielding one sample per time measurement withdrawn from the bottom as opposed to several simultaneous samples from the multiple-side ports. These devices use testing volumes of approximately 4 to 12 L (1 to 4 gal). The Brombach and the NIVA columns (less than 1 m deep and 5 cm wide) are more amenable to field use. These methods also provide a truer representation of high settling-velocity SS because the concentrated sample is situated above the settling column and dropped into it at t_0. The Aston column stands at least 2.2 m tall and requires more assembly than the other two, as it rotates about the center of the column.

Unlike the Long and CERGRENE settling column designs which sample the WWF mixture, the Brombach and NIVA methods separate, dry, and then reintroduce the SS into clean water. The Aston column was previously tested directly against various forms of the CERGRENE column (Aiguier et al., 1995). Results of these tests suggested that the derived settling-velocity curves from the various innovative methods tend to give different results. For this reason, only the Long and the CERGRENE columns were analyzed for the purposes of this project.

Theory of Settling Design

Several factors are used in the design of a settling basin including design flow, required detention time, and desired percent removal. In order to design for percent removal, the characteristics of the SS in the WWF must be taken into account. For settling tanks (Tchobanoglous and Burton, 1991), the design velocity, V_c (m/s), can be related to the liquid depth, D (m), in the tank and the detention time, t_d (s), as follows:

$$V_c = D/t_d \qquad (1\text{-}1)$$

Given a certain flowrate through the settling tank, Q (m^3/s), and the plan area of the tank, A (m^2), Vc (m/s) can be related to the overflow rate, q ($m^3/m^2/s$ or m/s), in the following manner:

$$V_c = q = Q/A \qquad (1\text{-}2)$$

This assumes that all SS with a settling velocity > V_c or q will be removed with some fraction of all other particles with settling velocities < V_c also being removed. For the purposes of this project, q will be used as a surrogate for a design settling velocity, instead of V_c, which inherently implies a single design settling velocity for a particle instead of a settling-velocity distribution.

Settling can also be broken down into four types: discrete, flocculant, hindered, and compression (Tchobanoglous and Burton, 1991). The settling velocities of discrete and flocculant particles are of most concern with respect to WWF. The hindered and compression zones of settling are issues of high concentration waste streams, which typically occur at a wastewater treatment plant (WWTP) handling sanitary sewage in secondary-settling tanks and sludge-handling devices or

industrial applications.

Various studies used discrete settleable solids and various column devices or settling methods to determine settling velocities. In Stoke's Law (Equation 1-3), the velocity of an ideal sphere is proportional to the square of the particle diameter and is represented as follows:

$$v_s = g(\rho_s - \rho)d^2/(18\mu) \quad (1\text{-}3)$$

where:
v_s = velocity of sphere, m/s
g = acceleration due to gravity, 981 m/s^2
ρ_s = density of the particle, kg/m^3
ρ = density of the fluid
d = diameter of sphere, m
μ = dynamic viscosity, N⋅s/m^2

As previously mentioned, settling columns have been used to observe and analyze flocculant settling. Settling of WWF is often a combination of discrete and flocculant settling.

While direct measurement of sedimentation efficiency can be made on WWF storage and treatment facilities after installation by taking grab samples at the influent and effluent of the facilities, the settling column and its predicted removals can assist the engineer in the selection of design parameters before installation for WWF facilities. Settling columns can help determine the settling-velocity distributions for local conditions, e.g., WWF and waste streams containing silty particles may require larger facilities for a desired percent removal, while WWF waste streams with gritty particles could achieve the same percent removals with much smaller facilities. Observation of the actual settling-velocity distribution of SS in WWF is a better basis for design than the representation of ideal settling velocity derived from Stoke's Law, which only relies on the ideal settling of discrete monolithic particles.

Field Sampling

In order to collect a representative sample of WWF, sampling devices must be able to capture the heavier SS or settleable solids and not manifest biased results. For an automatic sampling device, this means that port intake velocities must be greater than the mainstream velocity and should be placed at multiple levels in order to avoid stratification and capture both the lighter SS in the top of the water column and the heavier particles near the channel invert.

The importance of the in-field settling test is to minimize any changes in settling properties of SS due to storage, transport, and any other processes. In a comparison of two tests, Dalrymple et al. (1975) showed that two distinct Long column tests had different results on two consecutive days, even though both were run on the same sample. The difference in the test was attributed to the storage of the sample for 24 h prior to the second test. This difference in stored samples was also confirmed by CERGRENE (Aiguier et al., 1995) when the settling velocity of four samples, all collected at the same time, yielded four different settling-velocity distributions. A fresh sample had the settling test performed in the field and was compared to the settling velocity of three samples stored for 24 h at different temperatures (room, refrigerated, and frozen).

Field Site

In identifying field sites for Phase III, the UWMB and John Meunier, Inc. looked for municipalities ready to share technical information regarding location and configuration of combined sewers and overflow sites. The municipalities needed to supply information on drainage area (preferably residential to minimize influences due to industrial sources), number and volume

of overflows per year, SS concentration of overflows, and frequency distribution of overflow events. Ideally, candidate sites would not yet have identified or installed treatment options for their CSOs. Additionally, the municipalities would have to be willing to permit the project team access to their facilities during CSO events in the summer of 1999 and to publish results based on data collected.

The City of Perth Amboy, NJ operates a combined sewer system and wastewater transfer pumping station that collects combined sanitary sewage, industrial wastewater, and storm runoff from an approximately 7 km^2 drainage area and pumps it to a regional WWTP owned and operated by the Middlesex County Utility Authority. The wastewater transfer pumping facility is located at the junction of Water Street and Sadowski Parkway in Perth Amboy. A CSO regulator is located about 6 m (20 ft) below the Sadowski Parkway with an overflow weir and a 2-m (7-ft) diameter CSO tide-gated outfall to the mouth of the Raritan River.

The pumping station inflow from the interceptor passed through mechanical coarse bar screens which removed large debris and into one of two wet-wells prior to being pumped to the regional WWTP. Samples were collected from the wet well, since the inflow is a part of the CSO and has the same characteristics at the outfall point during storm events. The wet-well is approximately 9 m (30 ft) deep.

Field Sampling Review

As a background for this project, John Meunier Inc. reviewed literature and wrote an internal report (Champigny et al., 1997) on state-of-the-art field-sampling practices. This field of expertise is often overlooked in studies and generally considered as a secondary subject. It was a weak point in many recent characterization studies. The objective of this assessment review was to evaluate the importance of the variability of solids found in sewer systems and to identify the most reliable method to obtain representative samples from a combined sewer. While many of the methods analyzed in the assessment were not developed for the study of WWF, the following general conclusions and recommendations from the complete internal report were made:

- In dry weather conditions, the vertical concentration gradient of SS can be related to the flow velocity pattern in the pipe or channel.
- A first flush phenomenon where the concentration of SS is higher closer to the beginning of the storm has been observed by some researchers.
- Sediments found at the bottom of the channels interact with the SS and should be included in the sampling.

Two separate sampling systems were recommended by this report for insewer design:

1. Sampling a complete cross section of the flow from bottom to top, and
2. Placing sampling port intakes at two points.

This second method would mount one sampling point just above the level of the DWF, near the pipe walls. The second sampling point would be maintained at 60% of the total water level throughout a WWF event.

2. MATERIALS AND METHODS

The design and fabrication of the columns and Phase I evaluations were conducted by UWMB in the EPA UWMB facility in Edison, NJ, and by John Meunier in the offices of John Meunier, Inc. in Montreal, Quebec, Canada. In Phase II, a set of 15 experiments was conducted by the same parties from June 9, 1998 through June 17, 1998. Additional testing was conducted on the CERGRENE columns at the EPA UWMB laboratory in November of 1999. In Phase III, three combined sewage field events were performed by UWMB in Perth Amboy, NJ, from March till May 2000.

Conclusion of Phase I: Preliminary Testing

The preliminary results (Phase I) determined the expected homogeneity of the mixing basins and the initial performance of the respective columns. Phase I testing showed that adequate mixing was provided in the mixing basins, that SS were transferred to the settling columns for further testing, and that the microsand and Neshaminy clay particles were recoverable in the columns. Other materials were tested, e.g., glass beads, but were found to be unsuitable. The Long column had insufficient head to sample rapidly from the top two ports, and drawdown would have eliminated these ports as testing progressed. Only ports 3, 5, 7, and 8 were used during the evaluation for determination of settling methods. At the conclusion of Phase I testing, analysis had been performed independently by the EPA and John Meunier, Inc.

Column Description and Delivery

Long Column

An accepted but non-standardized settling-velocity-distribution determination method in the United States employs a 1.8- to 2.5-m (6- to 8-ft) column to study settling characteristics of solids in wastewater. The EPA designed a 2.5-m (8-ft) modular column (Figure 2-1) consisting of four separate modules: a base section, a 1.2-m (4-ft) section (which must be attached to the base), and two 0.6-m (2-ft) sections. The column was constructed from cast acrylic tubing with a 203-mm (8-in.) outer diameter, a wall of 6.5 mm (0.25 in.), and a 190-mm (7.5-in.) inner diameter. The volume of the column was approximately 70 L (18 gal). The modules were attached by acrylic flanges with foam gaskets to eliminate leakage. A cap was also available to prevent foreign material from entering the top of the column, in the case of outdoor sampling .

Sampling ports (125 mm [0.5 in] NPT thread) equipped with quick-disconnect fittings with flow size diameters of 9.5 mm (0.375 in.) were spaced vertically 30 cm (1 ft) on either side of the column for a total of 16 ports at eight depths. Sampling from both sides of the column was meant to yield a more representative sample of the contents, minimizing “wall effects” and increasing the sampling area. It was originally thought to be more important to sample from both sides toward the bottom of the Long column where withdrawal velocities were greatest than at the top where withdrawal velocities were slower due to decreased head. The base section included a 1-in. diameter drain which was connected to a three-way valve. This valve was used for filling and draining the column. A conical plastic piece (funnel) was installed above the drain inside the column to facilitate resuspension of solids during the filling process and aid clean-out between experiments. A wooden baffle screwed into the cone dispersed the flow and kept the influent well-mixed.

Filling was accomplished by pumping from a mixing basin through the bottom valve. Before filling, the pump was primed and the bottom valve turned to “fill.” Prior to and during filling, the mixing basin (described in Mixing Basin) stirred the solids to keep them suspended. After filling, the pump was turned off, the bottom valve was turned to the middle position, and sampling from the side ports began.

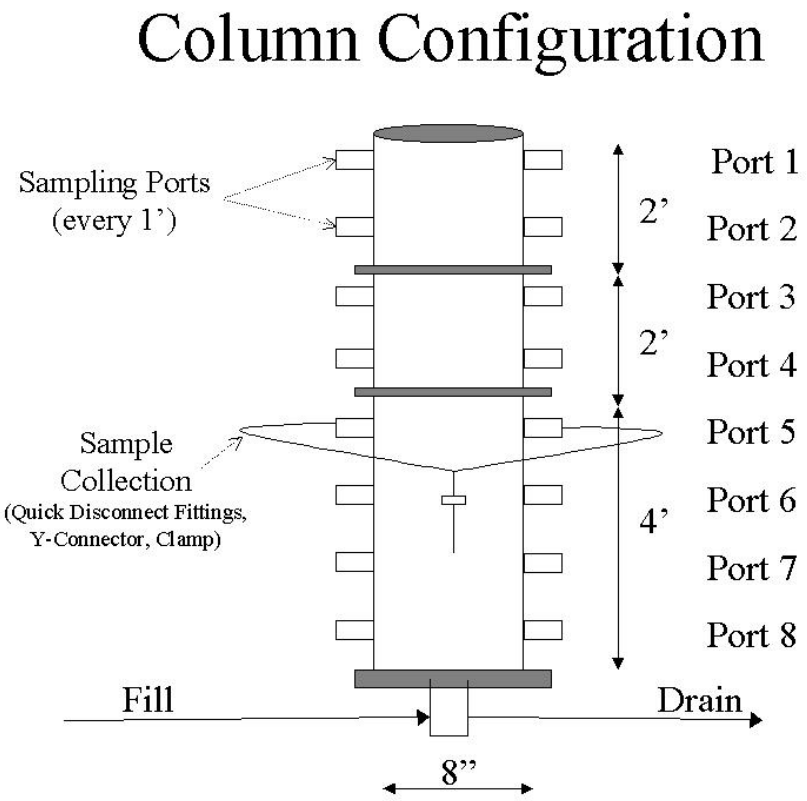

Figure 2-1. Long Column General Arrangement

Sampling tubes were attached to the male quick-disconnect fittings at each sampling port. For two-sided sampling, two tubes that were attached to the male quick-disconnect fittings lead to a T-connector which was attached to a short tube. This short output tube brought the sampling streams together. Sampling from the end of this output tube was controlled by attaching another set of quick-disconnect couplings.

Sampling was initiated at the upper ports of the column and progressed downward for each time interval. Sampling tubes were purged before sampling. The output tube was placed in the plastic bottle marked "Purge," and a male pipe adapter was attached to an elbow hose barb. The "Purge" bottle was filled to a measured marking (at a minimum), and then in midstream the tube was quickly moved to a plastic storage bottle. Each plastic storage bottle was marked with an individual identification number which was recorded along with the corresponding port (1, 2....8) and sample time. After sufficiently filling the plastic storage bottle, the male quick-disconnect adapter was removed from the output tube. Storage bottle size was nominally 250 ml, which appeared to match the 10 to 20 mg target mass range for SS analysis for the media in Phase I. Cold storage was only required for Phase III samples, as all other samples contained inert material (e.g., sand and clay). Combined sewer samples taken during Phase III were stored in coolers with ice in the field and during transport, and in refrigerators back in the laboratory

according to Standard Methods (1995).

CERGRENE Columns

The CERGRENE columns were designed following a series of tests. CERGRENE, Centre d'Expertise en Gestion des Eaux d'Orages (CEGEO, a subsidiary of John Meunier, Inc.), and the University of Aston undertook a study to optimize settling-velocity- distribution measurements. The objectives of the European study were to:

- Compare the results of existing methods and protocols on identical samples;
- Compare and contrast the advantages of each method; and
- Understand the influence of each parameter (settling height, column diameter, concentration of SS, temperature, etc.) on the settling-velocity distribution.

In light of the European study results, a new column test was proposed to meet the following criteria:

- The sample should not to be pretreated;
- The sample should remain in its original matrix (water and SS) for tests;
- A sufficient sample size should be collected for analyses;
- The column should be easy to use; and
- The column should be compact for in-situ measurements.

The resulting settling test apparatus was the CERGRENE columns. These were tested with a prototype and then in full scale. John Meunier, Inc. constructed four replicas of the CERGRENE column based on equipment available in North America. The column had a 65-mm (2.5-in.) inner diameter constructed of clear PVC and stood approximately 1 m (3 ft) tall. The volume of this column was approximately 2.5 L (0.66 gal). The column (Figure 2-2) had three valves located at the top, bottom, and middle. The middle valve, a 65-mm (2.5-in.) inner diameter ball valve, was approximately 2/5 of the length from the bottom and divided the column into two sections.

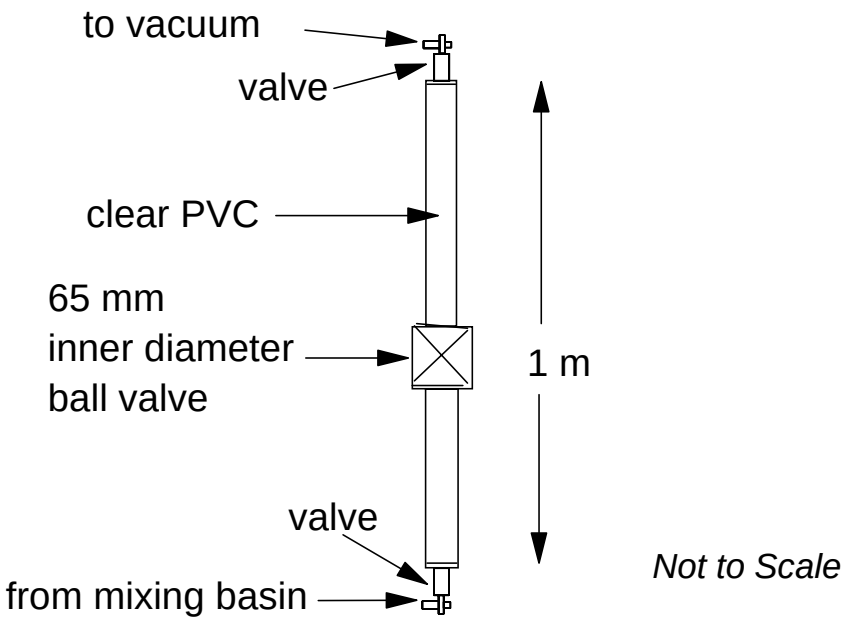

Figure 2-2. CERGRENE® Column Configuration

The column was filled by vacuum aspiration to minimize the variation of SS concentration between the bottom and top sections. The vacuum was applied to the top valve of the column and drew wastewater up into the column through the bottom valve. A vacuum pump doesn't break SS apart as readily as a typical positive displacement water pump which tends to grind and shear particles, thereby changing the settling characteristics. After filling, the top and bottom valves were closed. At the specified sampling time, the two sections were separated by turning the middle ball valve. The bottom portion was the sample. This volume of approximately 1 L (0.26 gal) was drained and SS analysis was performed. As previously discussed, the major premise for performing this comparison was to determine whether the CERGRENE column provided truer representation of high-settling velocity SS at the test starting time, t_0, than the Long column.

Each CERGRENE column was sampled independently at discrete times and represented one sample for settling-velocity-distribution analysis; this differed from the Long column which required multiple samples to be taken per time interval. Filling of the columns was conducted sequentially. Results from Chebbo et al. (1995) indicated that sequential filling of the columns did not significantly impact results.

Mixing Basins

Two mixing basins were used in the course of the experiments to provide a well mixed matrix, i.e., CSO or water and testing media, to supply both column testing systems. The John Meunier mixing basin design was used for Phases I and II. The mixing basin was 0.66 m (2 ft) in diameter, 1.3 m (4 ft) high, and had a 300-L (80-gal) holding volume. Four vertical baffles were inserted at 90-degree intervals to prevent the formation of a vortex (Dickey and Hemrajani, 1992; Etchells et al., 1992). The mixer was mounted on a sawhorse above the basin. The mixer shaft was in the middle of the basin and two impellers were used; a marine impeller at the bottom and a Rushton impeller above.

A marine impeller with three blades was placed about 1 cm (0.4 in.) from the bottom of the basin to create an axial flow in the basin, provide complete mixing of fluids, and suspend particles that may settle naturally (Dickey and Hemrajani, 1992; Etchells et al., 1992). The mixer manufacturer (Greey Lightnin) recommended a 25.4-cm (10-in.) diameter impeller based on the existing basin configuration. The Greey Lightnin mixer, model XJ-43 with 1/3 hp of power, has a constant mixing velocity of 350 rpm.

The use of a Rushton impeller was based on previous mixing studies done by John Meunier, Inc. (Gagné and Bordeleau, 1996) and was also verified by the CERGRENE group (Chadirat et al., 1997). The dimensions of the Rushton impeller (four equally spaced 60-mm wide by 90-mm tall paddles) were also linked to the physical dimensions of the basin. The Rushton impeller creates an axial flow that keeps the particles suspended by the marine impeller and well mixed throughout the basin. During Phase I, the Rushton impeller was tested at 20 cm (8 in.) above the marine impeller.

CERGRENE showed that mixing velocities between 200 and 600 rpm were adequate to generate complete mixing in the basin and achieve consistent results (Chadirat et al.,1997). The mixer was turned on 15 min prior to sampling and stayed on throughout.

During the Phase II experiments, the mixing basin was filled to an initial SS concentration of 300 mg/l. On the sixth side-by-side experiment, the volume in the mixing basin was changed from 200 to 250 L and the initial mass of 60 g of media was increased to 75 g to maintain the known concentration at 300 mg/l. This extra volume prevented the water level from falling too low which caused excessive vibration in the mixer after filling the Long column.

The Long column and CERGRENE system were filled from the mixing basin in an alternating sequence.

The point where water was withdrawn from the mixing basin for Phase II was 7 to 10 cm (3 to 4 in.) from the wall, set halfway between two baffles and at an alternating height of 18 to 35 cm (7 to 14 in.) from the bottom, which maintained a volume of water in the basin throughout the experiment. The alternating sequence for filling and height of withdrawal was intended to reduce bias in the experiment as described in Experimental Design. The four wooden baffles deteriorated slightly during the tests and may have had a minor impact on the loadings.

The EPA also developed a mixing system that was used for Phase I, the additional laboratory testing of the CEGRENE columns after Phase II, and for the field experiments of both columns in Phase III. The EPA mixing system used a 208-L (55-gal) tank with a 2.54-cm (1-in.) NPT fitting in the center of a conical bottom. The tank, which can be drained from the bottom, stood 94 cm (37 in.) tall and is 66 cm (26 in.) wide with a 6-mm (0.25-in.) wall. The mixer was a Chemineer, model 2JTC 350 RPM, and had a 0.25 hp motor with a constant mixing velocity of 350 rpm. There were two 20.3-cm (8-in.) diameter marine impellers, one at the bottom and the other 25 cm (10 in.) above, attached to the 76-cm (30-in.) long and 1-cm (0.375-in.) diameter shaft. Initial testing showed that baffles were necessary to eliminate a vortex. Three vertical baffles made of polypropylene were attached to the basin wall at 120-degree intervals. Only three baffles were chosen instead of four, as the EPA mixer shaft was inserted into the basin on an angle instead of straight down as in the John Meunier, Inc. design. It was felt that more room was needed to place the bottom marine impeller between baffles due to the tilt. The EPA baffles were made of the same material as the wall of the basin and were attached with metal blocks and U-bolts as mounts. A PVC three-way ball valve was attached to the bottom effluent; this valve could be switched to deliver the sample volume to the Long column or return flow to the top of the tank for recycle, which provided additional mixing. During Phase III, withdrawal was made from the top 5 to 10 cm of the mixing basin for the CERGRENE column, while the Long column was filled from the bottom drain. The CERGRENE columns, except for the 2-h sample, were filled first as there was not adequate volume to keep the mixer on after filling the Long column.

The John Meunier mixing configuration used in Phase II was more thoroughly tested, and indications were that sampling closer to the surface of the water was better due to the power of the mixer and mixer configuration. While configuration of the EPA column was different, the results of samples taken directly from the mixing basin during Phase III were consistent with a well mixed system.

Sampling

Long Column

The Long column was sampled at only four of the potential eight port depths in the actual side-by-side comparison to increase the number of samples that could be obtained at different times and depths in the first few minutes of sampling. Samples taken from the top of the column required more time, i.e., 7 s at Port 1 in Figure 2-1 when the column was full, while samples taken from the bottom six ports had sufficient head to ensure a shorter sampling time period, i.e., < 3 s at Port 3 and below. Also, if all depths were sampled there would not have been enough sample for the top ports for the later times. An analysis of discharge velocities from the ports showed good correspondence to theoretical values.

The fill time of the Long column ranged from 69 to 76 s for a height of 0.24 m (95 in.). On average, the upflow velocity of water in the 10 out of 15 experiments where both height and

time were measured was 3.3 cm/s.

For each set of Long column samples (one set = samples from ports 3, 5, 7, and 8), average decrease in water height in the column was 4.5 cm (1.8 in.), averaging 1.1 cm (0.45 in.) per sample. These average values were used to adjust the depth of the Long column in the calculation of overflow rates. The decrease in water level height for one set includes both purge and sample volume.

CERGRENE Columns

In Phase II, the vacuum pump filled the CERGRENE columns in an average of 8.2 s where time was measured from the appearance of water in the column until shut off. Using a standard height value of 0.91 m (3 ft) for the columns, the estimated velocity of water pumped upwards into the columns was approximately 11 cm/s. The slowest filling time was 11.5 s which was most likely a function of a cold start of the vacuum pump. Even with a worse case sample height of 0.76 m (2.5 ft), the upflow velocity in the CERGRENE would still exceed 6.6 cm/s. The filling velocity in the CERGRENE column was at least twice as fast as the Long column.

During Phase II, the CERGRENE columns were never actually filled to capacity, always being a little short from the top. This height of the sample level in the CERGRENE columns was measured for calculation of the settling-velocity distribution. Problems with the sample height measurement of the upper chamber of the CERGRENE columns are discussed in Chapter 3, and specific recommendations and modifications are presented in Chapter 4.

For the additional sampling and Phase III experiments, a more powerful vaccuum pump was used which significantly reduced the filling time. The average time to fill the column was 4.9 s with a standard deviation of 0.3, and ranged from 4.5 to 5.5 s for five measurements. As the CERGENE columns were overflowed by approximately 0.5 L, time was measured from the first appearance of water in the column to its arrival at the top. The average velocity was 20 cm/s.

The intent for overflowing the CERGRENE column was two-fold. Primarily, overflowing eliminated the height measurement of the upper half of the CERGRENE columns needed for analysis. Completely filling the columns simplified the analysis procedure; problems with the filling procedure during Phase II are detailed in Chapter 3. Also, overflowing should have minimized start-up velocity flow impacts and hopefully allowed the system to achieve a steady state velocity, which might lead to a better equilibrium in concentration between the top and bottom components of the column.

Quality Assurance Samples

During each experiment, a set of triplicate samples was taken to show that the "background" SS concentration was uniform. During Phase II, these samples were taken using the pump for the Long column and were dubbed “Recycle” samples. In phase III, triplicate hand-grab background samples were taken from the mixing basin. The background samples served as the t_0 concentration for the Long column and were a basis of comparison to the concentration of the t_0 CERGRENE column. Three samples were also collected to perform gravimetric settleable solids analysis, discussed in Solids Analyses below. Other QA samples included laboratory and field blanks.

Solids Analyses

Solids analyses were the critical measurements of these experiments. Table 2.1 presents the summary of Standard Methods used. The selection of analytical methods was based on the following priorities:

1. Standard Methods, 19th Edition
2. EPA Method

Table 2.1 Summary of Standard Methods and Procedures*

Parameter	Sample Type	Method No.	Method Title
Suspended Solids (SS)	Water	2540 D	Total SS Dried at 103 to 105 ^{B}C
Settleable Solids	Water	2540 F	Settleable Solids
Volatile Solids (VSS)	Water	2540 E	Fixed and Volatile Solids Ignited at 550 ^{B}C
Total Solids (TS)	Water	2540 B	Total Solids Dried at 103 to 105 ^{B}C

* All methods used from Standard Methods 19th Edition (1995).

The upper limit for SS sample sizes is 200 mg of residue. The lower limit for SS is 4 mg/l as specified by EPA method 160.2. Suspended solids were calculated by the following procedure:

$$\text{mg suspended solids / L} = \frac{(A - B) \times 1000}{\text{sample volume (mL)}} \qquad (2\text{-}1)$$

where: A = weight (mg) of filter and dried residue, and
B = weight (mg) of filter, mg.

The grain size of the particles for Phases I and II and the additional laboratory experiments was larger than the filter paper pore size (1.5 :m, Whatman 934-AH) of the filters being used for the SS analysis. Filters with a 47-mm diameter were used.

To perform settleable solids in Phase II, a graduated cylinder was filled from the pump used for the Long column. After 1 h, a 250-mL sample was siphoned from the approximate center of the graduated cylinder and was analyzed for SS. These are the *non-settleable* solids. This concentration was subtracted from the initial SS concentration as derived from separate samples. As settleable solids are an extension of SS analysis, the same limits apply.

Settleable solids were calculated by the following method:

mg settleable solids / L = mg suspended solids / L - mg nonsettleable solids / L (2-2)

Volatile solids were measured for Experiments 1 and 2 of Phase III. The equations for this method are:

$$\text{mg volatile solids / L} = \frac{(A - B) \times 1000}{\text{sample volume (mL)}} \qquad (2\text{-}3)$$

$$\text{mg fixed solids / L} = \frac{(B - C) \times 1000}{\text{sample volume (mL)}} \qquad (2\text{-}4)$$

where: A = weight (mg) of residue, filter, and dish before ignition,
B = weight (mg) of residue and dish after ignition, and
C = weight (mg) of dish and filter.

Total solids were measured for Experiments 2 and 3 of Phase III. The equations for this method are:

$$\text{mg total solids / L} = \frac{(A - B) \times 1000}{\text{sample volume (mL)}} \qquad (2\text{-}5)$$

where: A = weight (mg) of dried residue and dish, mg, and
B = weight (mg) of dish, mg.

The CERGRENE developers originally envisioned multiple types of analysis from one CERGRENE sample. Ideally, for the purposes of these experiments, the whole sample from either column method was to be evaluated as one sample using SS analysis to measure the settling rates. However, during Phase II the CERGRENE column samples held more SS than could be efficiently collected on a single filter, and all samples of CSO from Perth Amboy clogged the filters before the whole sample could be filtered for SS as one sample. Therefore, only a portion of the sample was actually analyzed. While 70-mm diameter filters are recommended by Standard Methods for the raw wastewater samples, at the time of the experiments filter housings were only available for 47-mm filters. In lieu of splitting each sample and performing several SS analyses in Phase III, only a portion of the collected samples was used for SS analyses in Experiments 1 and 2. Total solids analysis was performed on the remaining portion of the sample of Experiment 2, and the whole collected sample was analyzed for TS for Experiment 3. This should not affect the outcome of the experiment, as obtaining an accurate measurement of the solids concentration in the sample, especially the settleable portion, was what was most important.

Identification of Experimental Materials for Phase II

Initial experiments were performed using microsand, Foullon's Earth, glass beads, and natural soils. The media were mixed in tap water prior to introduction into the mixing basin. Microsand was chosen to test the mixing basin and for the laboratory experiments. The initial characteristics of the microsand used for the design of the experiments were:

$d_{10} = 85$:m
$d_{60} = 125$:m
D $= 2.62$ g/cm^3

The calculated settling velocities for these particles using Stoke's Law (ideal sphere assumed) were <1 cm/s, which is less than the upflow velocities measured in the columns. An analysis of the microsand by a Coulter® LS Particle Analyzer determined the following particle diameters:

$d_{10} = 156.2$:m
$d_{50} = 232.8$:m

which translates to less than 10% of the microsand having calculated settling velocities of less than 1.36 cm/s and the microsand having an average settling velocity of 2.15 cm/s. This analysis was performed in January, 1999 after Phase II was complete and the Coulter Counter first became available for use at UWMB. Appendix J shows the Coulter Counter report.

A surficial soil excavated near Princeton, NJ, was used as an additional reference. The soil (Neshaminy) is a silty clay loam, containing 17% sand, 46% silt, and 37% clay. Although

this soil has a greater proportion of very small particles, it also has a wider particle size variation with d_{10} = 75 :m and d_{60} = 700 :m (Fischer, 1995).

Experimental Design

Table 2.2 shows the original experimental design of the Phase II side-by-side experiments which were designed to account for bias due to the order of filling the columns and variations in the height of water in the mixing basin. One duplicate was performed for each medium (microsand, Neshaminy, and mixture) for a total of 15 experiments. The experiment order was randomized to reduce bias due to one soil type being repeated or increased precision from experience.

Table 2.3 provides a prototype sampling strategy for microsand. A set of samples from the Long column were withdrawn at specified intervals (e.g., 1, 3, 5, or 10 min) with time measurements to the nearest tenth second for the individual sample end-times. Four samples comprised one set of samples for the Long column. For each CERGRENE column, the valve was turned to capture SS at a time corresponding to a time interval for the Long column. The initial time for the individual CERGRENE column was designated to be $t_{0,\,i,}$ where i represents the number of the column. The time for the CERGRENE column was the time from the moment each column was filled to the time the sample was isolated by turning the valve of each column. The Long column t_0 was the time that filling was completed. Initial concentration in the entire column was assumed to be a background or "recycled" concentration taken from the mixing basin by the pump, as explained in Chapter 3.

Table 2.2 Experimental Design for Phase II Laboratory Experiments

Media	Experiment #	Randomized Experiment # Order	Withdrawal Height (cm)	Column Filling Order	End Time (min)
Microsand	1	8	18	Long / CERGRENE	10
Microsand	2	15	36	Long / CERGRENE	10
Microsand	3	4	18	CERGRENE / Long	10
Microsand	4	13	36	CERGRENE / Long	10
Microsand	Duplicate - 13	12	18	Long / CERGRENE	10
Clay soil	5	5	18	Long / CERGRENE	60
Clay soil	6	10	36	Long / CERGRENE	60
Clay soil	7	14	18	CERGRENE / Long	60
Clay soil	8	1	36	CERGRENE / Long	60
Clay soil	Duplicate - 14	6	36	Long / CERGRENE	60
Mixture	9	9	18	Long / CERGRENE	60
Mixture	10	11	36	Long / CERGRENE	60
Mixture	11	3	18	CERGRENE / Long	60
Mixture	12	2	36	CERGRENE / Long	60
Mixture	Duplicate - 15	7	18	CERGRENE / Long	60

Table 2.3 Critical Time Measurements for a Microsand Experiment, Phase II

CERGRENE Column		Long Column				
Initial Time	Time	t_0 - initial time	Port 3	Port 5	Port 7	Port 8
$t_{0,1}$	$t_{0,1}$	< 1 min	$t_1 - t_0$	$t_2 - t_0$	$t_3 - t_0$	$t_4 - t_0$
$t_{0,2}$	1 min - $t_{0,2}$	< 2 min	$t_5 - t_0$	$t_6 - t_0$	$t_7 - t_0$	$t_8 - t_0$
$t_{0,3}$	3 min - $t_{0,3}$	- 3 min	$t_9 - t_0$	$t_{10} - t_0$	$t_{11} - t_0$	$t_{12} - t_0$
$t_{0,4}$	5 min - $t_{0,4}$	- 5 min	$t_{13} - t_0$	$t_{14} - t_0$	$t_{15} - t_0$	$t_{16} - t_0$
$t_{0,5}$	10 min-$t_{0,5}$	- 10 min	$t_{17} - t_0$	$t_{18} - t_0$	$t_{19} - t_0$	$t_{20} - t_0$
Duplicate - $t_{0,x}$	x min - $t_{0,x}$	Cannot perform duplicate on Long column				

A similar time measurement scheme could be constructed for the Neshaminy soil and other particle mixtures with the time of the samples extended out to 1 h. The initial estimated settling rate for the Microsand with a d_{10} of 80 :m was < 15 min for the Long and < 10 min for the CERGRENE columns. The settling times were actually much less than that, given the larger average diameter of the particles.

Figure 2-3 shows the laboratory setup. Since only four CERGRENE columns were available for the experimental sequence of six or seven separate time measurements for each experiment, the CERGRENE columns were sampled, rinsed out, and refilled from the mixing basin during Phase II. This procedure was used for the first nine experiments until it was discovered that the individual CERGRENE columns were each producing unexpectedly random settling results. Only one CERGRENE column was used for the remaining six experiments of Phase II. The column was rinsed out after each time interval, before the column was refilled and another sample was collected. Phase III also used only one CERGRENE column and a slightly modified setup, which is presented in Chapter 5.

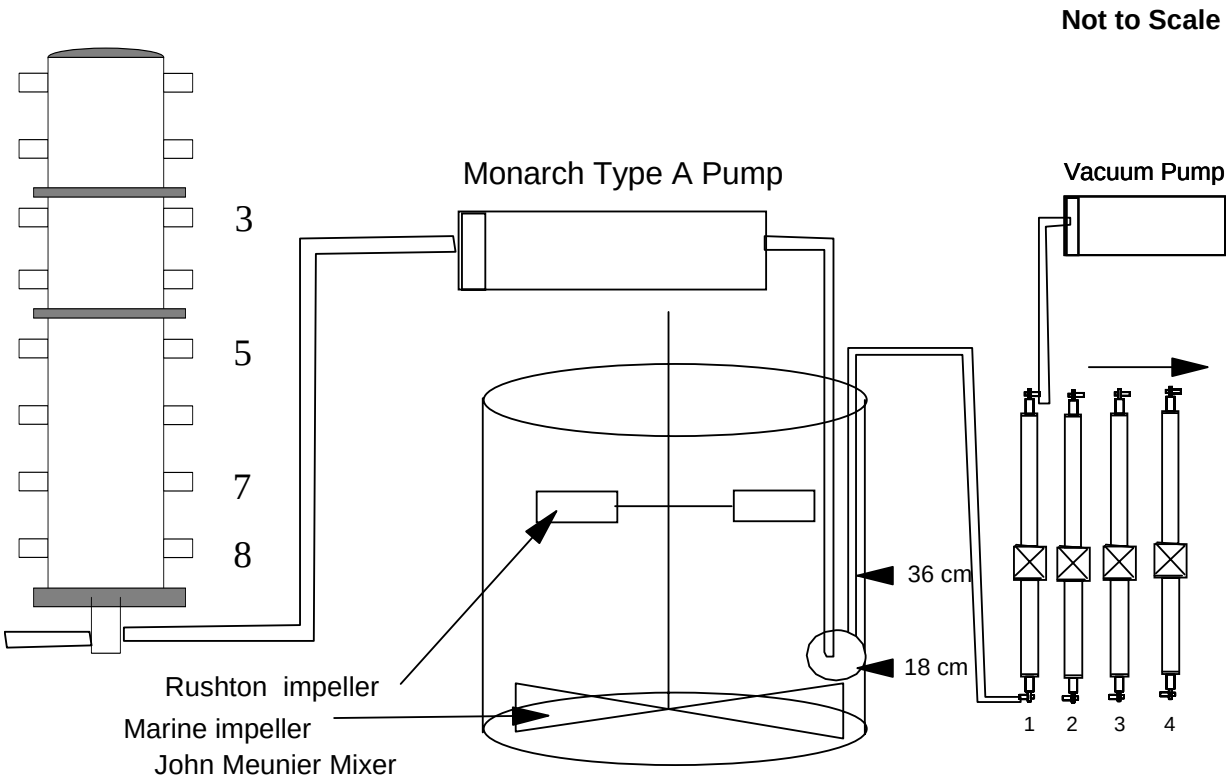

Figure 2-3. Configuration for Side-by-Side Phase II Experiments

3. RESULTS OF PHASE II

All graphical figures for this and the following sections are presented in the appendices (e.g., Figures A-1 - A-5 are in Appendix A, Figures B-1 - B-32 are in Appendix B).

Quality Control Analysis

Several levels of experimental procedure were incorporated to ensure quality control in all phases of the project. Those specific to the Phase II analysis are described below.

Table 3.1 Estimated Number of SS Analysis for One Experiment of Phase II

Sample Location	Number of SS samples
CERGRENE columns	5
Long column - various ports	15-25
Recycle - QC samples on mixing basin	3
3 settleable solids (for Clay soils and mixture only)	6
Duplicate CERGRENE column	1
Laboratory QC - Standard Reference Material	3
Blank - Tap Water in Mixing Basin	1
Blank - distilled water	1

Blanks and Standards

Method blanks were run either on de-ionized, tap, or basin water before the delivery of the media. The purpose of blanks was to ensure SS were not introduced during sample collection or analyses. All blanks had concentrations below 4 mg/l (Figure A-1). Experiment 3 did not have a corresponding blank while experiment 9 had two blanks.

The accuracy of the SS procedure was determined from the analysis of laboratory control samples with known concentration of SS. Standard reference materials (SRM) were the same materials used in the experiments, namely, microsand, Neshaminy silty clay loam, and a 50-50 mix of the sand and Neshaminy.

Table 3.2 QA Objectives for Measurements

Measurement	Method	Reporting Unit	Initial Concentration*	Standard Deviation*	Relative Standard Deviation*	Complete-ness
Suspended Solids	2540D	mg/l	15	5.2	33%	90%
			242	24	10%	90%
			1707	13	0.76%	90%
Settleable Solids	2540F	mg/l	NA	NA	NA	NA

* From Standard Methods (1995)

Accuracy is expressed as percent recovery. The formula used to calculate this laboratory QC values for a SRM is:

$$\%R = 100\% \times C_m / C_{srm} \quad (3\text{-}1)$$

where: %R = percent recovery
C_m = measured concentration of SRM
C_{srm} = actual concentration of SRM

Excluding one extreme, which was most likely a mislabeled sample or an error in transcribing, the average percent recovery was 80% with media results of 66%, 83% and 88% for sand, mixture and clay, respectively.

Figures A-2 through A-5 show graphs of the measured standards versus the expected percent recovery (the log linear line in all the graphs) for diatomaceous silica as developed from the values for relative standard deviation in Table 3.1. To plot a comparison versus the relative standard deviation values in Table 3.1, %R was adjusted by subtracting from 100% to get the relative percent difference (RPD) values.

Figure A-2 shows RPD for all the media and Figures A-3 through A-5 are media specific. The Neshaminy (Figure A-5) exhibits the best RPD, equivalent to the recoveries of diatomaceous silica. The mixture (Figure A-4) had several RPD within acceptable limits but for most cases exceeded the limits of diatomaceous silica by up to 45%. The microsand (Figure A-3) exceeded the expected RPD for diatomaceous silica in all but one case.

The microsand was the most difficult media to work with when performing SS, as particles tended to stick to the surfaces of analytical equipment due to water tension. The analysis of microsand produced the most pronounced losses. Neshaminy soil was much easier to analyze (except when the filters began to clog) as the results indicate. Except for the one extreme outlier of -189% for a mixture sample (A-4) which represented a gain in mass, all SRM analysis indicated a loss in SS.

Another factor that may have contributed to this error in the SRM was the smaller sample sizes, 125 mL bottles. All Long column samples were 250 to 300 mL and CERGRENE samples were 250 mL aliquots for Neshaminy and 960 mL for the microsand and the mixture.

Completeness

The completeness is defined for this study as the ratio of the number of valid measurements to the total number of measurements planned for each parameter. A completeness objective of 90% is expected to ensure that enough valid data points are collected to evaluate the settling velocity distributions. Samples were assumed valid unless voided due to the following QA procedural problems: samples with no identification, duplicate identification, missing data (which could not otherwise be discerned), torn filters, incomplete solids transfer to filters or spills. Table 3.2 shows the completeness for critical SS measurements made for all 15 experiments. The formula used to determine completeness is:

$$\%C = 100\% \times V/T \quad (3\text{-}2)$$

where % C = percent completeness
V = number of measurements judged valid
T = total number of measurements

The Recycle and the Settleable Solids samples were the only sample types that did not achieve the completeness criteria of 90% in Table 3.2. However, they approach 90 %, and are within one sample of passing this criterion.

As noted in Table 3.3, only 17 of the 340 Long column samples were voided for faulty procedures (e.g., sample volume not noted). Additionally, three microsand samples fell below the 4 mg/l limit of detection for the EPA SS method, but these samples do appear in the graphs as approaching zero concentration, or 100% removal.

Table 3.3 Completeness of Suspended Solids Analysis

Type or location	Total Samples	Voided Samples	Expected Completeness	Measured Completeness
Blanks	17	0	90%	100%
CERGRENE	101	0	90%	100%
Long	340	17	90%	95%
Recycle	45	5	90%	88.9%
Settleable Solids	16	2	90%	87.5%

Of the 101 separate CERGRENE samples, none of the samples were voided. However, in lieu of incomplete information, when omissions in measurement could not be deduced, standard values were assumed. These values had to do with measured volumes of the CERGRENE column. The bottom of the column was assumed to be 960 mL, which did not vary noticeably when measured directly, and in fact should not have varied at all, as the bottom portion was filled to capacity. After the first few runs, it was decided more error was introduced by measuring than assuming the 960 mL value. The default bottom volume of 960 mL was used in calculating the upper chamber volume and percent removals, but when available the measured volume was used for actual SS concentration of the bottom effluent.

Due to faulty recording procedures, height measurements, which represents the volume of the top chamber in the CERGRENE columns, were not recorded for several individual CERGRENE runs. This measurement was not critical at the time of the laboratory analysis but some indication of height is essential during settling velocity analysis using CERGRENE's iterative matrix program. Where no height measurement was available, a value of 41.9 cm (16.5 in.) was used. This value is the mode for the 86 out of 101 samples for which a height measurement is available, with a mean of 41.4 cm (16.3 in.), a standard deviation of 1.7 cm (0.65 in.), and a coefficient of variance (CV) of 0.040. As the experiments proceeded, better control of the level in the CERGRENE columns was exhibited. For experiments 10 through 15, the mode was 41.9 cm (16.5 in.), the average was 42.1 cm (16.6 in.), with a tighter standard deviation of 1.3 cm (0.53 in.) and CV of 0.032 for fewer samples (31 of 40 samples). Measurements could only be made to the nearest eighth-inch, which implies a virtually identical mean and mode.

The error introduced by the lack of height measurements is minor in comparison to errors introduced from other sources. The major cause of variability in the SS analysis was the use of the microsand itself. During sample preparation, sand could be observed clinging to the filter housing, and was subsequently scraped onto the filter. Testing media sticking to the filter housing was not as apparent with the mixture, as the Neshaminy clay soil clung to the sand and reduced water tension of the sand to the filter housing.

Neshaminy soil tended to clog the filters for the larger volume CERGRENE samples. For this reason, 250 mL aliquots were obtained of Neshaminy CERGRENE samples from beakers with magnetic stirrers, and these aliquots were analyzed for SS. Thus filters were not overloaded for Neshaminy runs (where overloaded is defined by SM 2540 as exceeding 200 mg of residue). The aliquot method could not be used for microsand or mixture runs, as sand particles tended to be more discrete and a representative sample could not be obtained with magnetic stirrers as with the Neshaminy which formed a more uniform mixture. The larger sand and mixture CERGRENE samples exceeded 200 mg thus overloading the filters.

Mixing Basin - Recycle

Three background or "recycle" samples were obtained immediately prior to filling the Long column. Recycle samples were an additional level of quality assurance. The known concentration in the mixing basin was 300 mg/l, so recycle concentrations should have centered around that number. The recycle concentration of each experiment was used as the t_0 of the Long column in lieu of averaging the initial measurements at each port in the Long column. The recycle samples were taken from the same pump that filled the Long column, at the same side wall height that the CERGRENE and Long columns were being filled. The recycle concentration was thought to better represent the concentration delivered to the Long column. The average recycle concentration for all 15 experiments was 272 which represented less than a 10% loss overall from the known concentration.

Figure A-6 shows all recycle concentrations for all experiments. The data appear to be spread over a wide range of concentrations, but when viewed by soil type (Figure A-7), it becomes apparent that Neshaminy soil, with its higher percentage of clay and silt, yields tighter distributions around 300 mg/l, while the microsand tends to be much more widely distributed and unpredictable. This is due in part to the nature of the sand particles, which are discrete and dense, and may elude the sampling container or settle beneath the mixer. In addition, the SS analysis was much more robust for Neshaminy than for sand. Thus the mixed soil, with its combination of Neshaminy and sand, shows a distribution not quite as tight as Neshaminy, but not as widely distributed as sand.

Figures A-8 and A-9 show recycle concentrations by order of filling and depth of sampling, respectively. The recycle concentration distribution is closer to 300 mg/l for the experiments where the long column was filled first and for the experiments where the height above the bottom of the basin was to 35 cm (14 in.) rather than 18 cm (7 in.). A second finding is that filling concentrations are closer to the known concentration when the intake is closer to the surface of the water in the basin. The first finding shows tighter distributions when the Long column was filled first, which is probably a result of larger volumes of water providing better mixing. When the CERGRENE columns were filled first, enough water was removed from the basin to interfere with the mixing process. An analysis of variance showed that the order of filling, media type and intake depth did not significantly impact recycle concentrations.

Settleable Solids

The gravimetric settleable solids analysis (SM 2540F) entails first performing a SS analysis on a representative sample. During these experiments, settleable solids samples were taken the same way the Recycle samples were taken.

Figure A-10 shows the non-settleable solids concentration for this method for Neshaminy and mixture media. The settleable solids method was not performed on the microsand as insignificant concentrations of non-settleable solids were expected. The concentrations of the mixture medium is about half that of the Neshaminy, which is expected as the mixture contains

half the mass of Neshaminy soils. An interesting result, however, is the tighter distribution of the mixture results, possibly due to a flocculant effect, where charged clay particles may cling to microsand particles and settle more predictably.

Laboratory Experiments 1-15

Concentration versus Time

Figures B-1 through B-30 show plots of the raw data for the Long and CERGRENE columns for the 15 experiments. The first nine CERGRENE graphs are shown for completeness only. As mentioned previously, the inconsistency between CERGRENE columns makes it unadvisable to use the data from the first nine CERGRENE runs. Experiments 10 through 15, where one CERGRENE column was used repeatedly, show a pattern of increasing concentration in the graphs, as would be expected.

The graphs of the Long column results show the pattern of settling for particles of each type. Note the rapid settling for the sand experiments, where concentrations at all ports quickly tail off to near zero. Neshaminy experiments exhibit a more gradual settling pattern, with the SS concentration of the higher ports decreasing gradually, and the lower ports less so, as they receive the settled particles from the higher elevations. The mixed soil type shows an initial rapid settling of the sand particles, followed by the more gradual Neshaminy pattern. This becomes even more apparent in Figure B-31, which shows the results of the 15 experiments on the Long column, averaged by soil type.

Long Column Shortcomings - Initial Concentration Gradient

An inherent problem in the design of the Long column is the lack of reliable uniformity in initial concentration (C_0). The height and volume of the column makes it difficult to deliver the sample quickly enough to ensure minimal settling of solids during the delivery time. Thus, depending on the density and particle size in the sample being delivered, a concentration gradient appears in the time zero measurements. This is compounded by the fact that simultaneous t_0 measurements were impossible to achieve in the Long column by hand (three peolple were perfoming the sampling). Because of the very nature of the sampling methodology, a lag will develop between completion of sample delivery and initial measurements, and between the port measurements themselves. A full minute may elapse between end-of-delivery and first sampling at port 8.

Figure B-32 shows port-by-port (represented by height above the column bottom) average concentrations for each soil type and each time interval. For a well mixed column, t_0 measurements should yield a straight line with zero slope and a y-intercept equal to the recycle concentration. The slope of the t_0 line indicates the severity of the gradient. While the sand shows a severe lack of mixing, due to the size and density of the particles, the Neshaminy soil shows more uniform concentrations and exhibits better mixing. This is because Neshaminy contained clay particles which generally have lower specific gravities than pure sand. The Neshaminy also took longer to settle with significant concentrations after one hour while the sand had settled out within five minutes. The lack of reliable uniformity in initial concentration of heavy material has long been recognized as a shortcoming of the Long column, and causes the scatter that can be seen in the initial measurements of these experiments.

Concentrations, which were expected to decrease with time, were relatively flat throughout the experiments, except for an initial dip. Due to slower settling rates, concentrations for the lower Ports 5, 7 and 8 , especially 7 and 8, during the experiments using the Neshaminy soil may have been demonstrating hindered zone settling (defined, in part, as a suspension of intermediate concentration in which interparticle forces are sufficient to hinder the settling of

neighboring particles, from Tchobanoglous and Burton, 1991). This could be observed visually over the extended sampling times (30 - 60 minutes) when a distinct supernatant developed in the top of the Long column. The concentrations for the lower ports 7 and 8 even began to exceed the known delivered concentration of 300 mg/l after one hour as demonstrated in Figure B-31.

CERGRENE Shortcomings - Lack of Repeatable Results

The precision of the measurements for SS concentration in the mixing basin can be calculated from the analysis of triplicate samples. The precision of the CERGRENE columns can be calculated from the duplication of a sample at a specified time.

Precision for duplicate analysis was estimated by calculation of the relative percent difference using the following equation:

$$RPD = ((C_1 - C_2) \times 100) / ((C_1 + C_2)/2) \quad (3\text{-}3)$$

where RPD = relative percent difference
C_1 = the larger of the two observed values
C_2 = the smaller of the two observed values

When three or more replicates were available, the relative standard deviation (RSD), instead of the RPD, was used as follows:

$$RSD = (\mathbf{F}/y)x100\% \quad (3\text{-}4)$$

where: **F** = standard deviation, and
y = mean replicate analysis.

The standard deviation is defined by:

$$\sigma = \sqrt{\sum_{i=1}^{n} \frac{(y_i - \bar{y})^2}{n - 1}} \quad (3\text{-}5)$$

where: **F** = standard deviation
y_i = measured value of the *i*th replicate
y = mean of replicate measurements
n = number of replicates

For each run, a duplicate CERGRENE column was tested and three Recycles were taken The differences in these values is presented in Table 3.4.

These data indicate that the variation of the recycle concentration for each experiment was random and not media driven (microsand, Neshaminy and mixture). This variability is driven partly by the limited amount of samples but may also be due in part to the size of the samples taken (about 250 mL, a larger sample may have had lower variability between samples) and the force with which the sample bottles were filled by the pump (the same pump used to fill the Long column and the pump may have been too powerful for the sample bottle size).

The duplicate results for the CERGRENE column tell a different story. A duplicate analysis was performed by filling a CERGRENE column at the same or duplicate time interval. The duplicate served to measure the settling performance and QA for recovery from the

experimental apparatus. During the first nine experiments, four different CERGRENE columns were used, and any CERGRENE column could have been used to perform the duplicate. The same CERGRENE column was used for the remaining six experiments.

Table 3.4 Duplicate Analysis for Recycle Concentration and CERGRENE Columns

Experiment #	QA #	Withdrawal Height (cm)	Filling Sequence	Media	Recycle		CERGRENE Duplicate	
					RPD (%)	RSD (%)	Duplicate Time (min)	RPD (%)
1	8	36	C/L	Neshaminy	- -	0.53	NA	No Duplicate
2	12	36	C/L	Mixture	26.1	- -	3	28.6
3	11	18	C/L	Mixture	- -	14.7	3	18.6
4	3	18	C/L	Microsand	- -	24.2	1	7.2
5	5	18	L/C	Neshaminy	- -	6.2	0	23.8
6	14	36	L/C	Neshaminy	2.6	- -	60	9.8
7	15	18	C/L	Mixture	- -	11.8	10	35
8	1	18	L/C	Microsand	- -	13.3	5	5.9
9	9	18	L/C	Mixture	- -	9.1	3	8.2
10	6	36	L/C	Neshaminy	- -	5.6	1	0.56
11	10	36	L/C	Mixture	- -	8.8	0	0.25
12	13	18	L/C	Microsand	- -	5.3	10	22.2
13	4	36	C/L	Microsand	17.8	- -	5	12.6
14	7	18	C/L	Neshaminy	4.9	- -	60	1.1
15	2	36	L/C	Microsand	- -	9.6	1	2.1

The duplicate analyses of the CERGRENE columns for the first nine do not appear to follow any discernable pattern, not dependent on what time sampling occured, which media is measured or criteria of experimental design. The CERGRENE columns appear to behave randomly or independently for the first nine experiments. The duplicate analyses improve dramatically for the last six experiments when only one column is used as a distinct pattern can be correlated from the media being tested. The Neshaminy and mixture appear to have better duplicate analyses than the microsand. While the amount of data may not be large enough to state this finding with statistical certainty, this observable result is expected. The percent recovery analyses of SRM as discussed under ***Blanks and Standards*** indicated that microsand had the largest variation while the Neshaminy had the least with the mixture somewhere in between. That the difference in the CERGRENE columns duplicate analyses in the last six experiments was better than the expected recovery from the SRM analyses may be due in part to the larger sample size of the CERGRENE columns than was used in the SRM analyses.

The measured Recycle SS concentrations continued to behave randomly during the final six experimnets. This indicates that the improved CERGRENE performance in the latter experiments was not merely due to overall enhanced technique of the experimenters as the experiments progressed. One column, instead of several columns, each with their own idiosyncracies, produced repeatable results. This duplicate analysis only compared the SS concentration and not settling rates.

Percent Removal Long Versus CERGRENE

Traditional methods of computing settling velocity distribution based on settling column data rely on a simple depth per time relationship. In the Long column, the depth measurements from each port are divided by time of the sample to calculate the settling velocity distribution or the design overflow rate which can then be used in settling tank design. Though this computed number is in units of length per time (cm/s), it is not equivalent to a discrete particle settling velocity. The C_0 in the Long column are presumed to be uniformly distributed at all depths; however no direct measurement can be made to the length of the particles' flow path.

This design overflow rate was plotted versus the percent removal. For the Long column, percent removal is defined as the SS concentration at the port compared to the average recycle concentration for that run, which is the theoretical C_0 at every port. Though the actual C_0 at each port was obviously not equal to the recycle concentration (see discussion on lack of well-mixed conditions), this is a necessary assumption to construct a plausible settling curve and resulted in practical results with little scatter for the slower settling solids.

For the CERGRENE column, the overflow rate is compared to percent removal for each column of time greater than zero. Overflow rate is computed by dividing the distance an average particle traveled by the time measurement of the column. Thus, for each CERGRENE column, the number is computed by dividing one-half of the length of the upper portion of the water column (from the middle ball valve to the top water level) by the column's time, be it 1, 3, 5, 10 or 60 minutes. The C_0 in each column is assumed to be equal to the time zero column's bottom portion concentration. Percent removal is defined to be each column's top portion concentration (computed by comparing to the bottom portion concentration) divided by the column's assumed C_0 multiplied by the ratio of bottom volume over the top volume.

Figures C-1 through C-9 show Long column results for experiments 1 through 9. The CERGRENE results are not reliable and are therefore not shown. Figures C-10 through C-21 show Long and CERGRENE results for experiments 10 through 15. The shapes of settling curves are comparable for the two methods; the immediately obvious differences are apparent in the sand experiments (experiments 12, 13, and 15; Figures C-14 — C-17, C-20 and C-21, respectively). The Long column may overstate overflow rates for the fast settlers, as the right hand side of the Long column graphs should represents a larger spread of settling rates, and the CERGRENE columns under estimates removal rates, as they should attain 100% on the left side of the graphs. For the Long column, this is most easily explained due to the lack of adequate initial mixing. The assumption of C_0 being equivalent to average recycle concentration may yield a false concentration for the rapid settlers. For the CERGRENE column, the very large volumes of analytes made it difficult to do the SS analysis for sand. Theoretically, all the sand should have settled in the first three minute which corresponds to a settling rate of 0.5 cm/sec for a diameter of 85 **:**m, and the percent recovery at five and ten minute should have approached 100% . Losses of mass result in prediction of lower concentrations. Besides the problems with the SS analysis already discussed in this section under ***Completeness***, some microsand particles may have been trapped in the ball valve mechanism.

Matrix Iteration Process for CERGRENE Columns

The CERGRENE group of France (Lucas-Aiguier et al., 1997) developed a software application called VICTOR to use the data from the small columns to produce settling velocity distributions. VICTOR utilizes an iterative method to solve simultaneous equations, resulting in a matrix *M(i,j)* which contains mass removed for each particular time interval *i* and pollutant *j*. Based on this matrix, a distribution of settling velocities may be constructed. The resultant

analysis is presented in spreadsheets and figures. A more complete description of the derivation is in Appendix L.

The nature of the CERGRENE settling column method sometimes results in experiments for which the matrix analysis cannot find a solution or a limited solution at best. Thus a graph of M(i,j) for a particular pollutant concentration, in our case SS, versus time, which should increase monotonically, may have discrete points which exceed the following temporal point. Certain data points may not follow this pattern, and this may cause the VICTOR spreadsheet application to be unable to find a solution. The software allows the user to choose either analysis of all data points, which includes all data in the computation of the velocity distribution, or analysis with "suppression," which allows data points to be excluded. In the analyses performed for this project, the choice of suppression or non-suppression was based upon whether or not data points showed the expected increase in concentration versus time. Unless the points in question are significantly skewed to one direction, it should not have a severe impact on the resultant velocity distribution, and use of suppression can be minimized.

As discussed earlier, further analysis of CERGRENE experiments 1 through 9 is not warranted due to the inconsistencies between columns. Figure D-1 illustrates experiment 9, where the column order was randomized. Suppression was not possible with this data, as no pattern can be inferred from the mass removal graph. This experiment shows the limitations to the VICTOR software in relationship to the data presented to it. The points at 200 and 300 s (figure to left) exceed the points at later times 600 and 3600 s, which confounds the ability of the software to breakdown the experiment into a meaningful velocity distribution profile (figure to right). This may be contrasted with Figure D-2, which shows the results from experiment 10, where one column was cleaned and reused for each time interval. Monotonically increasing mass removal values are seen (left), as well as a more varied velocity distribution (right).

Figure D-3 shows the results of experiment 11, utilizing all points. Figure D-4 shows the results after suppressing points 2 and 5, which fall outside of the expected pattern. Note the differences in the velocity distributions, especially in the slowest reaches, where the 3600 s point was suppressed. The basic shape of the distribution, however, remains the same.

Figure D-5 shows experiment 12, where suppression was not possible, because suppression would leave only 2 points for analysis (a minimum of three is necessary). The shape of the velocity distribution, however, is similar to that of experiment 13 (Figure D-6), both of them being sand experiments. The third point in Figure D-6 could have been suppressed, but it does not fall far outside the curve, and thus is probably more useful being left in the analysis. Suppression of this point results in a sharper drop-off at the slower settling velocities.

Figures D-7 through D-10 illustrate experiments 14 and 15, with and without suppression. Note that the shapes of the velocity distributions remain similar whether or not points are suppressed.

VICTOR can prove a useful tool for computing a settling velocity distribution for the CERGRENE columns, as long as the data increases monotonically. Otherwise VICTOR may require data suppression, a euphemism for selectively choosing data points. In general eliminating or throwing out data points may be viewed as a questionable practice and is not advocated by the authors; it is presented here to complete demonstration of the method and the matrix calculations. Care should be taken in trying to compare these velocity results to the results from other types of analyses, which use different assumptions, computational techniques and methods for deriving settling velocity distribution. Additionally, VICTOR potentially may work better with higher numbers of samples and time intervals. The capability of the software to

track several pollutants could be very useful for partitioning tests, though this feature was not examined here.

Eckenfelder Analysis for Long Column

Use of Eckenfelder plots proved to be an inappropriate analysis for the media in Phase II. The Eckenfelder analysis is generally used to provide flocculant analysis. For the analysis to be successful, iso-concentration lines need to be developed from plotting concentration values for each sample depth (y coordinate) and time (x coordinate). The clay particles were not settling, and in fact concentration increased at the lowest port for several experiments at the one hour mark. This, as stated earlier, seemed typical of hindered zone settling. During the sand and mixture experiments, the sand settled within a five minute time frame and exhibited properties of discrete settling, not flocculant settling.

Design Removal Comparison

Table 3.4 shows calculated overflow rates versus percent removals for the Long and CERGRENE columns for experiments 10 through 15. Calculations were identical to those used to develop the graphs in Appendix C, except that outlying CERGRENE points were deleted if the Victor algorithm suppressed the points automatically. Results from the Victor analysis were wildly divergent from the calculated results in Table 3.4, possibly due to lack of sufficient data points to effectively utilize the Victor tool. In fact, settling velocity results of Victor runs do not even show a noticeable difference between media. Comparisons of Long to CERGRENE results show some similarities, though CERGRENE analysis is complicated by the lack of sufficient data points.

The calculated Stoke's Law settling velocities for ideally spherical sand at 15 ºC ranged from 0.5 cm/s for 85 :m diameter sand to 12.6 cm/s for 400 :m. At 230 :m, the d_{50} value as calculated by the Coulter® LS Particle Analyzer for the microsand, the settling velocity is 9.3 cm/s.

A graphical comparison of percent removal of the microsand for the two column methods is shown in Figure 3-1 and 3-2 (O'Connor et al, 1999). Concentration decreases over time in the Long column, while in the CERGRENE columns the concentration accumulates because samples are withdrawn from the bottom section. Figure 3-1 shows that the Long columns predicted nearly 100% removal for the microsand experiments (experiments 4, 8, 12, 13 and 15 as listed in Table 3.3) which is expected, as the microsand should settle out in the first 3 - 5 min, whereas the CERGRENE columns only predicted 50% removal with a wide variation. The microsand as a medium to measure SS recovery contributed a significant amount of loss during the SS analysis because of the physical properties of the microsand (e.g., stuck to wall of sample bottles). This bias error was estimated by calculation to be a 20% loss over a range of concentrations for standard reference samples. This expected loss of 20% was incorporated into the percent removal values for the microsand. Figure 3-2 indicates that there was still a significant amount of variation and loss for the CERGRENE column system which under predicts the expected 100% removal for microsand after ten minutes.

Table 3.5 Measured Overflow Rate and Predicted Percent Removal for Long and CERGRENE Columns

Experiment (Media)	Percent Removed (%)	Overflow Rate Long[†] (cm/s)	r^2	Overflow Rate CERGRENE[‡] (cm/s)	r^2 (#pts)
10 (Neshaminy)	30	0.069	0.81	0.072	0.96 (5)
	50	0.0077		0.010	
	70	0.00086		0.0015	
11 (Mixture)	30	4.4	0.61	0.30	0.99 (3)
	50	0.14		0.0014	
	70	0.0046		0.0000069	
12 (Microsand)	30	100	0.64	100	0.22 (4)
	50	18		1.27	
	70	3.1		0.016	
13 (Microsand)	30	120	0.65	1.8	0.92 (4)
	50	20.		0.076	
	70	3.4		0.0032	
14 (Neshaminy)	30	0.014	0.43	0.61	0.82 (4)
	50	0.00059		0.094	
	70	0.000024		0.015	
15 (Microsand)	30	220	0.66	31000	0.90 (3)
	50	30.		30.	
	70	4.0		0.00028	

[†] Based on average recycle concentration. Points with calculated %Removal<0 were deleted.
[‡] Points removed by the Victor "suppression" algorithm were deleted, often yielding few points. Number of points used in the analysis is shown with the correlation coefficient.

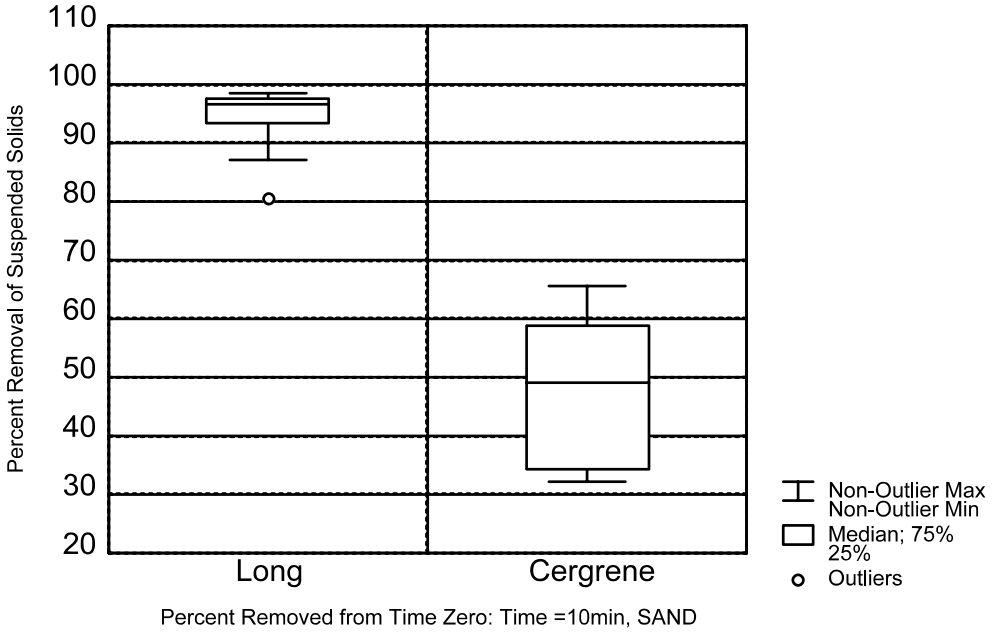

Figure 3-1 Comparison of Removals of Microsand

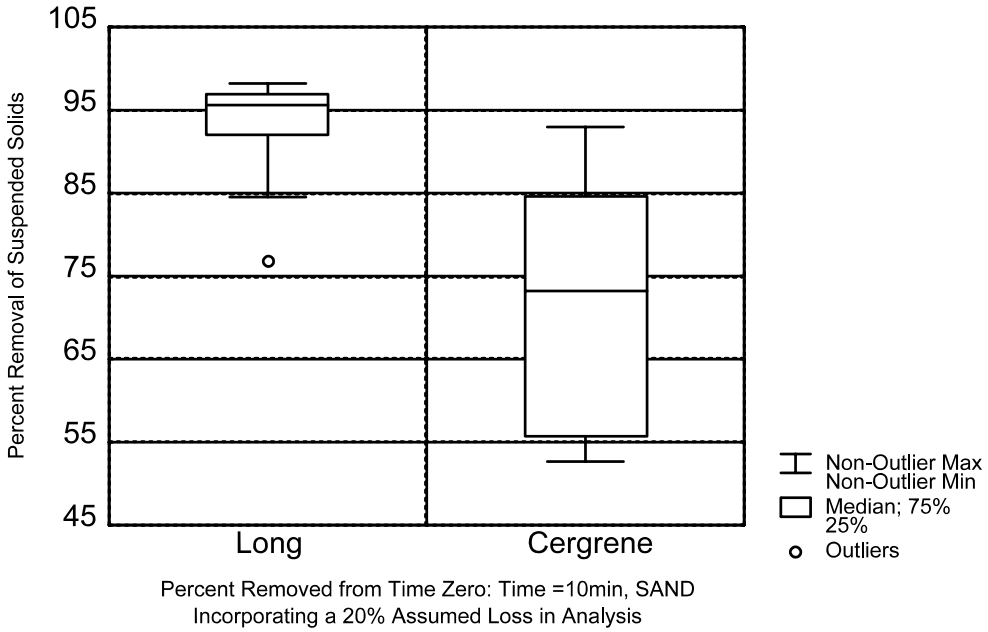

Figure 3-2 Comparison of Removals of Microsand with Error Included

Initial Concentration Comparison

Figure 3-3 (O'Connor et al. 1999a) shows that the CERGRENE column for determining the initial SS concentration for all experiments had less variation and was closer to the initial known concentration of 300 mg/l than the Long column. The CERGRENE column, a nearly instantaneous initial concentration measurement, approached 300 mg/l with a small deviation. The Long column required at least 40 s, and up to a minute as previously stated, before the four ports could be sampled for initial concentrations, thus "missing" many of the faster settling particles. Figure 3-3 also shows that initial concentrations, which should be equivalent throughout the column, decreased towards the top of the Long column (Port 8>7>5>3). Background concentrations for the Long column, measured by taking samples directly from the pumped influent to the column, averaged 270 mg/l with a standard deviation of 30 mg/l.

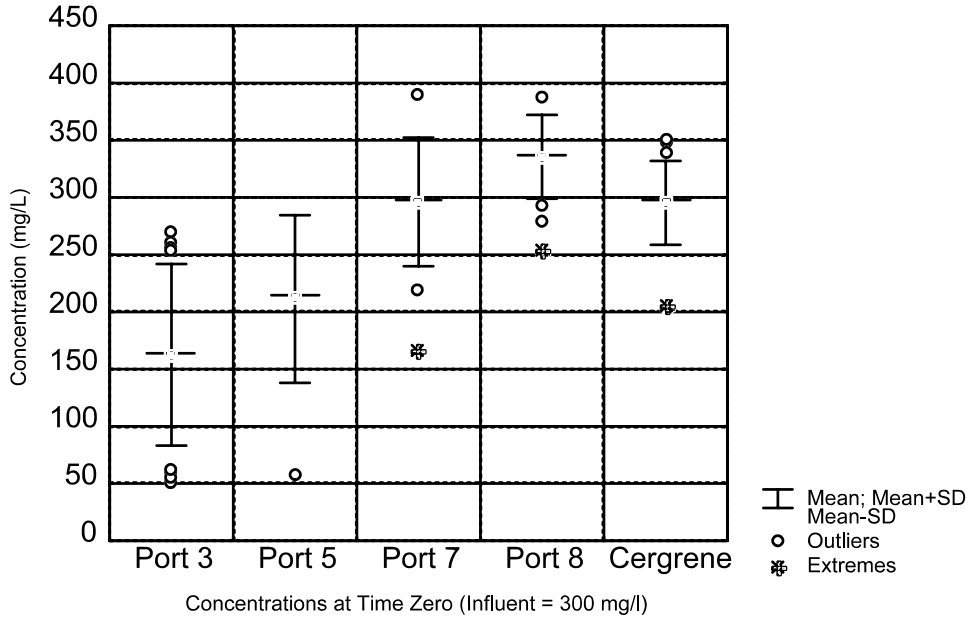

Figure 3-3 Comparison of Initial Concentrations

Discussion and Recommendations

The objective of the Phase II laboratory experiments was to compare, in side-by-side analysis, two methods of measuring settling velocity distributions of solids in water. Laboratory study results indicated that the CERGRENE columns have some advantages, such as ease of use, smaller testing volumes and a consistent initial concentration, but also significant problems such as loss of SS mass and lack of reproducibility for other time measurements. The Long column had its own advantages, such as repeatability and consistent (predictable) SS removals, while the disadvantages included poor initial concentration measurement, large testing volumes and large number of SS analyses required.

Phase II experiments were also designed to determine the optimal withdrawal point from the mixing basin as well as the withdrawal order on experimental results. Statistical analysis indicated that neither of these aspects of the experimental design were significant. Phase I

preliminary testing of microsand (not shown) indicated that the John Meunier mixing basin set up provided more than adequate lift to suspend particles and that the sampling points with the least random concentrations were toward the top of the water column in the mixing basin.

The original experimental design did not account for the three factors which most affected results during Phase II of the experiment:
1. Individual behavior of the CERGRENE columns
2. Overloading of the filter by the samples (when trying to pass whole sample through filter)
3. Wide variation in measured SS concentrations when analyzing micro-sand suspended in water

Initial conclusions from Phase II were:

1. Microsand was more difficult to work with than anticipated. It was difficult to recover all of the microsand during SS analysis. This is a result of the physical characteristics of the sand. While behaving discretely during settling in the water column, when not fully submerged, the particles tended to cling to analytical equipment due to surface water tension and losses of mass easily occurred. Each sand grain contains significant mass, so even a loss of several grains can increase errors. This loss was especially noticeable in the larger CERGRENE samples where the large volume of analyte caused the filters to become overloaded. The microsand was a major source of error to the experiment; however this error had a distinct bias toward a loss of microsand.
2. The performance of the CERGRENE columns was erratic for experiments 1-9 in which four different CERGRENE columns were used. While the expected results of a plot of concentration versus time would show an increase in the concentration with time, the columns in experiments 1-9 behaved almost randomly. In contrast, experiments 10-15, where only one column was used, indicated this trend of increasing concentration versus time and seemed to point to a lack of consistency between the four columns used during experiments 1-9. However, even this trend of increasing concentration for experiments 10-15 had scattered results.
3. The Long column was never fully mixed at t_0, especially for the microsand and mixture experiments due mostly to an inadequate way of delivering the mixed analyte to the settling column.
4. The CERGRENE columns were examined for defects and sizing specifications for volumes and height. No defects or deviations from the specifications were found, though a small indentation in the ball valve, part of the functional design, could be trapping some solids.

Recommendations for the CERGRENE column were:

1. CERGRENE Columns should be modified to allow filling to a constant head (which has already been adapted by the CERGRENE research group in France). The water height in the column is an essential measurement of the analysis procedure. Starting at the same height would also allow for better duplicate analysis.
2. The filling procedure should allow at least a ½ volume to overflow the column.
3. More data points should be evaluated. The matrix analysis spreadsheet “Victor” currently allows for nine data points not including the initial time and final time. Only four and five data points were collected for the microsand and other experiments, respectively.
4. Sample volumes should be reduced to ease analysis. This could be accomplished by reducing the volume of the bottom portion of the column and/or splitting samples to avoid overloading.
5. Evaluations of other types of valves should be conducted to attempt to minimize interference of the valve mechanism on solids settling.
6. The concentration of the top and bottom parts of the column should be measured at t_0, to

ensure that the initial concentrations, before settling, are the same.

Long column recommendations were:

1. The long column should be retrofitted with a device that allows an overflow to achieve better mixing and to allow for a repeatable starting depth.
2. A more powerful pump and mixer should be employed to reduce the concentration gradient of SS in the column at time zero.
3. Delivery of a well mixed plug flow at the top of the column would allow for easier computation of settling velocity. This method should be further investigated.

General recommendations:

In future experiments using the microsand, the last sample time should be reduced to five minutes with sampling frequency increased from t_0, i.e., 15s, 30s, and 60s. As previously discussed, the microsand diameters were found to be larger than originally reported which increased the settling rate.

It was a benefit from the standpoint of this phase to analyze "standards" using the same media that was used in the experiments. This data confirmed an expected bias (or losses) for the media, i.e., microsand, in the course of the SS analysis. However, for the sake of confirming the SS analysis technique, diatomaceous silica should have been used for standard reference material. In addition, the same sample bottle sizes should have been used for the standard volumes as the experimental samples.

4. RESULTS OF ADDITIONAL LABORATORY SAMPLING

Following the recommendations of the interim report, further analyses were performed on the CERGRENE column at the UWMB laboratory. These additional experiments were conducted using microsand and the Neshaminy clay soil as the characteristics of these solids were already known. To standardize these additional experiments further, all the samples were all taken at t_0, as this was the most consistent sampling time for the CERGRENE columns during Phase II performed in John Meunier's laboratory in Montreal. The recommendations for the CERGRENE columns that were addressed during these experiments are:

- A procedure was developed where the CERGRENE columns could be filled to a constant head, which allows for the columns to start settling at the same height and eases measurement and computation,
- The same procedure allowed the CERGRENE columns to be overflowed,
- The sampling hose was purged between samples, and
- The SS concentrations in the top and bottom portion of the column were measured at t_0, to ensure that the initial concentrations, before settling, are the same.

An integral aspect of the CERGRENE design, as described in Section 2, is to fill the columns by vacuum aspiration instead of using positive displacement pumps which, when used with sewage, tend to breakup the particles and thus change the settling-velocity distribution of the sample. During the Phase II side by side experiments there was no precise control to the fill level in the CERGRENE column which was a critical measurement for the procedure. Overflowing the CERGRENE column eliminated the need for the height measurement and standardized the volume of the top chamber which was a required input for the Victor model. As previously mentioned in Section 2, the vacuum pump used for the remainder of the experiment was also much more powerful and filled the CERGRENE column faster than in Phase II.

The problem associated with the consistent height measurement of the upper chamber of the CERGRENE column was also addressed by the CERGRENE developers in France, who developed a similar overflow solution, although the exact configuration was not detailed. Figure 4-1 shows the configuration that was used for the remainder of the experiment, which basically entails the addition of a filtering flask to capture the overflow from the column. The numbers in Figure 4-1 detail how the experiment was broken down into several filling capacities to see if overfilling the samples would improve results.

Only the one column deemed reliable during Phase II was used in these and the Phase III field experiments. The samples were transferred to 1 L sample bottles and analyzed later. The intake lines from the mixing basin between each time measurement were purged by vacuuming two sequential overflow volumes into the CERGRENE columns of potable water between samples in this and the Phase III experiments. In Phase II, the influent line was only allowed to drain under its own head and the CERGRENE column was washed out under a tap.

Standard Method analyses were limited to SS as listed in Table 2.4. Two experiments were performed using the same experimental materials as were used in Phase II. Experiment 1 used Neshaminy clay soil, and Experiment 2 used the microsand. The sampling was conducted by EPA personnel and laboratory analyses were conducted by U. S. Infrastructure, Inc. (USI).

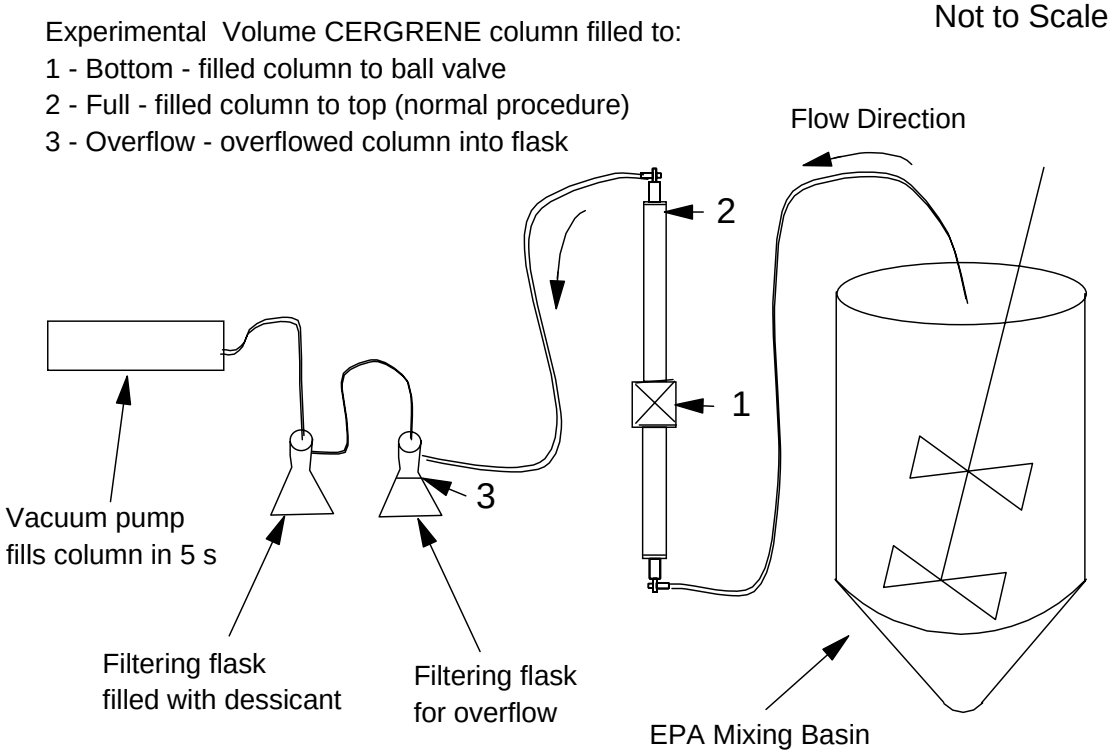

Figure 4-1 New configuration with additional flask to overflow CERGRENE column.

Quality Control Analysis

Blanks and Standards

Blanks were taken with either de-ionized, tap, or basin water before the delivery of the media. The purpose of blanks was to ensure the cleanliness of SS analysis and sample transfer.

For experiment 1, the measured SS concentration in the lab blank sample was -1 mg/l. A method blank, tap water in a sample bottle, had a SS value 2 mg/l. Two method backgrounds, water taken from the full mixing basin before the Neshaminy clay soil was put in, had SS concentrations of 2 and 17 mg/l. The concentration of 17 mg/l, may indicate some residual concentration in the mixing basin or the sample bottle. For experiment number 2, a laboratory blank of 0 and a method blank of 0.93 mg/l.

The SRM samples were from a manufacturer of laboratory control samples (Environmental Resource Associates, WasteWatR^{TM} Quality Control Samples). The accuracy expressed as percent recovery (equation 3-1) for the two laboratory standards that were run (one for each experiment) was 101% and 104% respectively. The SRM samples were within the control limits as provided by the manufacturer.

Two 250 mg/l QA samples of microsand were prepared. The percent recovery of these samples were only 48% and 67%. These results were typical of the Phase II results of the SRM samples (refer to Figure A-3 in Appendix A) and as different personnel performed the SS

analyses this serves as an independent confirmation of the typical results found during Phase 1 for microsand. Since the Neshaminy clay soils did not have similar recovery problems sas the microsand samples during phase 1, no QA Neshaminy samples were prepared

Completeness

Table 4.1 shows the completeness for critical SS measurements made for both experiments. Completeness is calculated using equation 3-2. Of the 24 separate CERGRENE samples, two were voided due to faulty data recording.

Table 4.1 Completeness of Suspended Solids Analysis

Samples	Samples	Voided Samples	Expected Completeness	Measured Completeness
ALL	31	2	90%	94%
CERGRENE	24	2	90%	92%

Laboratory Duplicate

One duplicate was performed for these two experiments. The laboratory RPD was calculated to be 0.51. The duplicate was performed on the Neshaminy clay soil as only a portion of the total sample was used, 100 ml out of approximately 1 L. The microsand experiments used the whole volume of the sample which was rounded off to 1000 L for all CERGRENE samples, which may have introduced some error to be discussed under the heading Mass Balance.

Results of Experiments 1 and 2

Tables 4.2 and 4.3 show measured concentrations and statistical analysis of the two experiments. Here RPD (equation 3-3) or RSD (equation 3-4) represents duplicates or triplicates of the CERGRENE columns dependent on the volume flowing in and through the column. The initial concentration of the Neshaminy clay soil was 270 mg/l and the microsand was 290 mg/l assuming the mixing basin was filled to capacity. The precision of the CERGRENE columns can be calculated from the duplicates or replicates of a sample at a specified time.

Results would appear to indicate two things, one positive and the other somewhat negative. The samples with the flow-through method had the lower RPD or RSD values and therefore overflowing the columns is a better method of filling the CERGRENE columns. However, averages at t_0 appear to be lower than the expected results of 270 mg/l and 290 mg/l for Neshaminy and microsand, respectively. Phase II t_0 results approached 300mg/l, which was the known starting concentration. This could indicate that the EPA mixing system was not as proficient at lifting the heavier particles as the John Meunier set up used in Phase I; however, this results still represent > 90% recovery. As noted during the experiments some solids were seen in the fitting grooves of the effluent valve of the CERGRENE column.

By sampling the top portion of the CERGRENE column of the experiments that either filled or overflowed the CERGRENE column, an attempt was made to verify that the concentrations were equivalent around the center ball valve of the CERGRENE column. This comparison was made by looking at the average concentrations of the experiments listed as Through and Top in Tables 4.2 and 4.3. This may not be as easy since the very act of turning the ball valve to drain the top portion will capture and separate a small volume of water from either the top or bottom portions.

Table 4.2 Experiment 1 Suspended Solids Concentrations of Neshaminy Clay Soil

Sample	Description	Concentration mg/l	Mean	**F**	RSD (%)
Bottom 1	15 cm above center ball valve	129	186	53	28
Bottom 2	12 cm above center ball valve	197			
Bottom 3	8 cm above center ball valve	233			
Full 1	full, no water in flask	198	158	90	57
Full 2	full, some water in flask	55			
Full 3	full, flask < ½ full with water	220			
Through 1	full, flask > ½ full with water	176	191	15	7.8
Through 2	full, flask > ½ full with water	192			
Through 3	full, flask > ½ full with water	206			
Top1	Top of Full 1	209	205	6.9	3.4
Top 2	Top of Full 3	197			
Top3	Top of Through 3	209			

Table 4.3 Experiment 2 Suspended Solids Concentrations of Microsand

Sample	Description	Concentration mg/l	Mean	**F**	RPD or RSD (%)
Bottom 1	11 cm above center ball valve	164	172	42	25
Bottom 2	6.4 cm above center ball valve	134			
Bottom 3	1.3 cm above center ball valve	218			
Full 1	full, no water in flask	162	172	89	52
Full 2	full, some water in flask	266			
Full 3	full, flask < ½ full with water	89			
Through 1	full, flask > ½ full with water	145	157	--	15
Through 3	full, flask > ½ full with water	169			
Top 2	Top of Through 2	159	172	--	16
Top 3	Top of Full 3	185			

In addition, volume measurements of the CERGENE column were done in the laboratory after Phase III field sampling was completed. The total volume of the column was approximately 2470 ml. The volume of the bottom portion of the column averaged 967 ml but was set at 960 ml for all Phase II and III calculation. The volume of the top portions of the column was more difficult to measure, as by the time of these volume measurements were made the column began to leak. Precise volumes for the top portion could not be obtained without including the ball valve component for a total volume of 1510 ml. The top chamber ranged from

1160 to 1235 ml, although it was approximately 1280 ml. The ball valve component measured approximately 230 ml.

This difficulty with obtaining volumes of the top portion of the column underscores the problems with trying to confirm equal concentrations on either side of a ball valve. The bottom portion of the CERGRENE column had to be drained before the top portion could be drained. The samples bottles used to collect the top portion held approximately 1 L, which meant the whole 1280 ml top volume could not be drained nor could the 230 ml contents of the ball valve. In the time it took to set up the CERGRENE column to drain the top portion, some settling may have occurred in the top portion and sample SS concentrations may not have been uniform.

This may have been more critical in the case of the Microsand where the whole sample volume was analyzed, the mean SS concentrations of the upper chamber reported at 172 mg/l (reported as Top in Table 4.3) may have been smaller by a 1000/1280 ratio if settling of the microsand occurred. The SS concentration of the upper chamber may have been as low as 134 mg/l. The lower chamber (Through in Table 4.3) measured at 157 mg/l for the samples.

For the Neshaminy, the volume differences may not have been as significant as only a 100 ml volume of the sample was analyzed for SS concentration of the lower and upper chambers (labeled Through and Top in Table 4.2) with concentrations of 191 and 205 mg/l respectively. The slight increase in concetration of the Neshaminy in the upper chamber may have been caused by lighter material being carried up by the large Reynolds numbers (6000 - 50,000 as calculated in Appendix M) produced by the flow to fill the column. It could also be caused by the settling mentioned above. However, this increase of the upper chamber concentration is not statistically significant and therefore shows good agreement, and is evidence of a mass balance between chambers for the lighter material. The same cannot be conclusively said for the Microsand. What is significant is that in the cases measured, overflowing the column led to a measurable SS concentration in the upper chamber.

Other Considerations

These experiments indicated that filling-through gave the most consistent and easiest to perform testing method for the CERGRENE columns. The selected procedure to fill the CERGRENE column was to turn off the vacuum pump once the first filtering flask was half filled (corresponding to the number 3 position in Figure 4-1).

By overflowing, the pump was on longer. This decreases the fraction of start up time for the pump to the total time period the pump is on. This may minimize start-up velocity flow fluctuations and possibly allows the pumped sample to achieve steady state flow through the system, i.e., column and influent hoses. For the idealized case, the time to one half the value of the steady flow velocity could be several seconds, i.e, 3 - 6 for the CERGRENE column and up to approximately ½ s for the influent tube. If all head losses, due to bends and turns, surface roughness, and kinematic viscosity are taken into account, these approximations may change. Appendix L shows the calculations for clean water using the measured flowrates of the EPA vacuum pump. In actuality, due to elastic waves and dampening, steady state is eventually achieved, while theoretically, the idealized case never reaches equilibrium. In practice, steady state flow should deliver a more uniform concentration then a flow that is oscillating.

Another consideration calculated in Appendix L is the wall effects on the settling rates in the column and transport of the sample to the column by influent tubes. The wall effects appear to be insignificant for the settling rates at the expected concentrations. The column or tube diameter would have to approach 0.5 mm before a 5% effect were measured.

Conclusions and Recommendations

Results indicated overflowing column achieved a more consistent result and had the lowest RSD of the methods tested in these additional experiments. The overflowing of the CERGRENE Column system was adopted for the field sampling and allowed filling to a constant head. The water height in the column is an essential measurement for calculation of the settling rates and also allowed for better duplicate analysis.

Use of diatomaceous earth as the SRM validated the performance of the USI laboratory. Again the microsand was a major source of error to the experiment, with a distinct bias as the analysis of a loss of sand.

A measurement of the upper and lower chamber SS concentrations was performed, but there were limitations to the effectiveness of this comparison. A 2 L sample bottle was needed for the top portion. The current configuration of the CERGRENE columns uses a ball valve to separate the top from the bottom; this ball valve holds a small volume of water and complicates comparisons of the top and bottom SS concentrations.

The EPA mixing basin had a slight mixing as the John Meunier mixing basin design. The vacuum pump used in these and the field experiment provided a much better influent flowrate.

A more rigorous approach may be needed to determine the fluid dynamics of the CERGRENE columns and the component pieces.

5. RESULTS OF PHASE III FIELD TESTING

Several recommendations were made for the CERGRENE and Long columns in the interim report that were intended to improve the final Phase III field experiments. The recommendations of further analysis performed on the CERGRENE column were detailed in the previous section. The Long column recommendations were:

- The long column should be retrofitted with a device that allows an overflow during filling to achieve better mixing and to allow for a repeatable starting depth.
- Delivery of a well mixed plug flow at the top of the column would allow for easier computation of settling velocity.
- A more powerful pump and mixer should be employed to reduce the concentration gradient of SS in the column at time zero.

Other recommendations for the CERGRENE column following Phase II and not addressed in the additional laboratory sampling were:

- More data points should be evaluated. The matrix analysis spreadsheet "Victor" currently allows 10 data points not including the initial time and final time.
- Aqueous volumes should be reduced for SS analysis. This could be accomplished by reducing the volume of the bottom portion of the column and/or splitting samples to avoid overloading filters used in SS analysis.

Only one of the three Long column recommendations was directly addressed. No adjustment was made for the first recommendation, although the additional laboratory experiments covered in Section 4 demonstrated the apparant usefulness of overflowing for the CERGRENE column. At a minimum, provisions should have been made for at least a minor controlled overflow so that the column could be filled to the top without guess work or spillage. An overflow did occur during the third field experiment and the Long column was not sampled due to the spill which interrupted the integrity of the experiment. This also impacted the 1 hr time measurement for the CERGRENE column during the third experiment.

No attempt was made to evaluate the second point of delivering a well mixed plug flow to the top of the Long column as an alternative method. For this method to be successful, it would have required significant redesign of the experiment and delivery system. This would have minimized the comparability of pumping from the bottom as the delivery system for both columns. During Phase I, rudimentary attempts to introduce hand mixed plug flows at the top of the Long column proved unsuccessful.

The third point was addressed as a more powerful pump was employed to reduce the concentration gradient of SS in the Long column at time zero. A Moyno pump (300 series) filled the Long column and pumped the raw combined-sewage from the Perth Amboy, NJ grit chamber. The Moyno progressing cavity pump, capable of 7.6 m (25 ft) maximum lift at 1750 rpm, was used to minimize the maceration of the combined-sewage sample. Due to the power of the pump, which had more than sufficient intake velocities, only one sampling port was exposed to the influent combined sewer flow at the Perth Amboy grit chamber. A 2.54 cm (1 in.) inner diameter, reinforced tube was manually dropped into the grit chamber and it was bobbed up and down, and back and forth to provide a variety of material in the mixing basin (210 L (55 gal) were collected). The original John Meunier, Inc. design, described at the end of Section 1, called for two intake points, but this was envisioned for a mounted, in-sewer sampling location.

The CERGRENE concerns were addressed in the following manner:

- Additional times of 7, 20 and 30 min were added to the experiment.
- The CERGRENE column was not redesigned so the volume of sample from the bottom

portion remained the same as in previous experiments. The second field experiment used split samples for SS and total solids analysis. The first experiment only used a portion of the sample for SS analysis. The third experiment used the whole sample for total solids analysis.

Experimental Design

The experiments produced three data sets from the first two field experiments for the Long column and four data sets from three field experiments for the CERGRENE column. During these experiments the CERGRENE columns were filled first, except for the last one hr time measurement. This was due in part to the smaller size of the EPA mixing basin than the John Meunier Mixing Basin. As the Long column was filled, the mixer would vibrate due to the decreasing water volume weighing down the mixing basin. For the CERGRENE columns, the sample collection tube was placed approximately 5 to 10 cm (2 to 4 inches) from the top of the water level in the mixing basin. Previously, the John Meunier mixing basin was shown to more than adequately lift the microsand from the bottom of the mixing basin. The EPA mixing basin did not have the same configuration, and as shown in Section 4, may not have provided the equivalent mixing. The EPA basin also had a port in the bottom through which the Long column was filled. This was easier to work with in the field, where there was an attempt to minimize direct contact between the sampling personnel and the combined sewage, than drawing the sample out from the top. Figure 5-1 shows a schematic of the field experimental setup.

The columns were transported to Perth Amboy, NJ which is approximately five miles away from the EPA laboratory in Edison, NJ. The Perth Amboy Wastewater Treatment Plant is an enclosed facility which allowed for a complex setup and rapid startup as the equipment was stored securely between events. The sampling and settling distribution analysis was conducted only during wet-weather flow events when the plant flow charts exceeded 90%, which indicated a significant wet-weather flow. At measurements of 100% on the flow chart, the system typically overflowed. The combined sewage was collected from the Perth Amboy grit chamber. Samples collected from the Long and CERGRENE column were brought back to the laboratory for solids analysis. At the time of the study, accumulated grit was removed from the wet-well once every three months.

Several field blank samples had unexpectedly high solids values. To help determine the cause, additional field blanks were taken at the sampling site after the original Phase III experiments were completed. An additional round of grab samples were taken from the grit chamber to perform Settleable Solids (SM 2540F listed in Table 3.1). This sampling also occurred during a rain event with > 90% flow.

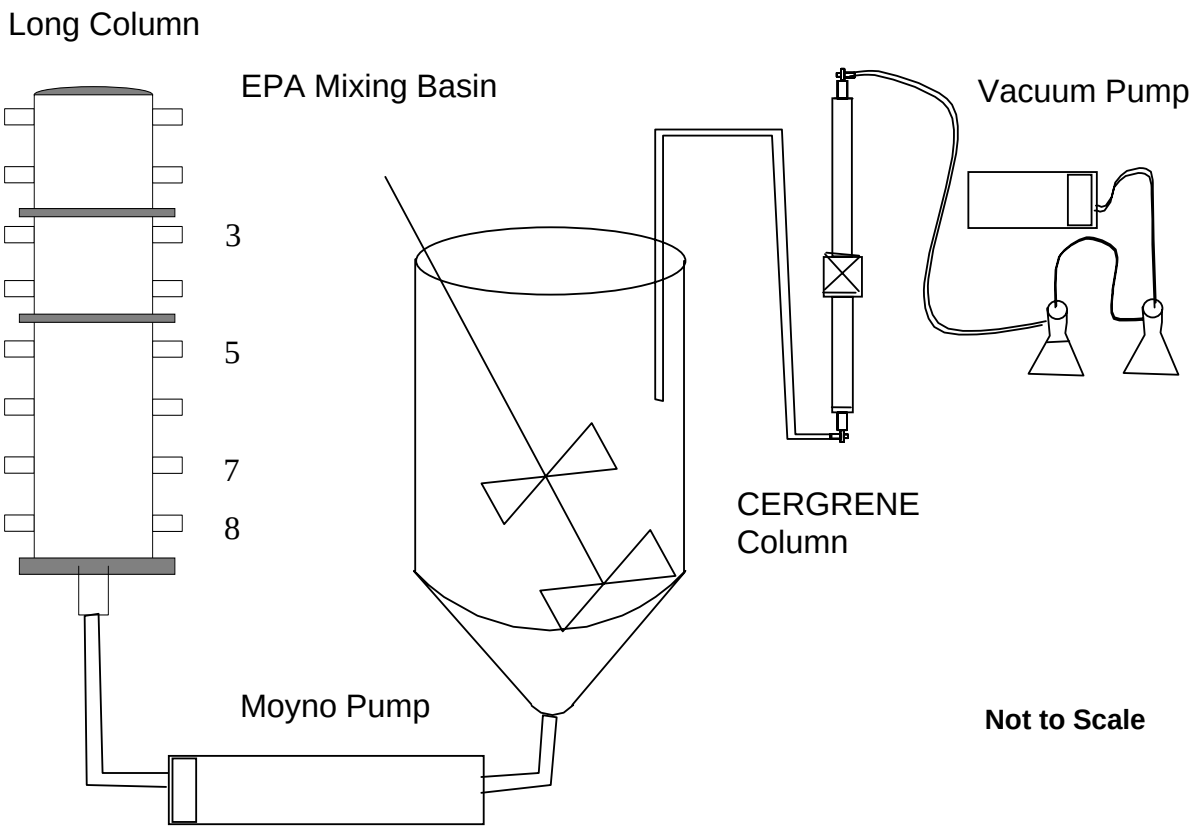

Figure 5-1 Configuration for Side-by-Side Field Analysis

Ideally, the whole sample, i.e., the approximate 1 L bottom portion of the CERGRENE column or the 250 ml Long column sample bottle, was to be analyzed for solids. During Experiments 1 and 2, samples were shaken and only a portion were measured for SS and VSS analysis. The SS concentration of Experiment 1 samples from Perth Amboy were for the most part under 100 mg/l and were still clogging the filters before the whole sample could be filtered for SS. During Experiment 2 only 100 ml was used for SS analysis of all samples. The remaining portion of the sample from Experiment 2 was analyzed using Total Solids (TS), which became the preferred method and was also used for Experiment 3 and the additional sampling. The TS analysis, which uses evaporation, was used as a more pratical approach to completely analyze the samples without splitting than the SS analysis, which uses filtration. A small portion of the sample at a time was poured into one dish for TS analysis instead dividing into several SS samples. Either procedure can introduce error, and the TS analysis was chosen as a better method to capture all the settleable solids of the sample which was the most important aspect of sample analysis.

Changing from SS to TS analysis should not have otherwise affected the outcome of Phase III results. A spreadsheet analysis of the average ratio of TS to SS values was similar to text book values, approximately 3.4, even though SS was completed within the holding time, and TS was not. Either solids method may be acceptable, and a portion of the sample may be used (as was also detailed in Section 3 with regard to the Neshaminy analysis), as long as the samples are well mixed when split. This is explained further under Quality Control Analysis.

Quality Control Analysis

Blanks and Standards

The laboratory blanks were drawn from laboratory de-ionized water. SS analysis of three of the four laboratory blanks yielded between -2 and 0 mg/l, which is acceptable. The first blank for TS analysis registered 29 mg/l, which was high. One explanation offered by the laboratory personal was that they were working with porcelain dishes which had a tendency to accumulate water vapor with time. The purpose of the laboratory blanks was to determine whether laboratory SS procedures introduce error in the SS analysis.

Field blanks were taken from a tap of the Perth Amboy potable water supply located in the grit chamber room. The purpose of the field blanks was to determine whether other aspects of the procedure, e.g. storage bottles and handling procedures, introduce error into solids analysis. Because of an apparent problem with the analysis of the field blanks taken on 3/28/00 and 5/19/00, some additional field blank samples were taken on 6/6/00 after the Phase III field measurements. All laboratory and field blanks results are listed in Table 5.1.

Table 5.1 Analysis of Blanks

Phase III Experiment	Date	Blank Type	Concentration (mg/l)			Comment
			SS	VSS	TS	
1	3/17/00	Laboratory	0	-2	- -	
		Field	- -	- -	- -	Voided by laboratory
2	3/28/00	Laboratory	0	0	- -	
		Laboratory	- -	- -	29	
		Field	95	- -	543	Perth Amboy tap water
3	5/19/00	Laboratory	- -	- -	0	
		Field	- -	- -	244	Perth Amboy tap water
Additional Field Blanks	6/6/00	Field	- -	- -	199	Perth Amboy tap water
		Field	- -	- -	188	Perth Amboy tap water
		Field	- -	- -	172	Perth Amboy tap water
		Field	- -	- -	118	Laboratory tap water (Edison)
		Laboratory	- -	- -	-25	De-ionized in dish
		Laboratory	- -	- -	-7	De-ionized in sample bottle

Because the field blank for Experiment 1 was voided (due to difficulties with static charge build up on porcelain dishes during weighing, as were three other samples), only the Experiment 2 field blank SS and TS concentration requires further explanation. The TS results for Experiment 3 are not significantly different from the results obtained from 6/6/00 additional field samples. Both results indicate that there is a large loading of TS in the Perth Amboy tap

water, approximately 200 mg/l, compared to the Edison potable water supply, approximately100 mg/l. The use of tap water for blanks was not a problem during the Phase I and Phase II results because the samples were filtered and dissolved solids were not analyzed.

The Experiment 2 field blank had unexpectedly high results for both the SS and TS analysis. This could have been caused by any number of reasons, i.e., faulty sampling technique, using a dirty sampling bottle, mislabeling of the sample in the field or the laboratory, or cross contamination of samples in the laboratory. Because additional field blanks results were not taken during Experiment 2, it is difficult to specifically identify where the fault lies.

QA objectives for solids analyses were limited to the parameters listed in Table 5.2 and those previously listed in Table 3.2. Two types of SRM were provided. One from a manufacturer of laboratory control samples which USI purchased. The second were made by EPA and provided to the USI laboratory personnel.

Table 5.2 QA Objectives for Measurements *

Measurement	Method	Reporting Unit	Initial Concentration	Standard Deviation	Relative Standard Deviation	Complete-ness
Total Solids	2540 B	mg/l	NA	6.0	NA	90%
Volatile Solids	2540 E	mg/l	170	11	6.5%	90%

* From Standard Methods (1995)

The manufacturer SRM samples were from Environmental Resource Associates, WasteWatR™ Quality Control Samples. For SS and TS analysis, the manufacturer SRM samples were all within the manufacturer provided control limits. The accuracy expressed as percent recovery was calculated using equation 3-1. SS percent recovery ranged from 89 — 104% and was well within the expected values in Table 3.1. The analysis of the manufacturers TS samples had a standard deviation of 2.9 for 5 samples which was less than the Table 5.1 value of 6.0.

The VSS samples were specially made and did not have manufacturer control limits. Even though the true value of the VSS SRM, i.e., 100 mg/l, did not coincide with the value in Table 5.2, 170 mg/l, the values of the RSD for two sets of five VSS SRM samples were within QA objective limits (< 6.5%) at 6.49% and 3.3%, respectively.

Two SRM samples were made from the Neshaminy clay soil by EPA. Results from Phase II indicated that the Neshaminy clay soil performed well as a SRM and provided SS results that were comparable to the Diatomaceous-silica reported in Table 3.1. The %R (equation 3-1) of the samples were 0.68% and 2.4% for known values of 979 and 232 mg/l, respectively. These values of %R fit within the expected RPD of Diatomaceous-silica in Table 3.1.

Because the standards and the laboatory blanks tested well, the anomalous results obtained from the analysis of field blank for Experiment 2 cannot be adequately explained and appears to only be a glitch in the sampling and analysis procedure. Results from experiment 3 and the additional field blank analysis confirm this. In future experiments it is recommended that more field blanks are collected during each experiment.

Completeness

Table 5.3 shows the completeness for critical solids measurements made for all experiments. Completeness was calculated using equation 3-2. Of the 31 separate CERGRENE samples, two were voided due to faulty data recording. Samples from Experiment 2 had more than one type of solids analysis performed.

Table 5.3 Completeness of Solids Analysis

Type* or location	Total Samples**	Voided Samples†	Expected Completeness	Measured Completeness
Lab Blanks	4	0	90%	100%
Field Blanks	3	1	90%	66%
Manufacturer Lab Standards	27	0	100%	100%
Prepared Standards	2	2	100%	100%
CERGRENE	31	0	90%	100%
Long***	65	5.5	90%	92.3%
Background (start and end)	12	1	90%	92%

* Does not include additional field blank or Settleable Solids sampling.

** There was an extra sample reported by the lab, which was not recorded in the log book or on the chain of custody sheets for Experiment 2.

*** No samples were taken during the third experiment. Recorded as 5.5 because the second solids analysis (total solids) on sample was voided due to result being below zero.

† One Long and two CERGRENE column samples were not included in the graphical settling-velocity analyses because the values were extremely large and threw off the analyses. These data omissions are noted here and later, and do not reflect laboratory performance as a Void because the laboratory was instructed to analyze everything contained in the sample.

Additional QA Concerns: Ratio of Total Solids to Suspended Solids

TS analysis was performed on the samples of Experiment 2, even though samples did not meet holding requirements according to Standard Methods at the time of analysis (after completion of SS analysis samples were stored at ambient temperature awaiting disposal). The analysis was performed because it was more important to attempt to analyze the settleable material, which is less likely to have been impacted by biochemical degradation, than to adhere strictly to Standard Methods. Also, because all samples were from the same place and date and experienced the same processes, storage effects should have been similar.

To assess whether the TS values for experiment 2 had any validity, an analysis of a typical ratio factor of TS to SS results was performed. The results presented in Table 5.4 are the averages, **F** and RSD of the RPD of TS measured to TS calculated of individual samples. The RPD of individual samples was used as values were changing with time.

Table 5.4 Comparison of Total Solids to Suspended Solids Ratio

	Relative Percent Difference *				Relative Percent Difference less extreme *				
Column Type	Samples	Average (mg/l)	**F** (mg/l)	RSD (%)	Samples	Average (mg/l)	**F** (mg/l)	RSD (%)	Ratio from data**
CERGRENE	11	30	28	92	10	23	12	52	2.9
Long	33	18	32	170	32	13	10	79	3.6

* Calculated TS (where TS/SS = 3.4) to Measured TS
** Ratio of measured TS to SS

Often, TS or SS values can be predicted by using an assumed ratio between the two. A derived ratio of 3.4 from literature values (averaged values from Metcalf and Eddy ,1991 , p.109, Table 3.16) was used on SS results to predict TS, and overall, the results bear out the validity of the TS analysis. There appears to be no substantial change in the results of the between the SS, completed within the holding time and that of the TS, which was not. While there was large individual variability, as borne out by s exceeding the average, this can be reduced by eliminating the one extreme data point from each column type. The extremes were caused by exceptional large pieces of grit, i.e., pebble sized, greater the 2 mm, and once the extreme values are removed, the averages dropped with **F** dropping below the average. The multipliers as calcualted from the data were 2.9 and 3.6 for the CERGRENE and Long columns respectively, with **F** =0.6 and RPD = 0.2, approach the literature value used.

The analyses conducted here was on portion of samples. As results would indicate that SS values can approximate the TS, when using a portion of the sample, multiple analysis of discrete volumes from one sample may be valid for any settling test, as it appears valid for these two methods. To decrease values of s between the split samples, whether performed as duplicates or separate analysis, samples should be thoroughly and continually mixed during withdrawal.

Field Experiments 1-3

Mixing Basin - Background

Several background samples were obtained during the experiments. The background samples consist of combined sewage samples taken by hand grabs from the top of the mixing basin and were collected and analyzed to establish starting and ending concentration in the mixing basin. The average background concentration of each test compared well to the t_0 of the CERGRENE and Long columns. The results of the background sample analyses are presented in Table 5.5.

T-test for paired two sample for means was performed to determine whether concentrations of the SS, VSS, and TS changed significantly during the course of the Experiment 2, with the following results:

	Suspended Solids		Total Solids
t Stat	1.052632		-2.2
P(T<=t) one-tail	0.24184		0.1358
t Critical one-tail		6.313749	

The P(T<=t) one-tail value is in excess of 0.05, which indicates that the SS concentrations in the mixing basin before and after filling of the columns are indistinguishable.

Table 5.5 Solids Concentrations in Mixing Basin during Field Experiments

Phase III Experiment	Sample Type	Suspended Solids (mg/l)	Volatile Suspended Solids (mg/l)	Total Solilds (mg/l)
1	Start	46	26	- -
	Start	50	31	- -
	Start	60	32	- -
	End	Void	Void	- -
	End	56	22	- -
	Average	53	28	- -
2	Start	200	- -	607
	Start	157	- -	518
	End	161	- -	497
	End	156	- -	482
	Average	169	- -	526
3	Start	- -	- -	276
	Start	- -	- -	304
	Start	- -	- -	301
	Average	- -	- -	294

Initial Concentration

An inherent problem in the design of the Long column is the lack of reliable uniformity in initial concentration (C_0) throughout the length of the column. C_0 is used in calculations for the Percent Removal. However, while this was very noticeable in the Phase II experiments, it did not appear as a significant problem with the well mixed CSO in the field. Table 5.6 shows that the initial C_0 measured in both columns compare well to the average background concentration and to each other.

A T-test for two samples assuming unequal variances was run on Experiment 1 VSS results because these had the widest variance, due in part to the low concentrations. The initial three samples of the Long column and the starting Background concentration were used to determine the concentrations were distinct, with the following results:

	Long Column	Background Start
Mean	35	29.62416107
Variance	43	10.16873114
Observations	3	3
Hypothesized Mean Difference	0	
Degrees of freedom	3	
t Stat	1.276964215	
P(T<=t) two-tail	0.291485258	
t Critical two-tail	3.182449291	

The P(T<=t) two-tail value is in excess of 0.05, which indicates that VSS concentration values and therefore SS concentration values in the mixing basin before the experiment began and in the columns at t_0, are indistinguishable.

Table 5.6 Comparison of Initial Column Concentrations to Background

Phase III Experiment	Sample Type	Suspended Solids (mg/l)	Volatile Suspended Solids (mg/l)	Total Solids (mg/l)
1	Long, t_1- $t_{0,}$ Port 3	Void	Void	- -
	Long, t_2- $t_{0,}$ Port 5	52	28	- -
	Long, t_3- $t_{0,}$ Port 7	46	36	- -
	Long, t_4- $t_{0,}$ Port 8	89	41	- -
	Average Long	62	35	
	CERGRENE, $t_{0,1}$	68	33	- -
	Average Background	53	28	- -
2	Long, t_1- $t_{0,}$ Port 3	165	- -	518
	Long, t_2- $t_{0,}$ Port 5	171	- -	522
	Long, t_3- $t_{0,}$ Port 7	180	109	526
	Long, t_4- $t_{0,}$ Port 8	151	- -	547
	Average Long	167	- -	528
	CERGRENE, $t_{0,1}$	167	112	554
	Average Background	169	- -	526
3	CERGRENE, $t_{0,1}$	- -	- -	241
	Average Background	- -	- -	294

CERGRENE Duplicate Analysis

Table 5.7 shows the duplicate analyses for the CERGRENE Columns. All duplicates were performed on the samples collected $t_{0,3}$, 3 minute time step.

Table 5.7 CERGRENE Duplicate Analysis

Phase III Experiment	Relative Percent Difference		
	Suspended Solids	Volatile Suspended Solids	Total Solids
1	21	15	- -
2	0.47	- -	3.9
3	- -	- -	0.11

Phase III RPD results were similar in range to Phase II results (0.25 - 22.2); however, the Phase II experiment used a known SS concentration of 300 mg/l and higher RPD values was primarily influenced by the use of Microsand. The higher RPD value for Experiment 1 in Phase

III is due in part to the lower SS concentration of experiment 1 (< 100 mg/l) of the combined sewage.

Concentration versus Time

Figures E-1 through E-10 show plots of the raw data for the Long and CERGRENE columns for the 3 experiments of Phase III. As in Phase II experiments, the CERGRENE columns should show an increasing pattern in the graphs, and the Long column should show a decreasing concentration (which can be confound in the lower ports by Zone settling and compaction, as previously mentioned). In Experiment 2 for the Long column a sample with a concentration exceeding 9000 mg/l, has been omitted from Figure E-7 because it would impact the scale of the figure.

The concentrations measured in the Long column show a decreasing trend in Figures E-1, E-3, E-5, and E-7, and especially in E-10 which is an isolation on Port 3 of Experiment 1. Figure E-10 shows an approximate 40% decrease in concentration occurring in the upper portion of the column, though data are not corrected for water depth.

The concentrations measured in the CERGRENE columns show only slight, if any increase with time in Figure E-2, E-4, E-6, E-8 and E-9. These figures also show the sharp changes and spikes in concentrations which cause problems with the Victor Matrix Analysis tool. This tool requires monotonically increasing data points which exceed the preceding sampling time step and in all cases the initial concentration. Inflection points (the 1, 3, 5, 10 and 20 minute time steps in Figure E-9) would have to be eliminated before a graphical result could be produced, leaving only three remaining data points for use in analysis

Percent Removal Long Versus CERGRENE

The design overflow rate was plotted versus the percent removal as was described earlier in Section 3. Two changes to the procedure were made. For the Long column, percent removal is defined as the SS concentration at the port compared to the average of the initial readings of all four ports which is the theoretical C_0 at every port, which is how the analysis is traditionally conducted. This is different than in Phase II, where the recycle concentration for each run was used as C_0. This change was made because the concentrations in the basins compared well to the initial concentrations in the columns as shown in Table 5.6. In Phase II discrete particles, e.g., microsand, were used which had rapid settling rates, while Phase III used combined sewage, which had a wider range of particle sizes and settling rates. Also, the recycle samples of Phase II were drawn from the same pump used to fill the Long column and the background samples of Phase III were hand grab samples.

For the CERGRENE column, the volume of the lower chamber was assumed to be 960 mL, as was done previously in Phase II, and the upper chamber was set to 1510 mL. The method of overflowing the CERGRENE column ensured that standard volumes could be used. This eased calculations and fulfilled one of the recommendations from Phase II. These volumes were also used in the Victor analysis.

Figures F-1 through F-10 show plots of the Percent Removals of solids for the Long and CERGRENE columns for the experiments of Phase III. As in Phase II Experiments, the graphs are expected to have a higher Percent Greater value for the slower settling rates and a lower Percent Greater value for the higher settling rates. Logarithmic best fit lines are presented for direct comparison between columns. Several of the CERGRENE graphs had correlation coefficients, R^2, higher for linear than logarithmic plots, i.e., Figure F-6 with $R^2 = 0.33$ and Figure F-8 with $R^2 = 0.69$. Scales were not normalized because there was widespread scatter in the results. The subsection “Design Removal Comparison” below will normalize results.

In Experiment 2 for the Long column a sample with a concentration exceeding 9000 mg/l, has been omitted from Figure F-7, and as noted on the Figures F-6 and F-8, two other data points were omitted which would have caused inverted trend lines, for the CERGRENE column analysis. Inclusion of the data points would have created trend lines that predict suspension of particles with time instead of settling. These latter data points are not included in the Victor analysis, with or without suppression.

The Long column represented in Figures F-1, F-3, F-5, and F-7, shows greater percent removal potential than the CERGRENE column. The CERGRENE columns show only slight, if any, increase in solids removal with increasing overflow rate in Figure F-4, F-6, F-8 and F-9. The exception is F-2, which has a large variance, $R^2 = 0.11$. When the two data points in excess of 100% removal are eliminated, the variance is decreased ($R^2 = 0.33$) but the removals are nearly zero and increase with decreased settling rates only slightly, as shown by F-10.

Matrix Iteration Process for CERGRENE Columns

The settling velocity distributions for Phase II using the spreadsheet application, "VICTOR," are presented in Appendix G. Each figure in Appendix G is comprised of six graphs from the experiment and the solids analyses performed. Graphs in the top row included all data, except those points previously described as being omitted from analysis and graphs in the bottom row were analyzed with suppression.

Reading from left to right, the first graph (represents the matrix-calculated mass removed over time (described as M(i,j) in Section 3 and Appendix L), the second is the idealized percent removal of mass from the upper chamber over time, and the last represents Settling Velocity Distributions, (at V_{s90}, 90% of the particles measured have a settling velocity less than the y-coordinate value). The scale on the graphs of Mass Removed (mg) versus Time (s) and Settling Velocity (mm/s) versus Velocity Percentile are the same for both sets of graphs (without and with suppression). The y-coordinate for Percent Removed (%) versus Settling Velocity (mm/s) was not scaled for both analysis. This graph typically had a default setting from 0% to 100%, a sensible limitation on percent removals. However, in order to expose in greater detail the problems with the analysis, this default was not used.

In the first row of each of the figure where all data was used (no suppression), there is much scatter. This is demonstrated in the Mass Removed graphs and the Percent Mass Removed graphs which show severe scatter and wildly exceed the theoretical limits of 0% or 100% for all five data sets. When the data is too scattered, the Settling Velocity Distribution graph defaults to a null set as it did in Figure G-2 and G-3. When data points are suppressed the graphs have less scatter. Results make more sense for Mass Removed and approach the limit of 100% removal, i.e. the error exceeds 100% by 40% in Figure G-4 which is a 120% improvement. However, eliminating data, while allowing the matrix to work, may overall yield less predictive results. While the use of data suppression resulted in the creation of Settling Velocity Distributions for all data sets instead of null sets, there are less Velocity Percentiles produced for some of the experiments as a result of using suppression, e.g., Figure G-1, G-2 and G-5.

Experiment 3 was shown to have limited removals by the previous analysis, as represented in Figure F-9. In Figure G-5, the suppressed data set predicts that 90% of the particle measures have settling rates of less than 0.5 mm/s, in comparison to the graph above which indicates a V_{s90} of 4.5 mm/s for all the data and has a larger spread of Velocity Percentiles. There was scatter in all the data sets, and suppressing data points appears to limit not improve settling velocity distribution interpretation.

Design Removal Comparison

The objective of this project was to compare the accuracy and precision of solids concentrations taken over a specified time range from two separate settling column methods. These measurements were used to develop settling velocity distributions. Currently no direct graphical method for comparison is available for the two columns as each method is derived through separate mathematical procedures. Direct graphical comparisons were made for measured parameters, i.e., solids concentration removal and time. This type of analysis demonstrated the differences in the processes and was used to indicate problems with the CERGRENE design (Appendix C).

Comparison of the predicted settling velocity distributions of the Long and CERGRENE columns can be inferred from Table 5.8., which shows calculated overflow rates versus percent removals for the Long and CERGRENE columns for experiments 1, 2 and 3. Calculations were identical to those used to develop the graphs in Appendix F. Comparisons of Long to CERGRENE results shows some similarities, though CERGRENE analysis is complicated by an insufficient number of data points. Interestingly, the results of the Long Column are similar for each experiment, predicting initial removals followed by a flattening out at 50% removal, which is typical of primary treatment removals. Some of the CERGRENE results, i.e., the total solids analysis, show no removal at all.

Results from the Victor analyses were wildly divergent as shown in Appendix G and are not represented in Table 5.8. The Victor matrix analysis results were limited to a range of 0.004 to 0.5 cm/sec, however it is difficult to link this to a percent removal because of the scatter in the data. It is interesting to note that the CERGRENE column's limited maximum settling velocity predictions, 0.5 cm/s by the Victor analysis and 0.54 cm/s from Table 5.8, is an order of magnitude larger in the Long column, 1.5 cm/s. This is partially driven by the configuration of the CERGRENE column which is shorter than the Long column, and the minimum time interval used during the experiments of 1 minute.

Table 5.8 Comparison Predicted Removal between Long and CERGRENE Columns

Experiment (Analysis)	Percent Removed (%)	Overflow Rate (cm/s)			
		Long	R^2	CERGRENE	R^2
1 (SS)	10	1.5	0.23	0.13	0.11
	30	0.057		0.057	
	50	0.0022		0.026	
1 (VSS)	10	4.4	0.38	0.029	0.33
	30	0.14		0.00038	
	50	0.0046		0.0000049	
2 (SS)	10	1.5	0.55	0.54	.31
	30	0.29		0.0034	
	50	0.00055		0.000022	
2 (TS)	10	0.54	0.30	0.0046	0.47
	30	0.0034		0.00000074	
	50	0.000022		1.2×10^{-12}	
3 (TS)	10	- -		0.000049	0.31
	30			7.9×10^{-11}	
	50			1.3×10^{-16}	

6. CONCLUSIONS AND RECOMMENDATIONS

General Conclusions

The CERGRENE settling velocity distribution test did not achieve all theoretical expectations. The anticipated benefits of a smaller, easier to use settling system has to be weighed against the ability to reliably produce usable results. There appears to be a tradeoff between settling testing volume and the number of experiments; larger settling volume may require less experiments, while smaller testing volumes may require more experiments to develop reproducible results.

Experimental Conclusions

The Phase I Preliminary Results established the predicted homogeneity of the mixing basins and the initial performance of the Long and CERGRENE columns. This testing showed that adequate mixing was provided in the mixing basin, that SS were transferred to the settling columns for further testing, and that the testing material of Phase II, i.e., microsand and Neshaminy clay particles, was recoverable in the columns. The Long column had insufficient head to sample quickly from the top two ports, so only ports 3, 5, 7 and 8 were used during the experiments.

The objective of the Phase II experiments was to compare, in side-by-side analysis and under the same conditions, the Long and CERGRENE column methods for measuring settling-velocity-distribution. Phase II was also intended to determine the optimal withdrawal point in the mixing basin and to examine the effect that filling order of the columns has on experimental results. Phase II study results indicated that the CERGRENE columns had some comparative advantages, such as ease of use, smaller testing volumes, and a consistent initial concentration, but also significant problems such as loss of SS mass during testing, lack of reproducibility, and large SS analysis volumes. The Long column had its own advantages, such as repeatability, consistent (predictable) SS removals, and smaller SS analysis volumes while the disadvantages included lack of uniform concentrations through column, large testing volumes, and large number of SS analyses required.

The original experimental design did not account for several important factors affecting results during Phase II of the experiment:

1. Individual behavior of the CERGRENE columns - one CERGRENE column does not behave like another
2. Overloading of the filter during SS analysis by the CERGRENE samples
3. Wide variation in SS concentrations in the attempt to capture the heaviest settling particles Microsand
4. Size of the Microsand, which had a larger diameter than anticipated and thus faster settling velocity.

Theoretically all the sand should have settled in five minutes or less and percent recovery should have approached 100%. Incomplete recovery of the Microsand resulted in predictions of concentrations lower than 100%. Besides the problems with the SS analysis already discussed under *Section 3 Completeness*, a small indentation in the ball valve, part of the functional design, could remove the particles from the water column and prevent any chance of recovery.

Conclusions from Phase II were:

1. Microsand was more difficult to work with than had been anticipated, especially during SS analysis. This was a result of the physical characteristics of the sand. The analysis of

microsand produced the most pronounced losses because particles tended to stick to analytical equipment through water tension. Each sand grain contains significant mass, so even a loss of several grains can increase errors. This loss was especially noticeable in the CERGRENE samples where the large volume of analyte caused the filters to become overloaded. Overall, the use of microsand was a source of error to the experiment; however, this error was distinctly biased in the direction of a loss of sand or incomplete recovery as demonstrated by the analysis of the "standard reference material."

2. There was a lack of consistency between the CERGRENE columns. The performance of the four CERGRENE columns was erratic for experiments 1-9. While the expected results of a plot of concentration versus time should have shown an increase in the concentration with time, the four columns in experiment 1-9 behaved randomly. In contrast, experiments 10-15, where only one column was used, indicated a trend of increasing concentration versus time. This indicated that the four CERGRENE columns being tested each had unique properties that influenced the settling experiments.
3. The initial SS concentrations through the Long column was never uniformly mixed at t_0, especially for the microsand and microsand/clay mixture experiments.
4. The CERGRENE columns were examined for defects and sizing specifications for volumes and height. The four CERGRENE columns appeared similar, no anomalies were found, and no explanation for varying results could be found. A small indentation in the ball valve, part of the functional design, could trap some solids.

After Phase II, the following recommendations were adopted for the Phase III analysis:

1. The CERGRENE column procedure was modified to allow filling to a constant head as the water height in the column is an essential measurement for this test. The filling procedure allowed at least a 0.5 L overflow. Starting the CERGRENE columns at the same height allowed easier mathematical analysis, especially with the use of Victor.
2. Additional data points, i.e., times of 7 and 20 minutes, per experiment were evaluated for the CERGRENE column.
3. The SS concentration of the top and bottom parts of the column were measured at t_0, to ensure that the initial concentrations, before settling, were the same above and below the ball valve.
4. More powerful pumps were employed for each column procedure to reduce the concentration gradient of SS in the columns at time zero.

During the Phase III field test, results of the CERGRENE column settling velocity distributions were consistently flat as in Phase II. The setup may have provided more solids to the Long column, as it was filled from the bottom of the basin. However, concentrations taken from the mixing basin by hand were statistically similar before and after column filling, and to initial concentrations of both columns. It is also noted that concentrations measured in the CERGRENE columns did exceed the background concentrations in the mixing basin and initial concentrations in the CERGRENE column but did not do so in a monotonically increasing manner that is required to complete analysis using the Victor matrix program.

Problems with filling the Long column to achieve a uniform initial concentration t_0 were clearly detailed during the Phase II analysis but were not significant during Phase III. The primary advantage in the Long column system was the larger number of samples, which means that the Long column analysis does not rely as heavily on the outcome of any one sample as the CERGRENE procedure.

There should have been more interim CERGRENE sampling times, i.e, 15 sec, 30 sec, 1 min, 2 min, for the development of settling velocity distributions. This is critical for heavier, discretely-falling particles as the configuration of the CERGRENE column with an effective

settling length < 1 m is much shorter than the Long column.

While the Long column may have only limited benefit in the direct measurement of settling velocities of sewer sediments or discrete solids, it appears to be more than capable in terms of predicting the percent removal of sedimentary treatment devices with equivalent depths. In retrospect and for purposes of design, samples taken from the upper ports of the Long column should have been used; the advantage to Long column is that you are measuring the solids going away, not the solids that are accumulating as in the CERGRENE columns. Samples were not collected from the upper ports due to the longer sampling time necessary because of decreased head, the top ports (1 and 2 in Figure 2-1) eventually fell below the water line as samples were taken and the perceived need to get as many sample as close together (in time) throughout the column to improve analyses. However, more samples from the upper ports and fewer from the bottom ports may actually have improved the settling velocity distribution curves. The Long column had a visible supernatent developing at the top of the Long column in the Phase III experiments.

Where possible during these experiments, the whole liter sample size was intended to be used to reduce additional error in splitting the samples. The sample volumes of the CERGRENE columns should be reduced prior to solids analysis. This could be accomplished by reducing the volume of the bottom portion of the CERGRENE column and/or splitting samples to avoid overloading filters. Splitting CERGRENE samples into replicates or triplicates may help somewhat with the analysis; however this would not change measured settling characteristics.

Discussion and Recommendations

With the current configuration and analysis protocols, use of the CERGRENE columns will most likely not result in fewer samples or a decreased sampling effort. The Victor analysis program did not work properly when results were scattered and not monotonically increasing as expected. In nearly every experiment performed results were thrown out to run the Victor program, which limited the number of samples used to create the settling-velocity-distribution curves. If continued field trips are required until the data resembles a pattern that the Victor Analysis Matrix can interpret, there is no discernable benefit to adopting this method. Selecting which data points for the Victor matrix analysis may also bring into question the validity of this approach. The theoretical basis of the CERGRENE approach did not fulfill expectations.

The adoption of additional procedures from other methods or further analysis of alternative settling test may be warranted to improve the current CERGRENE method. Gentle agitation of the column may keep some of the particles from adhering to the sides of the CERGRENE column especially during the longer experiments. Standard Methods settleable solids procedure (2540.F.a) recommends to “gently agitate sample near the sides of the (Imhoff) cone with a rod or by spinning” to keep material off the sides for a better representation of settleable solids.

The larger Long column was more consistent and can produce usable results despite the variability of CSO because it uses more samples than the CERGRENE approach. The Brombach method, an alternative settling test mentioned in Chapter 1 and not appropriate for direct comparison, is significant not in the design of the column or the analysis, which separates the solids from the analyte of sewage before re-introducing solids into clean water, but in the overall approach of sampling. Brombach (Michelbach and Wöhrle, 1993) developed settling distribution graphs from thousands of data points. While this approach is also subject to data scatter, the larger number of data points minimizes the effect of variability of individual measurements. The settling curves (from 35 - 98 curves for solids from different types of flows) became apparent because of the sheer magnitude of the sampling program (350 samples, each subject to settling

analysis). Over many storms and many sites, a pattern emerged. The CERGRENE column analysis currently relies heavily on individual data points, which, when not adhering to an anticipated concentration curve over time, result in limited settling velocity distributions and inconclusive results.

More data points could be collected for the CERGRENE column, and the matrix analysis program Victor should be modified to handle both variable data and larger data sets. These changes would incorporate data management techniques so that many storms could be sampled and experiments performed. Incorporating statistical parameters such as averages, standard deviation, and variance into the analysis may help solve the problem of the variability inherent in settling data of any one storm or any one sample, and would also provide statistical proof of outliers. Research may yet show that reliable data may only be achieved by multiple, large scale sampling programs, which use consistent sampling techniques. A cursory attempt to use Victor to analyze results using averages results from several of the Phase II experiments performed did not arrive at monotonically increasing concentrations suggesting that at a minimum a statistically appropriate number of well run experiments will exceed five.

The nature of the Matrix iteration analysis of the Victor program is not as flexible as are other forms of analysis due to the constraint of monotonically increasing results. Barring an outside forces causing resuspension, the amount of solids settling should increase with time. This common knowledge in itself is not sufficient to eliminate data points or minimize the influence of unwanted results. Only large amounts of data can minimize the influence of individual data points that upset expected results.

As both column methods tested in this project used pumps as the means to fill the columns, the size of the particles that can be tested was limited by the top sampling speed of the pumps. In practice, a pump that has achieved steady state flow should deliver a more uniform concentration then a flow that is oscillating. Ideally the purpose of the pump is to deliver a well mixed sample to the column so that there is a good representative mixture. Each of the two columns tested here, the Long and the CERGRENE, could be improved with flow through volumes to achieve steady state flow. This would require switching to a positive displacement pump for the CERGRENE column from the vacuum pumps which have a limited water volume that can be drawn up before the water reaches the pump.

The sample from the CERGRENE column represents 1/3 of the total volume sent to the column. The Long column samples only represent 1/280 of the fluid pumped. The Long column represented 1/3 of the CSO pumped to the mixing basin while the series of CERGRENE column experiments represented less than 1/20. The Long column reduces error due to the increased volume being settled and the larger number of SS samples. The reliance of the CERGRENE method on smaller settling volumes, fewer samples and increased size of the CERGRENE samples in comparison to the rest of the column may increase the possibility of error.

As previously mentioned, the ball valve in the design of the CERGRENE column probably inhibits settling (and filling) in the bottom chamber by intercepting near-wall settleable material. Evaluations of other types of valves should be conducted to attempt to minimize interference of the valve mechanism on solids settling. A valve designed on the workings of a camera shutter could function as an alternative to the current off-the-shelf ball valve. Old fashioned camera curtain or peephole shutters operate by a series of very thin metal leaves opening, then closing to expose the film, with the curtain shutter moving from one side to another, like a curtain and the peephole shutter, opening and closing radially, leaving a peephole, as the names imply. The ball valve is designed for pressurized flow which is unecessary in the current application. A shutter valve would have its own mechanical problems like leakage or

diffusion, rates that could be measured and accounted for in calculations to offset concentration changes. A shutter mechanism would be easier to automate than a ball valve. Figure 6-1A addresses some of these and the other recommendations mentioned above. Figure 6-1B presents an alternative configuration for the bottom ball valve to minimize headloss during filling and draining for sample analysis.

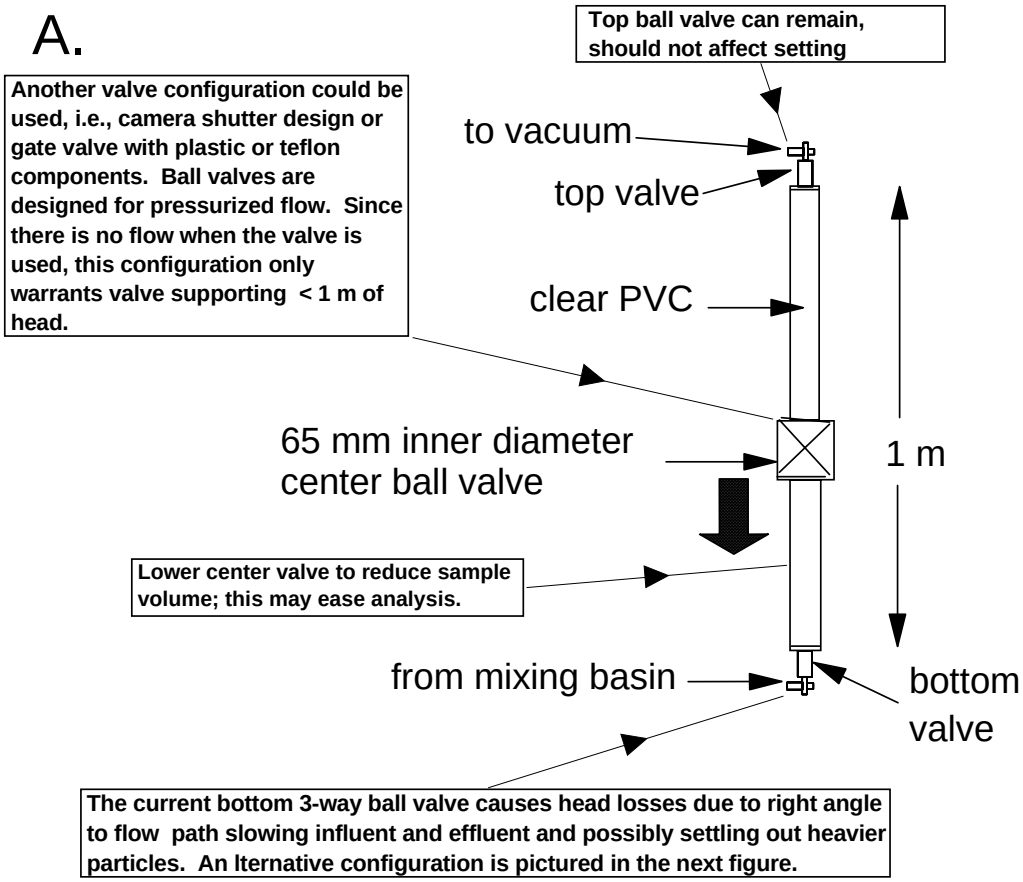

Figure 6-1A Suggested Modifications to the CERGRENE Column Design

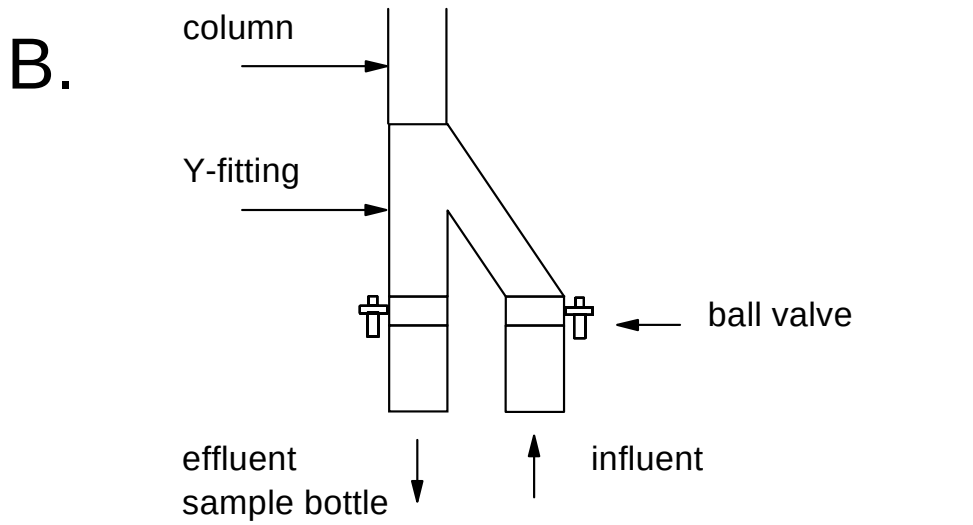

Figure 6-1B Suggested Modifications to the CERGRENE Column Design

The CERGRENE columns should be attached to a more permanent mounting to minimize movement of the columns and keep them erect during the settling portion of the experiment. However, a permanent mount might negate some positive effects of "the ease of use" in the field, transport and cleaning requirements. Without a proper mounting, the CERGRENE column, which is currently made of off-the shelf components, may not be robust enough for field work.

The CERGRENE columns appear to be behaving as independent events. Test developed around multiple settling devices need a higher level of precision in construction as results between columns are compared and need to be clearly identified to trace problems or malfunctions. An evaluation of the CERGRENE column's performance may also not be complete without specifications of peripheral equipment, i.e., vacuum pump, tubing, sample bottle size. In general, a much more rigorous treatment of fluid dynamics should be performed on the current design and any future modifications of the CERGRENE column. Multiple evaluations of the CERGRENE columns without the use of the same influent flowrate, intake sampling depth, and tubing size could influence results so much as to obscure any direct comparisons that could be made for an already statistically variable measurement such as CSO. Because each storm event is an independent event with varying concentrations of suspended and settleable solids and variable flowrates in a combined sewer, it may be difficult to produce repeatable results with CSO.

Development of a totally automated sampling system might reduce labor costs (initial deployment, removal, and transfer of samples for analysis), but it would significantly increase capital cost. Standard Methods currently does not have standardized settleability test requirements. Therefore laboratories and consultants can use low cost or in-house equipment to devise sampling plans. An automated settling sampler would require more sophistication than is currently available from a typical autosampler, and would therefore retail at a much higher price.

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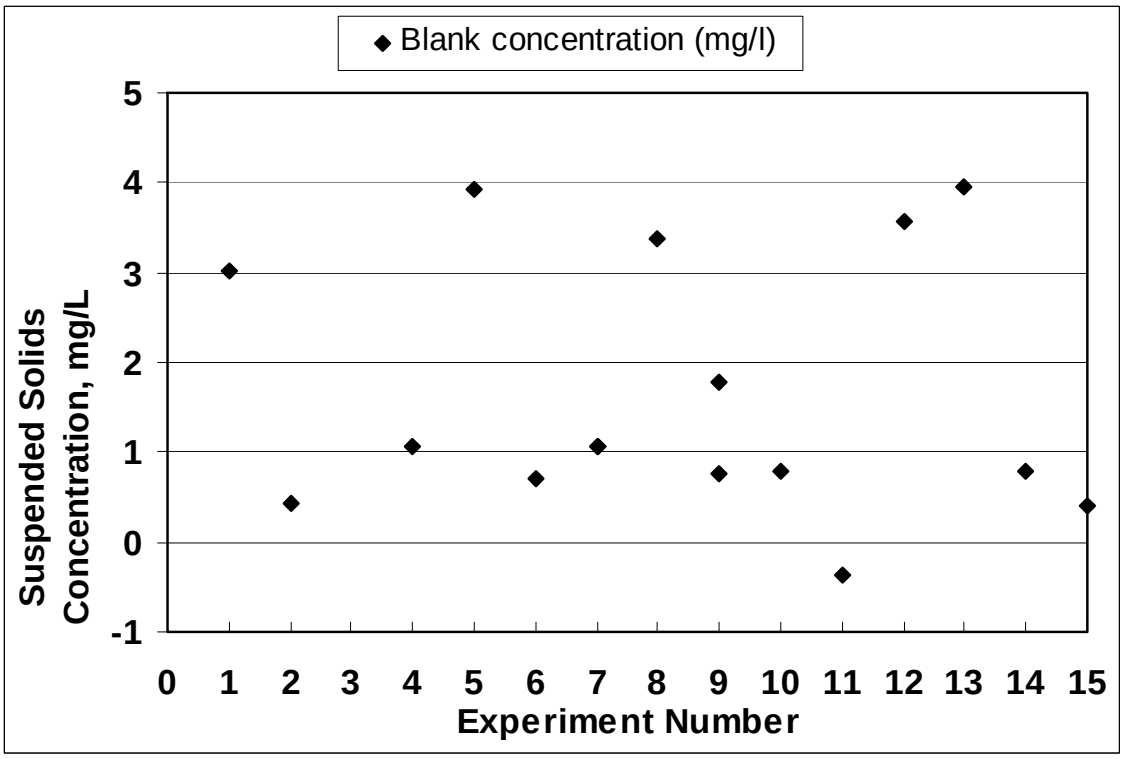


Figure A-1: Concentrations of Method Blanks

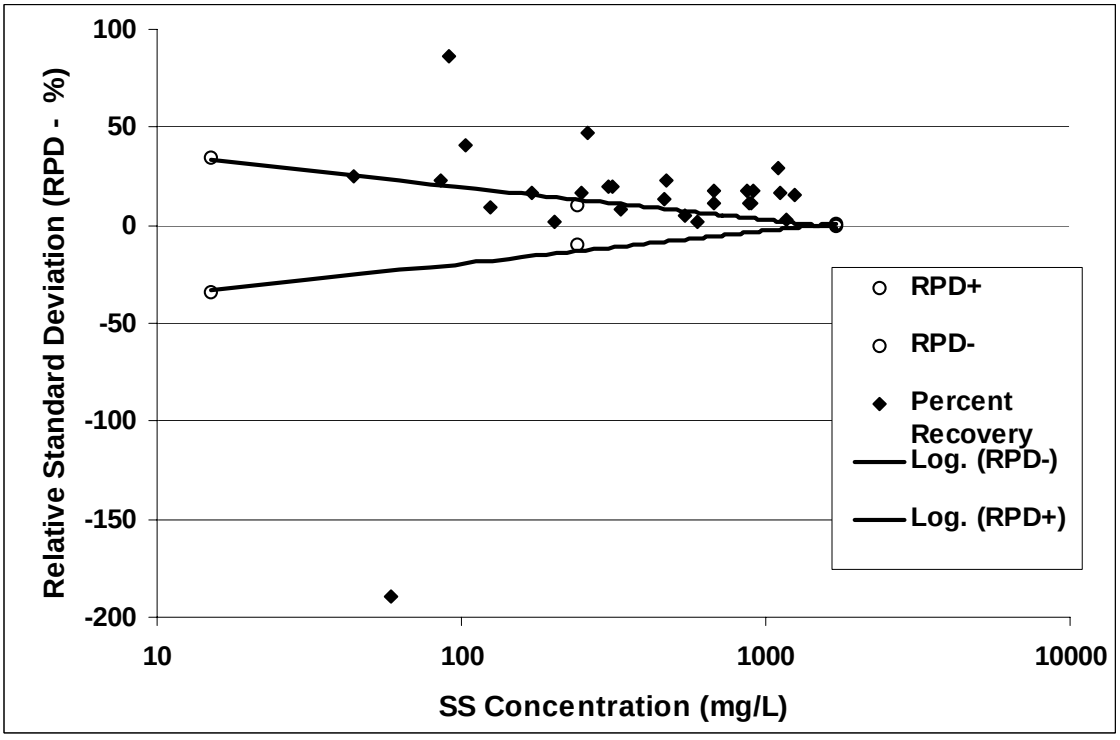


Figure A-2: Relative Percent Difference for Standard Reference Materials

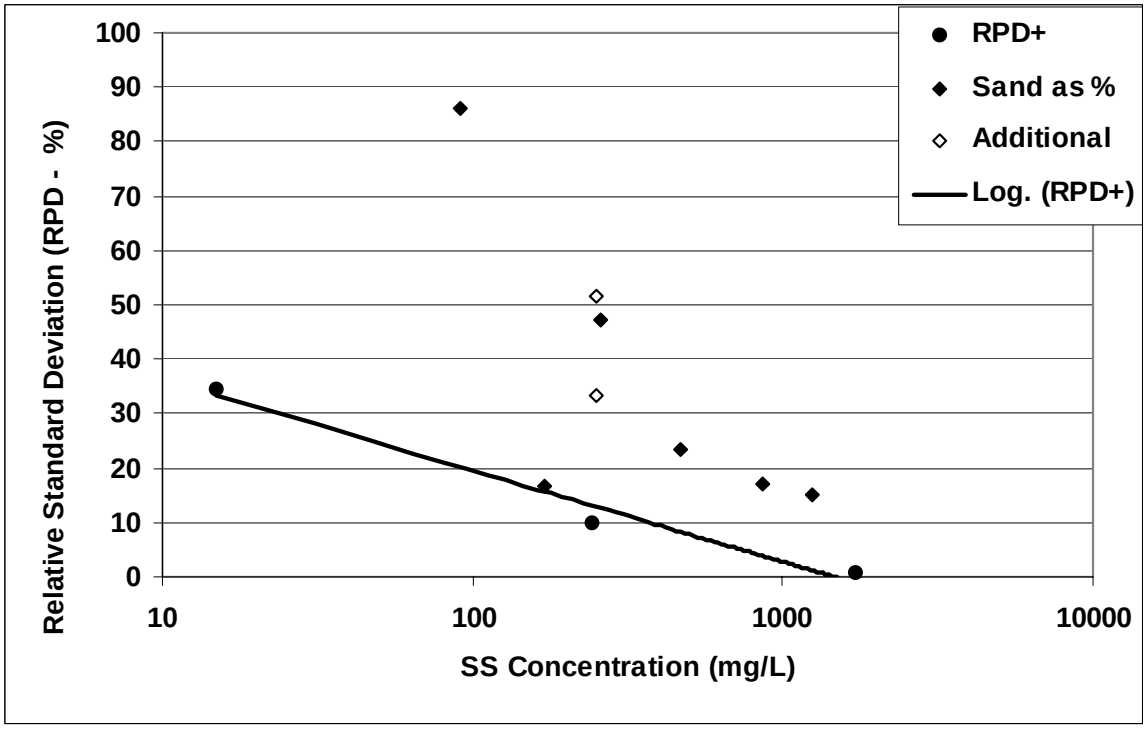


Figure A-3: Relative Percent Difference, SAND

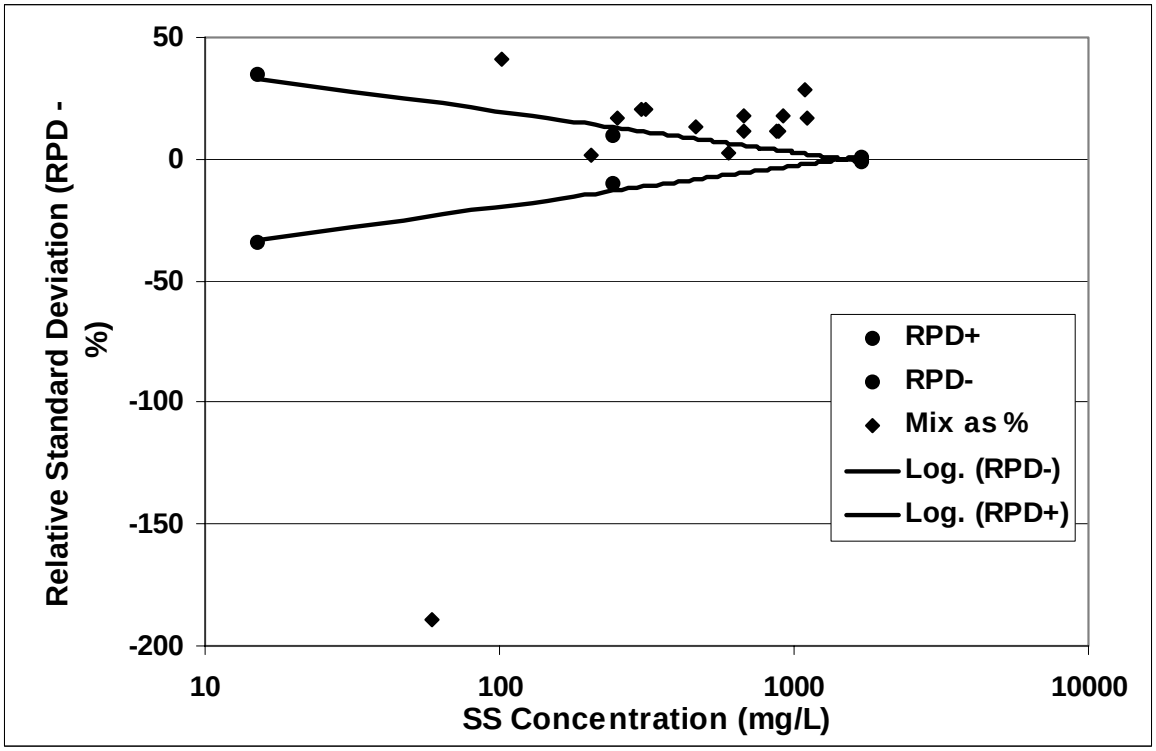


Figure A-4: Relative Percent Difference , MIX

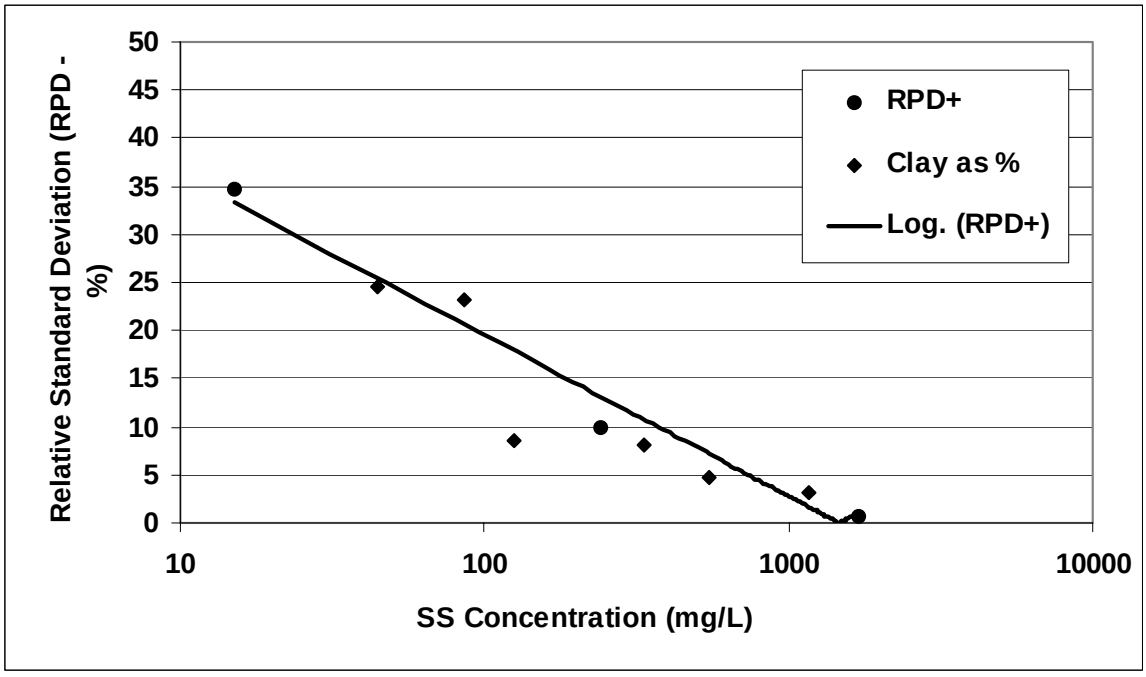


Figure A-5: Relative Percent Difference, NESH

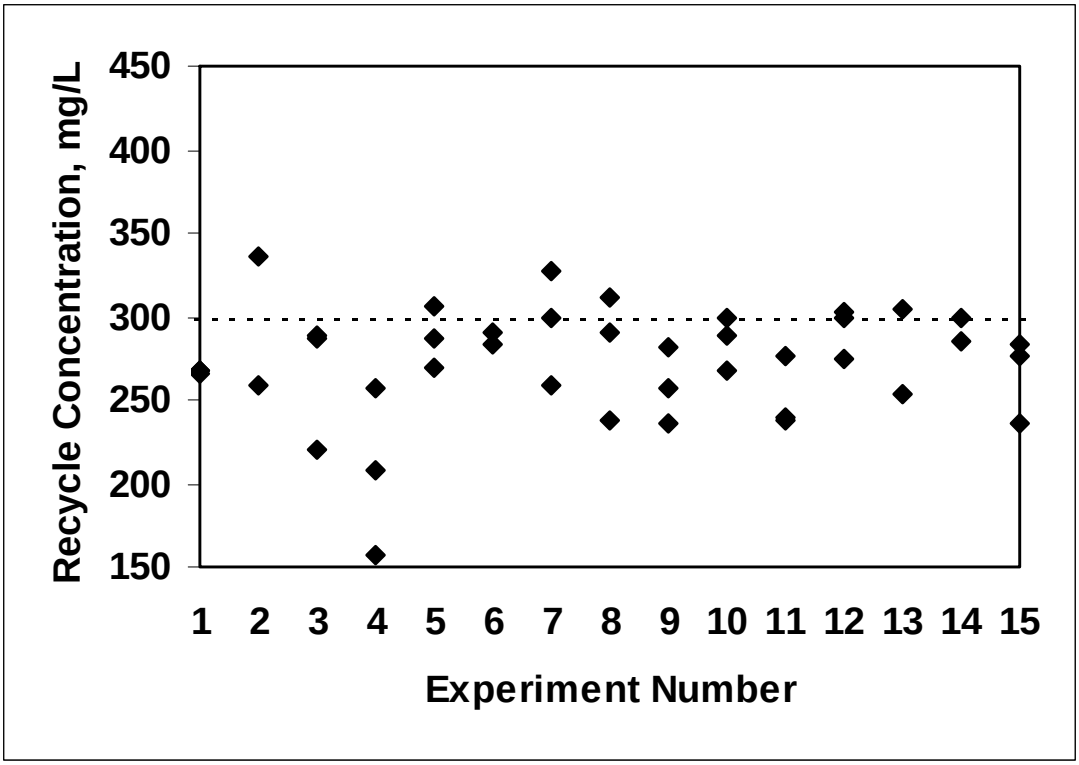


Figure A-6: Recycle Concentration, All Experiments

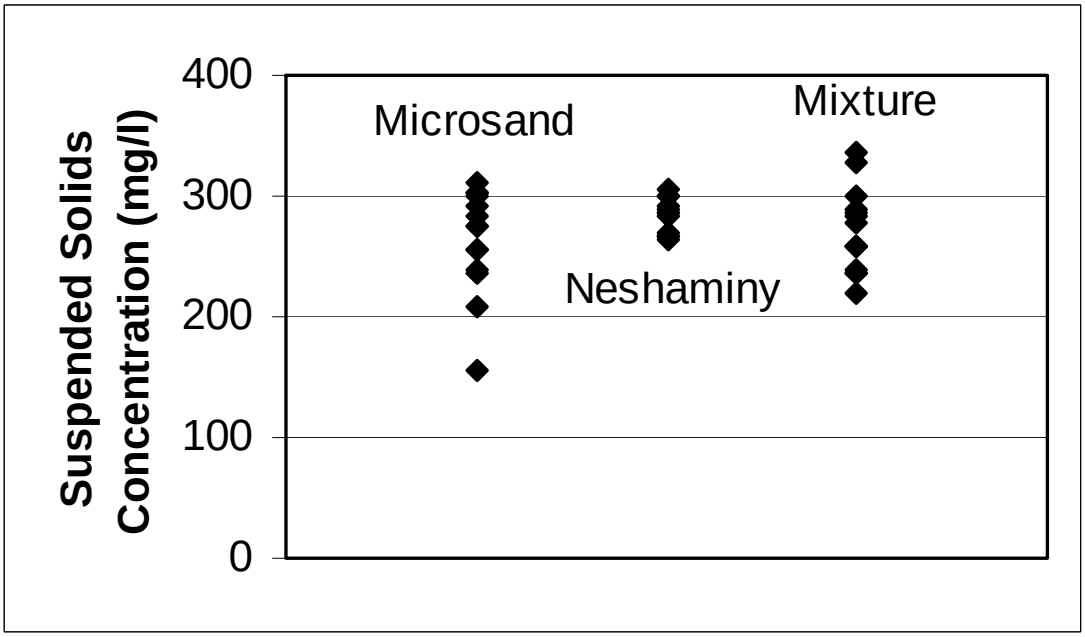


Figure A-7: Recycle Concentration by Soil Type

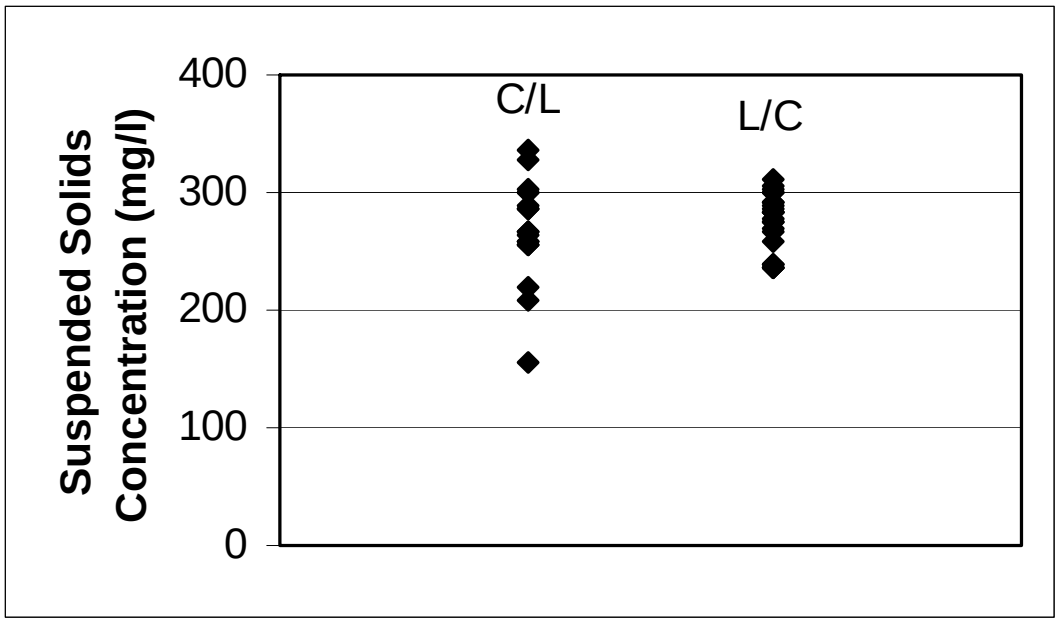


Figure A-8: Recycle Concentration (mg/l), by Order of Filling (C/L=CERGRENE-Long, L/C=Long-CERGRENE)

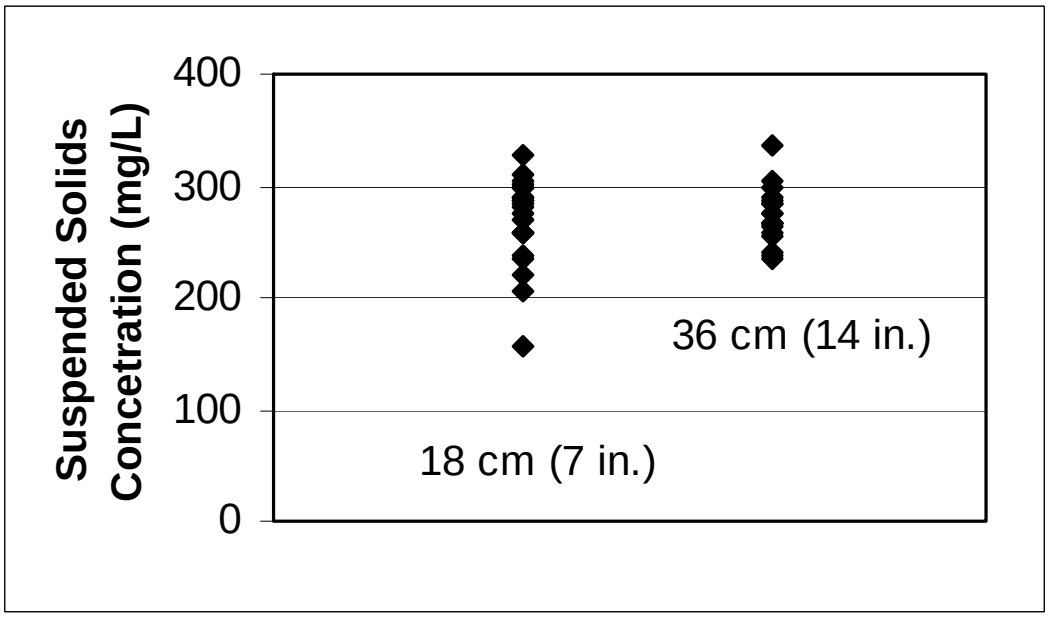


Figure A-9: Recycle Concentration by Intake Depth (height above bottom of basin)

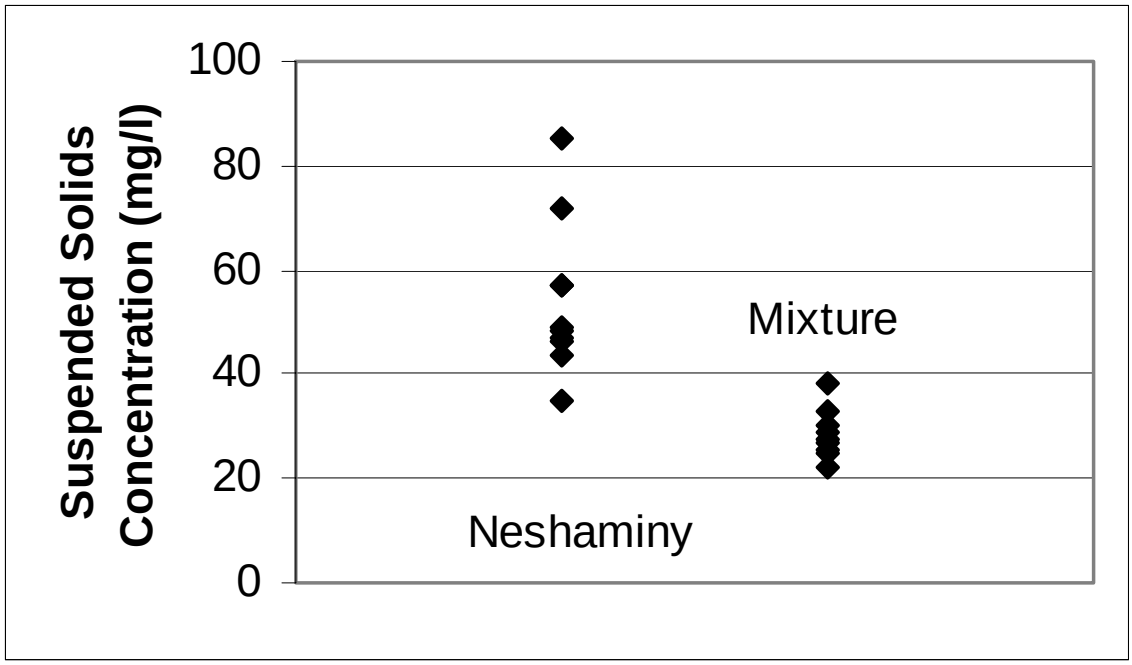


Figure A-10: Concentration in Standard Methods Graduated Cylinder after 60 Minutes of Settling, by Soil Type

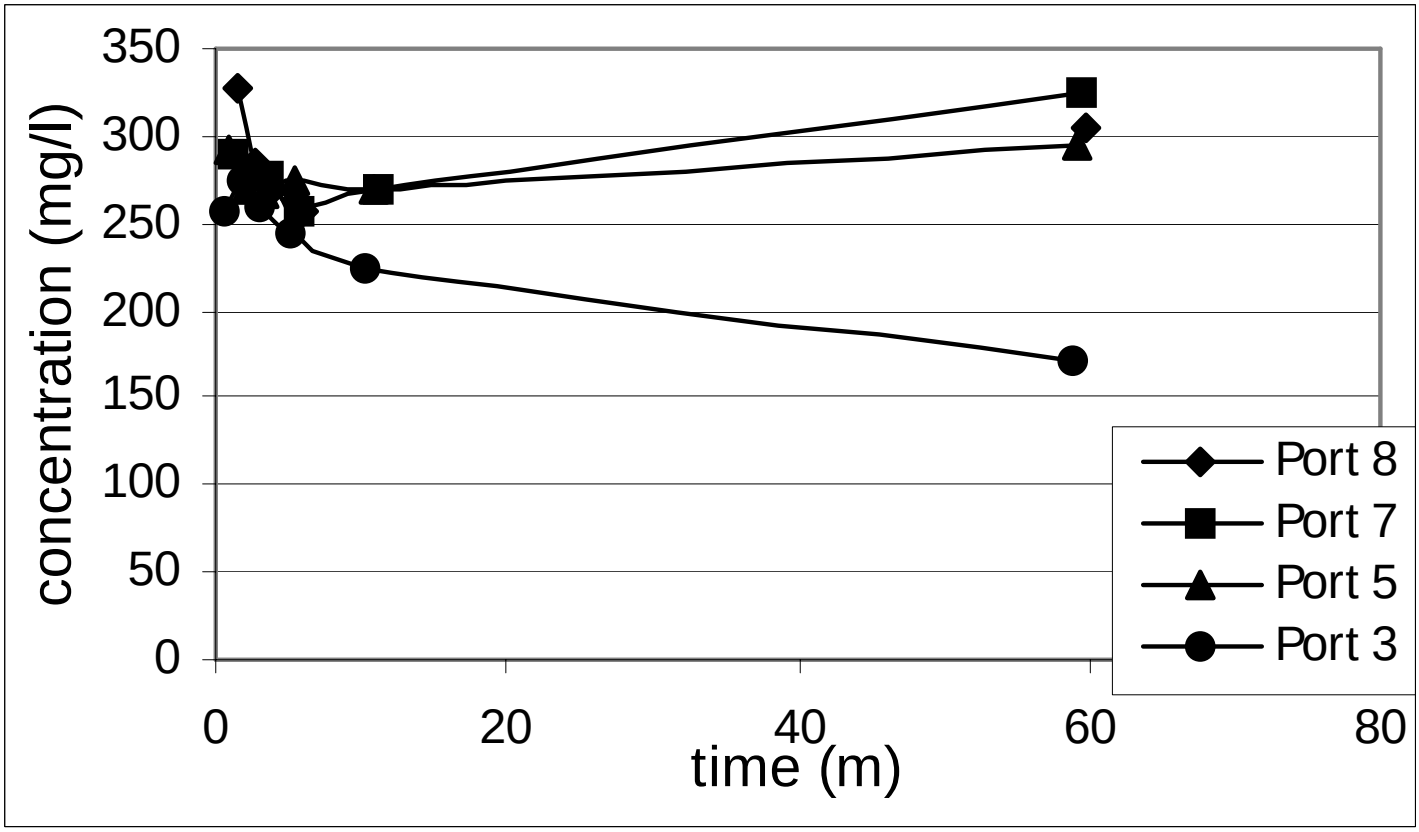


Figure B-1: Experiment 1, Long Column [Withdrawal height 36 cm, filling sequence C/L, media Neshaminy]*

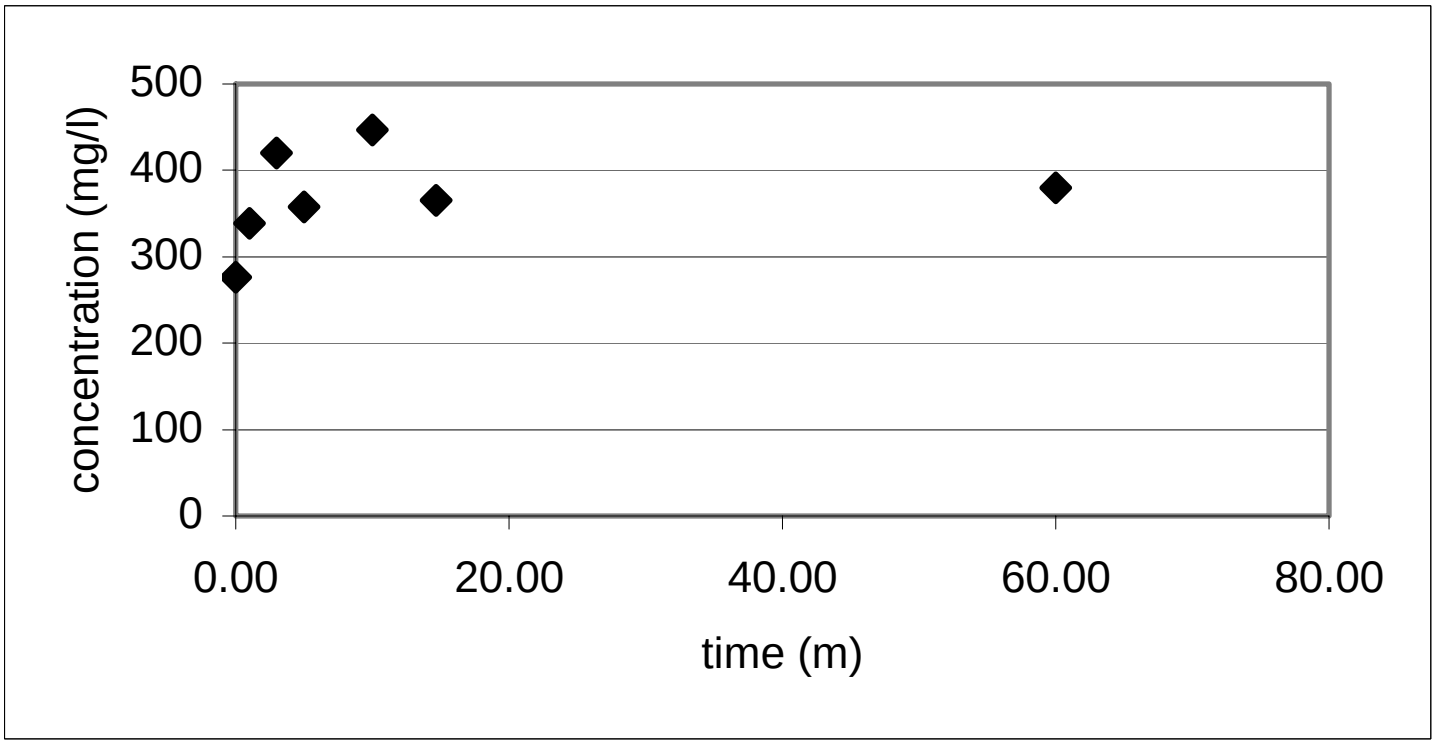


Figure B-2: Experiment 1, CERGRENE (multiple columns) [36 cm, C/L, Neshaminy]

* Experimental parameters in brackets, refer to Table 3.3

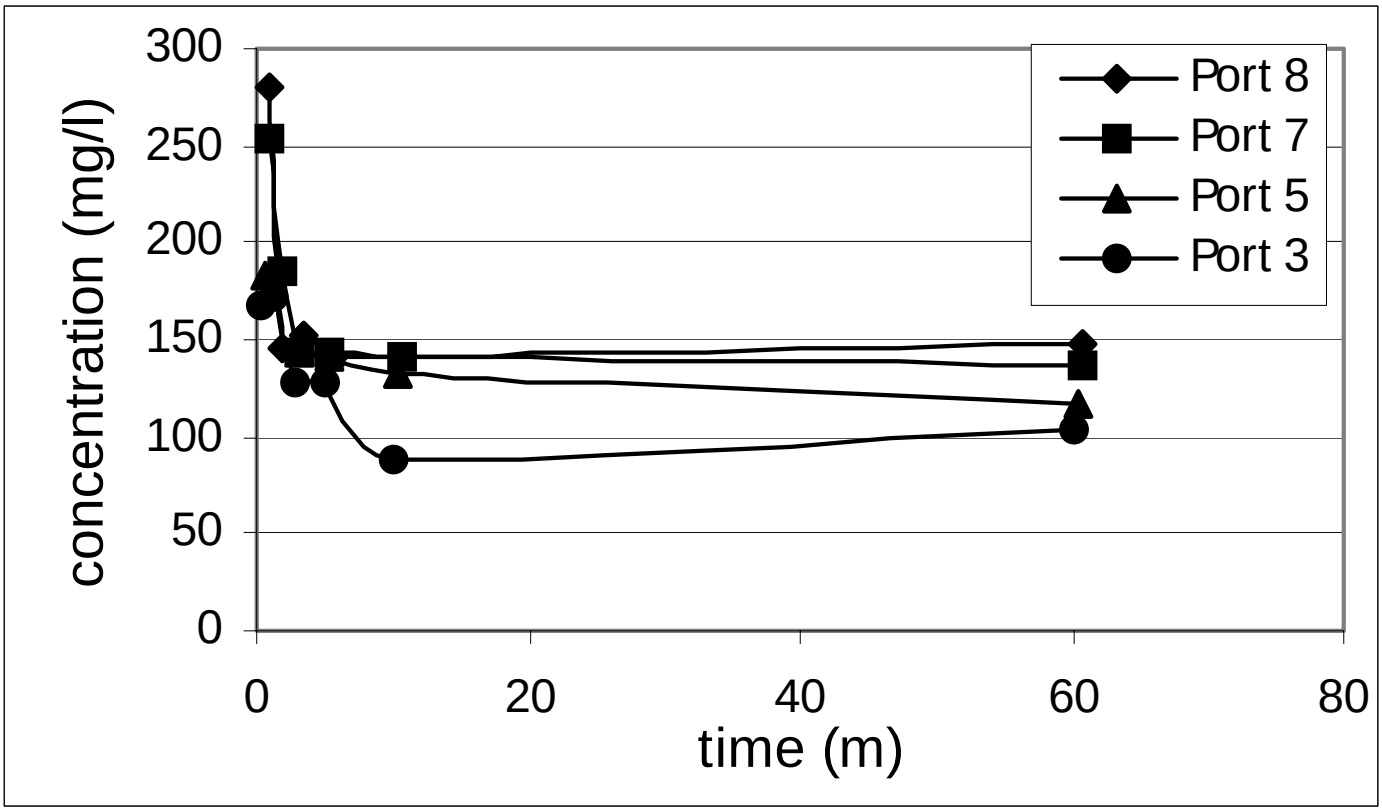


Figure B-3: Experiment 2, Long Column [36 cm, C/L, Mixture]

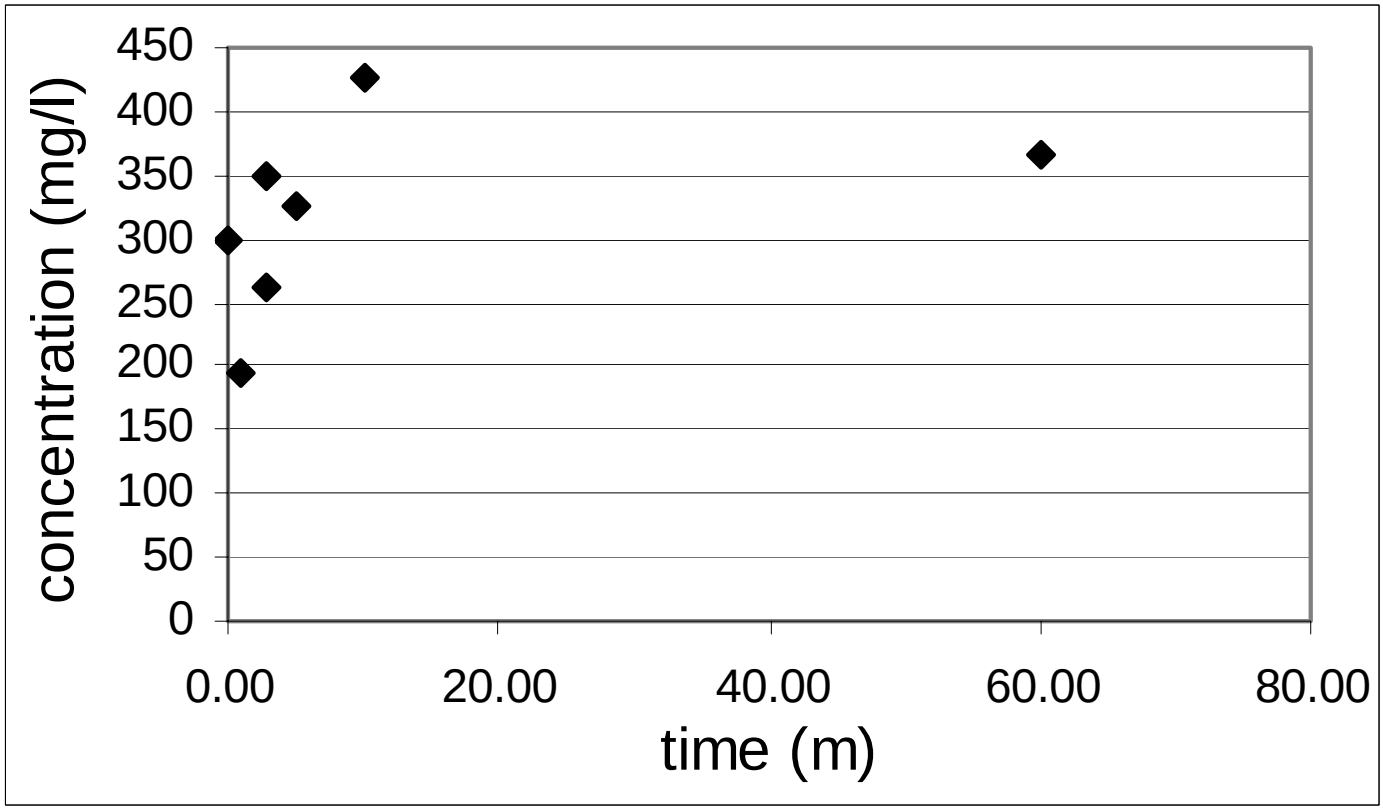


Figure B-4: Experiment 2, CERGRENE (multiple columns) [36 cm, C/L, Mixture]

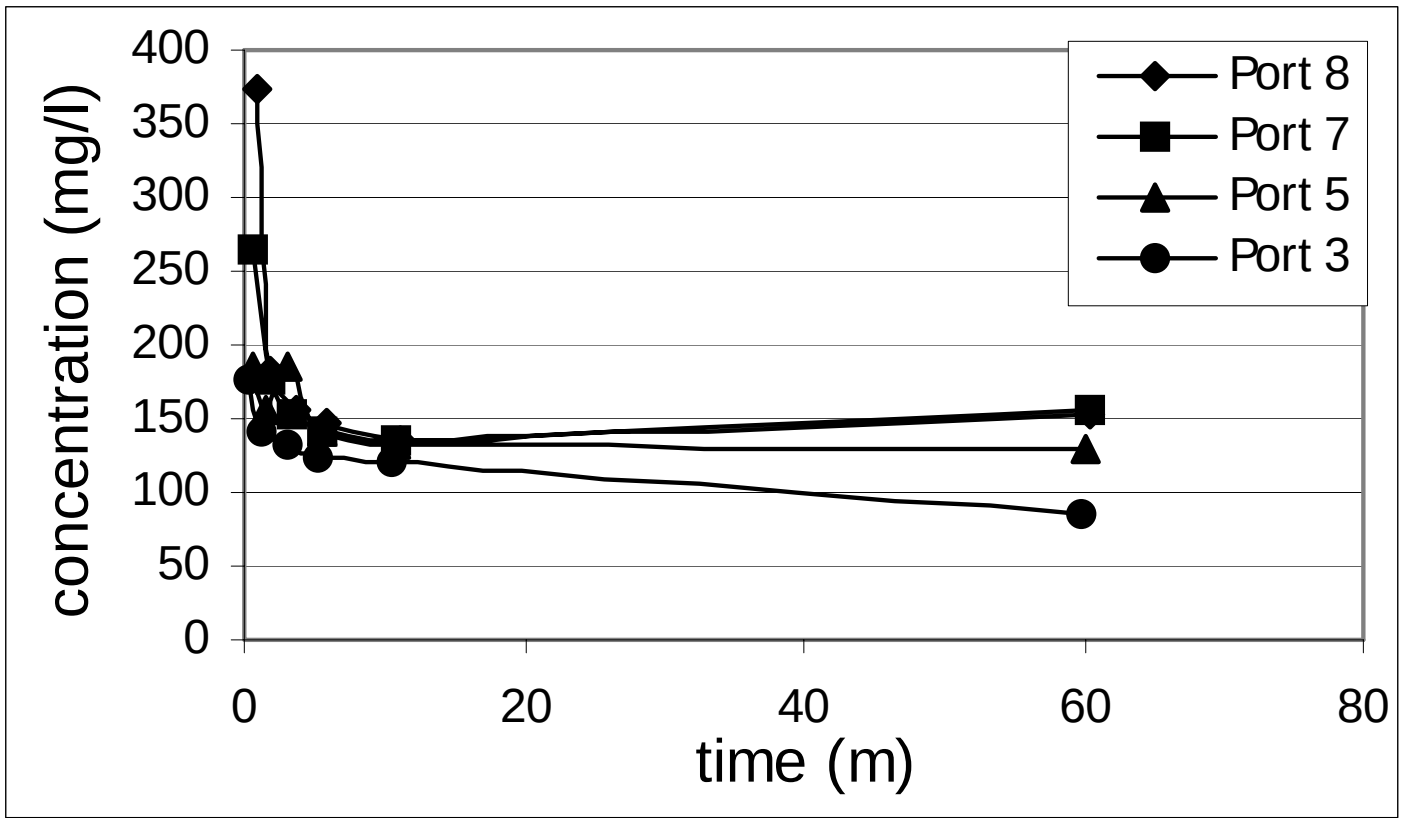


Figure B-5: Experiment 3, Long Column [18 cm, C/L Mixture]

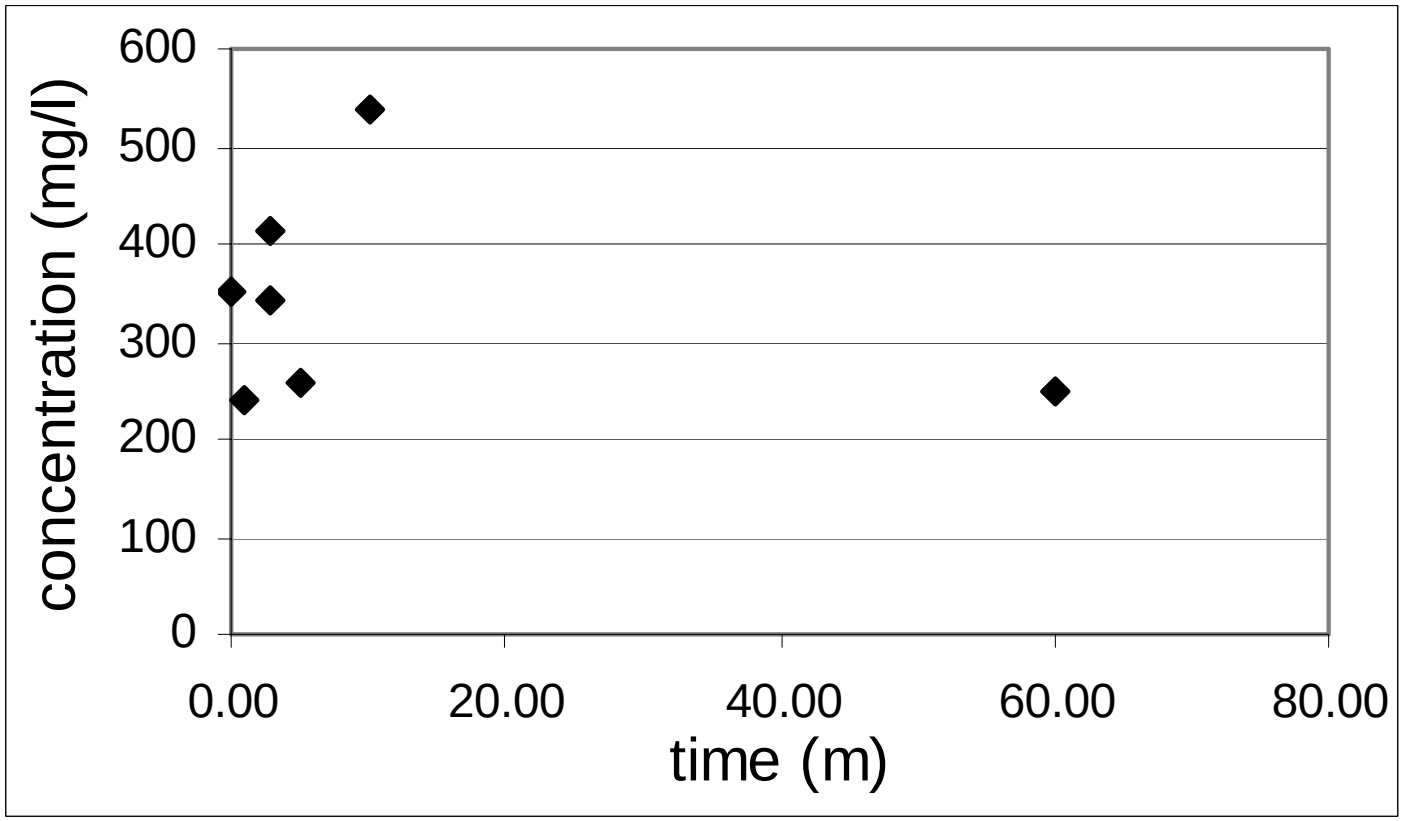


Figure B-6: Experiment 3, CERGRENE (multiple columns) [18 cm, C/L Mixture]

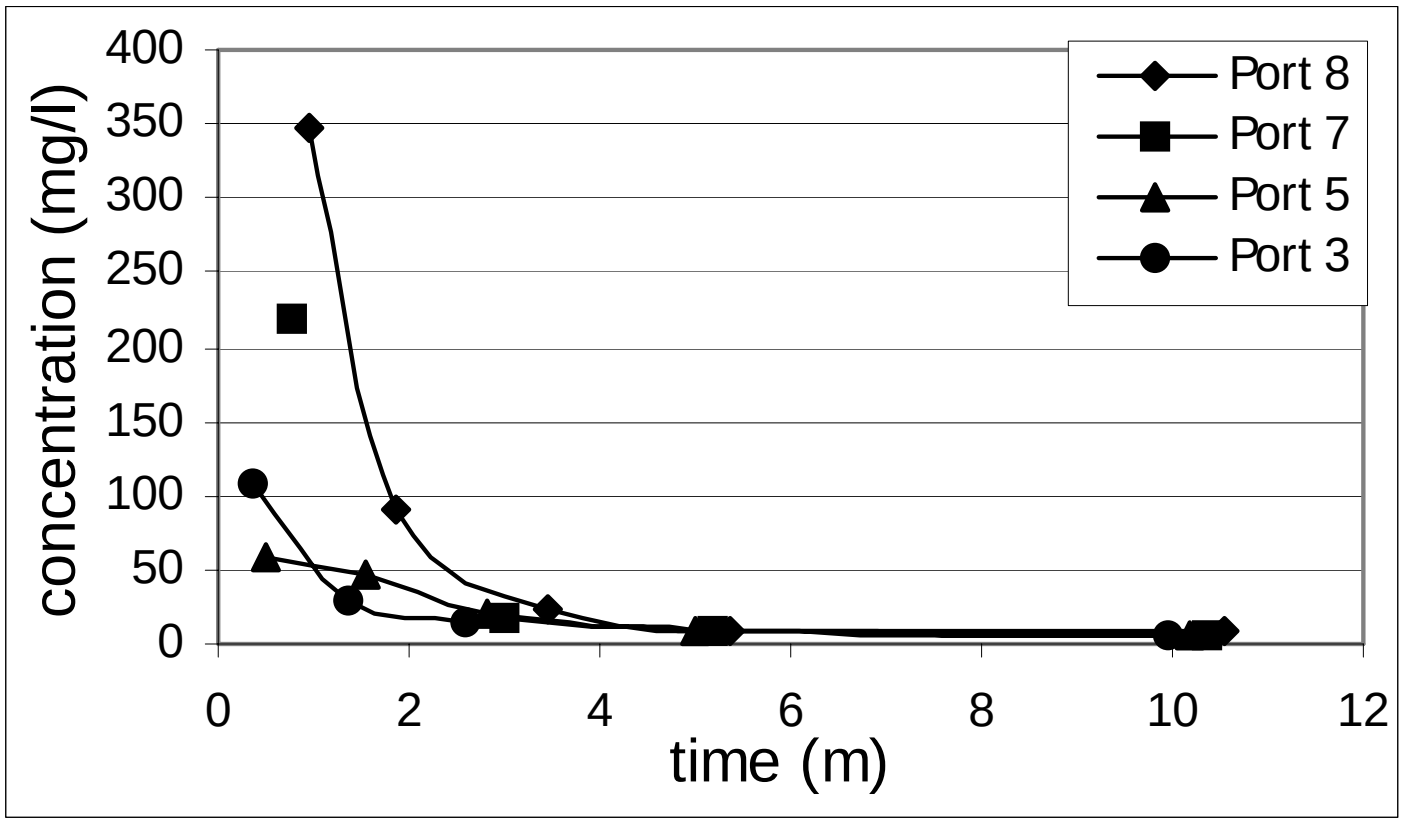


Figure B-7: Experiment 4, Long Column [18 cm, C/L, Microsand]

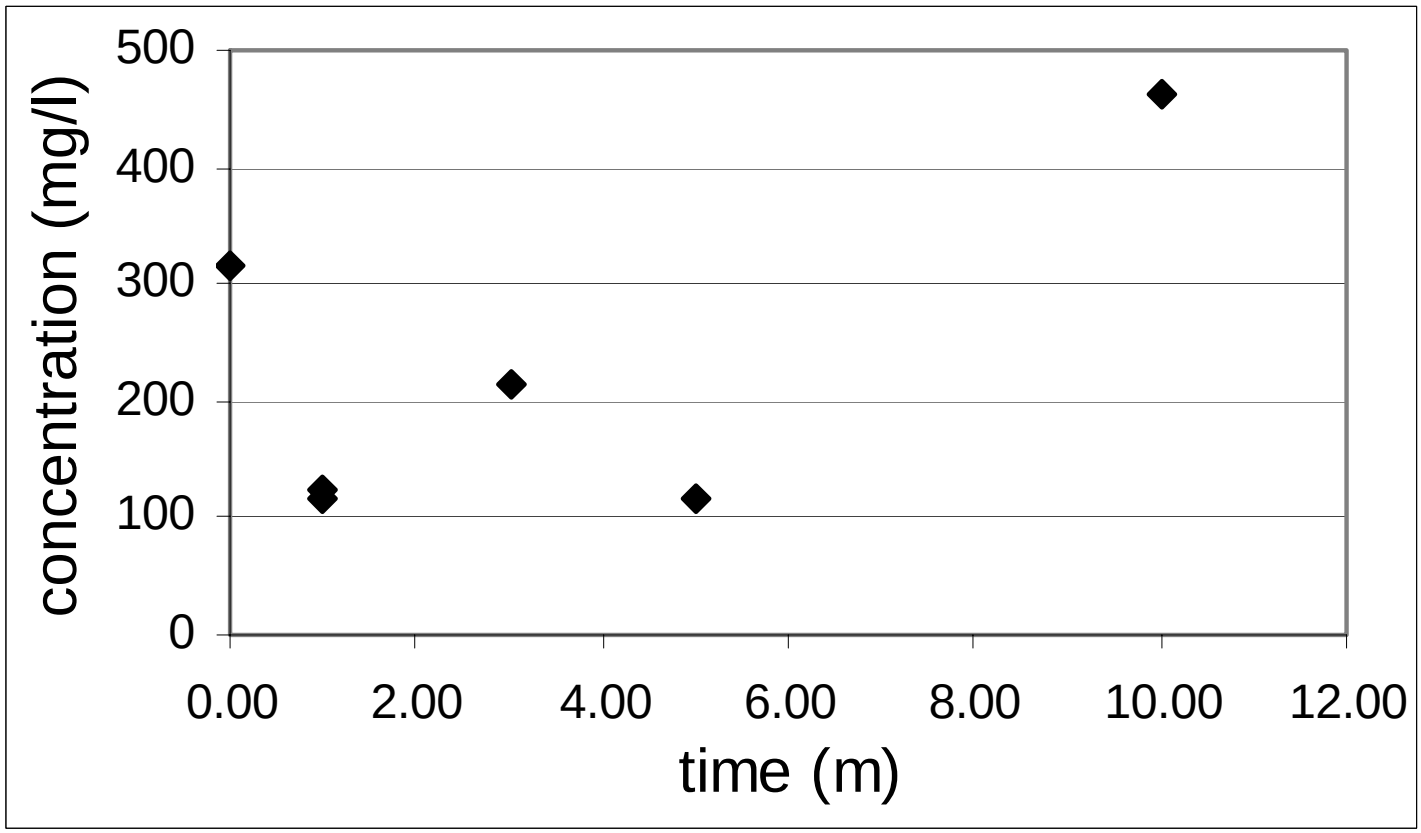


Figure B-8: Experiment 4, CERGRENE (multiple columns) [18 cm, C/L, Microsand]

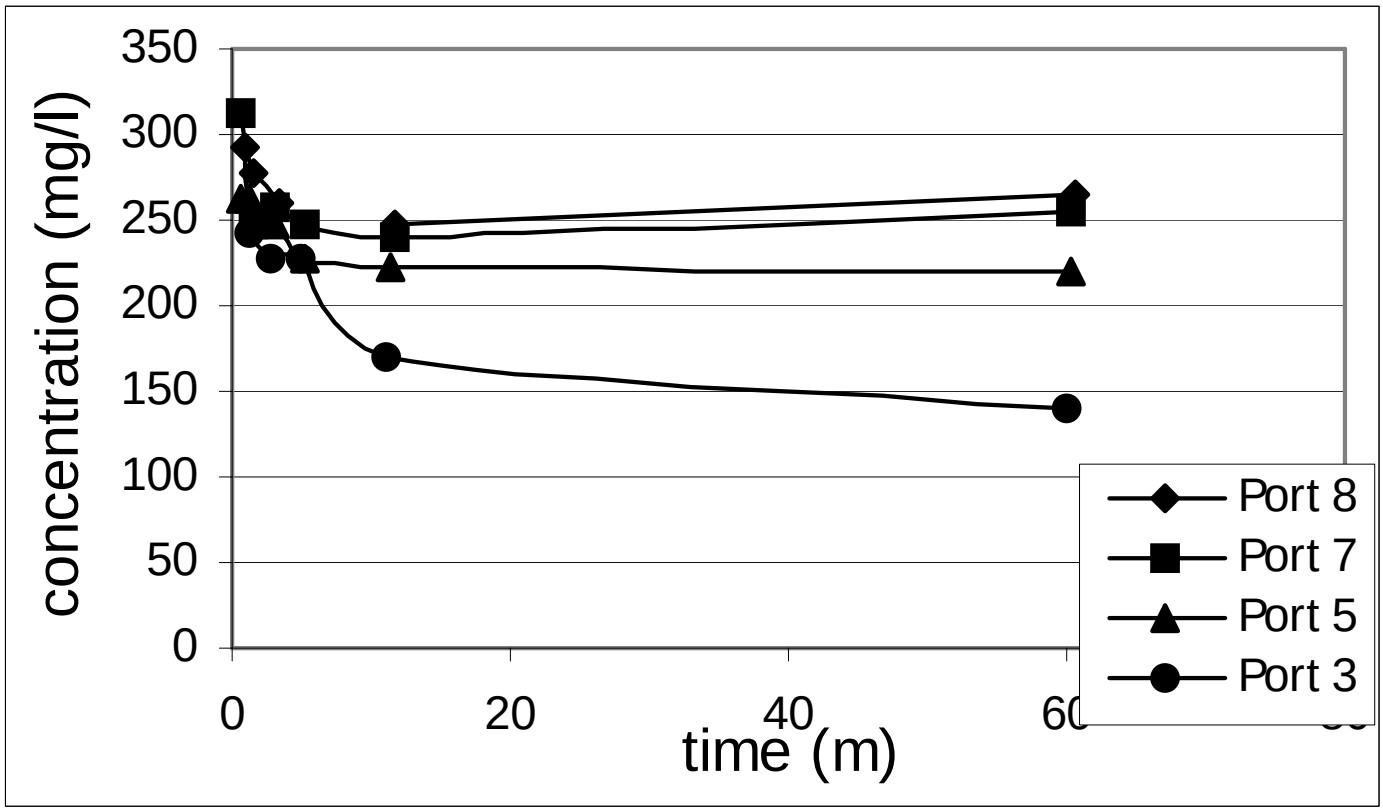


Figure B-9: Experiment 5, Long Column [18 cm, L/C, Neshaminy]

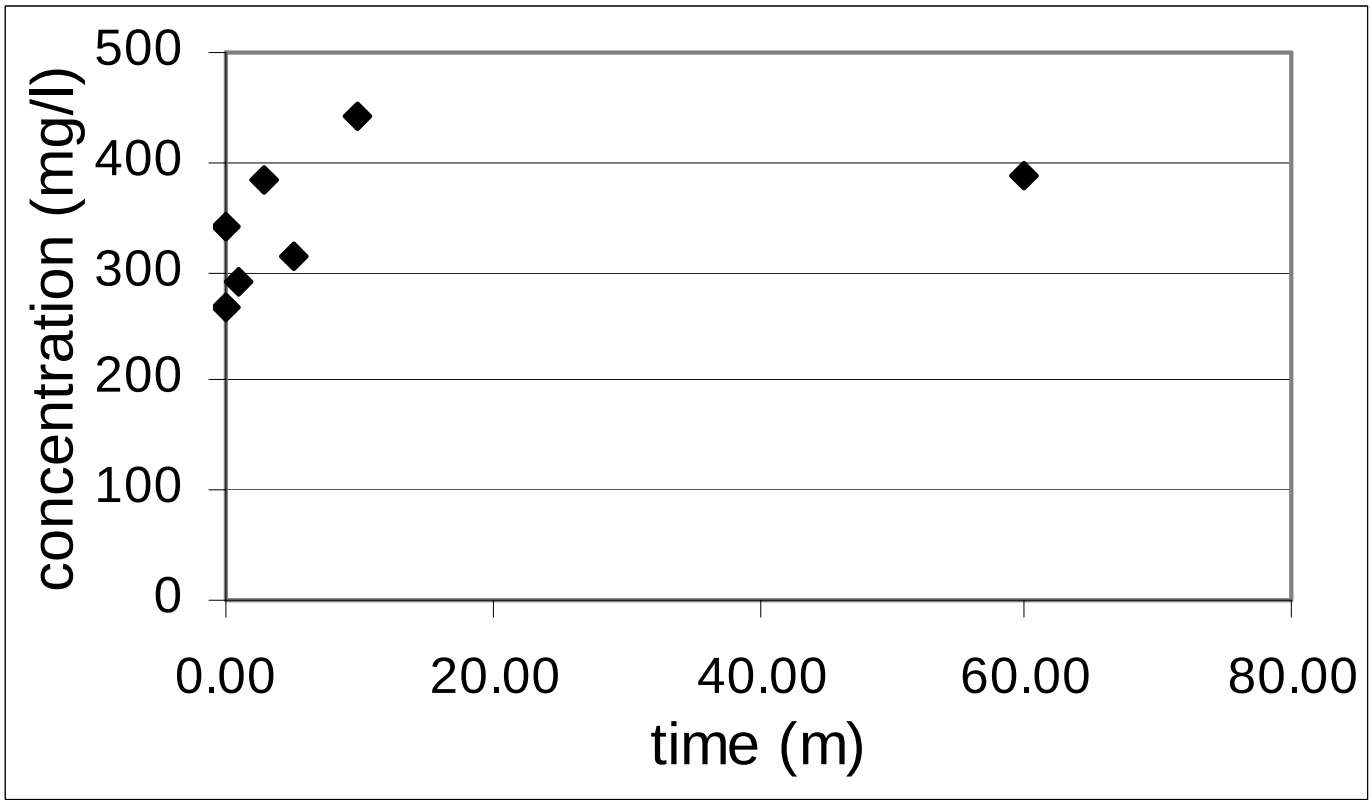


Figure B-10: Experiment 5, CERGRENE (multiple columns) [18 cm, L/C, Neshaminy]

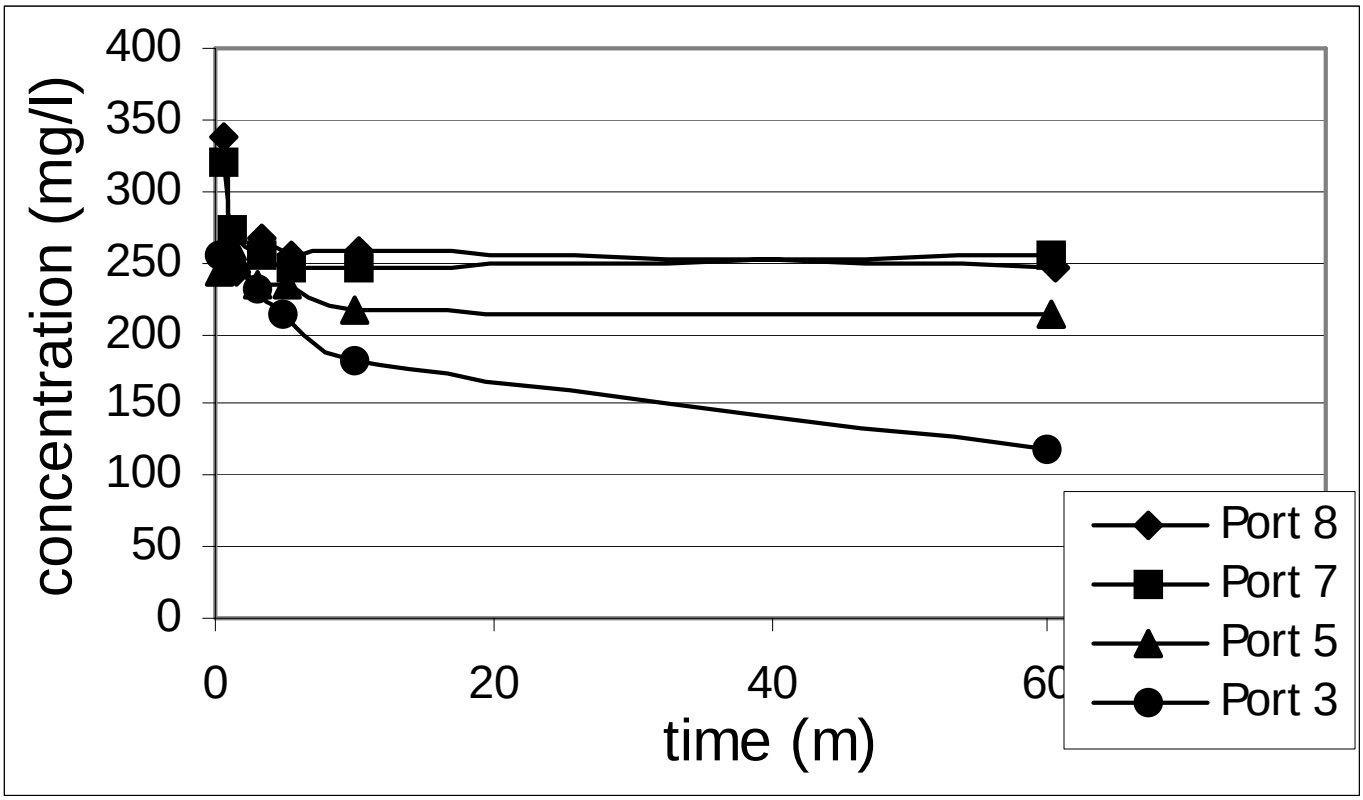


Figure B-11: Experiment 6, Long Column [36 cm, L/C, Neshaminy]

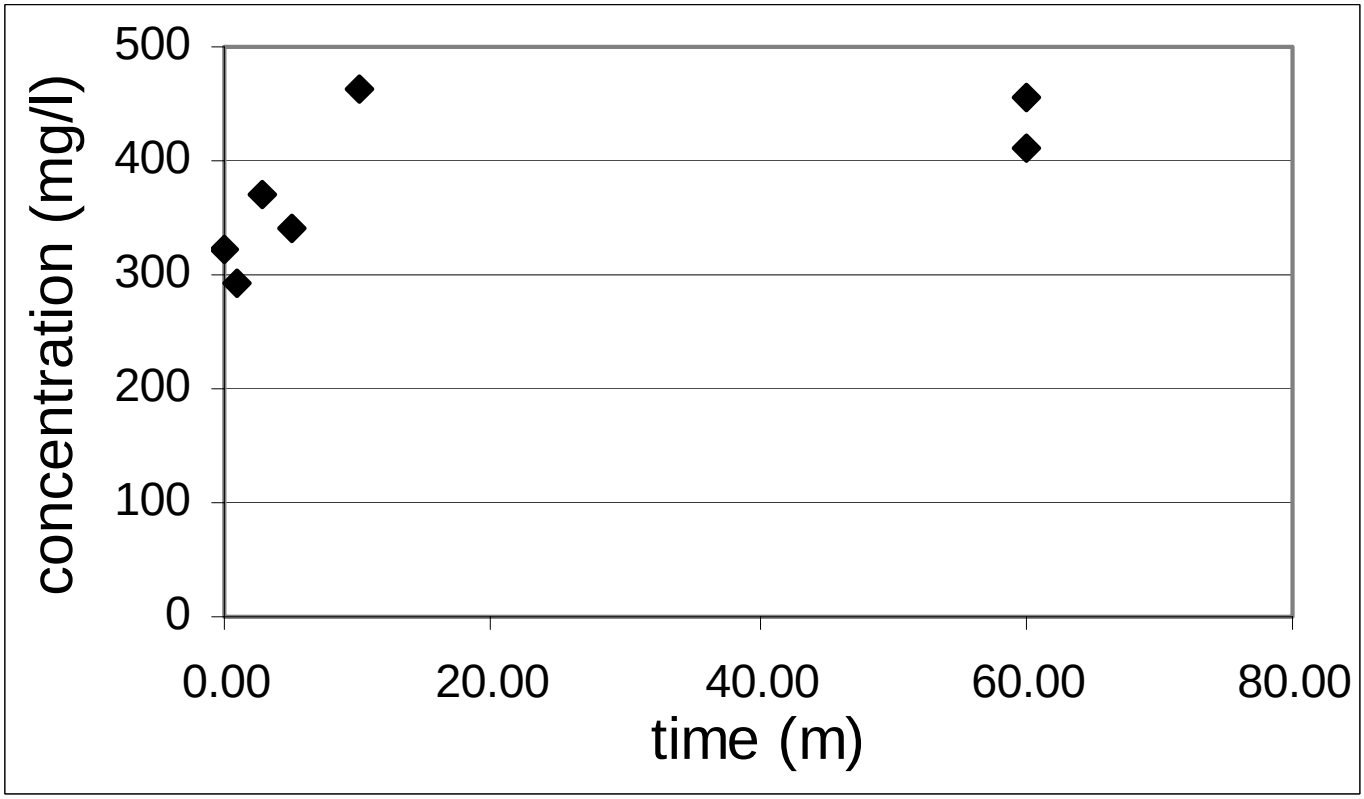


Figure B-12: Experiment 6, CERGRENE (multiple columns) [36 cm, L/C, Neshaminy]

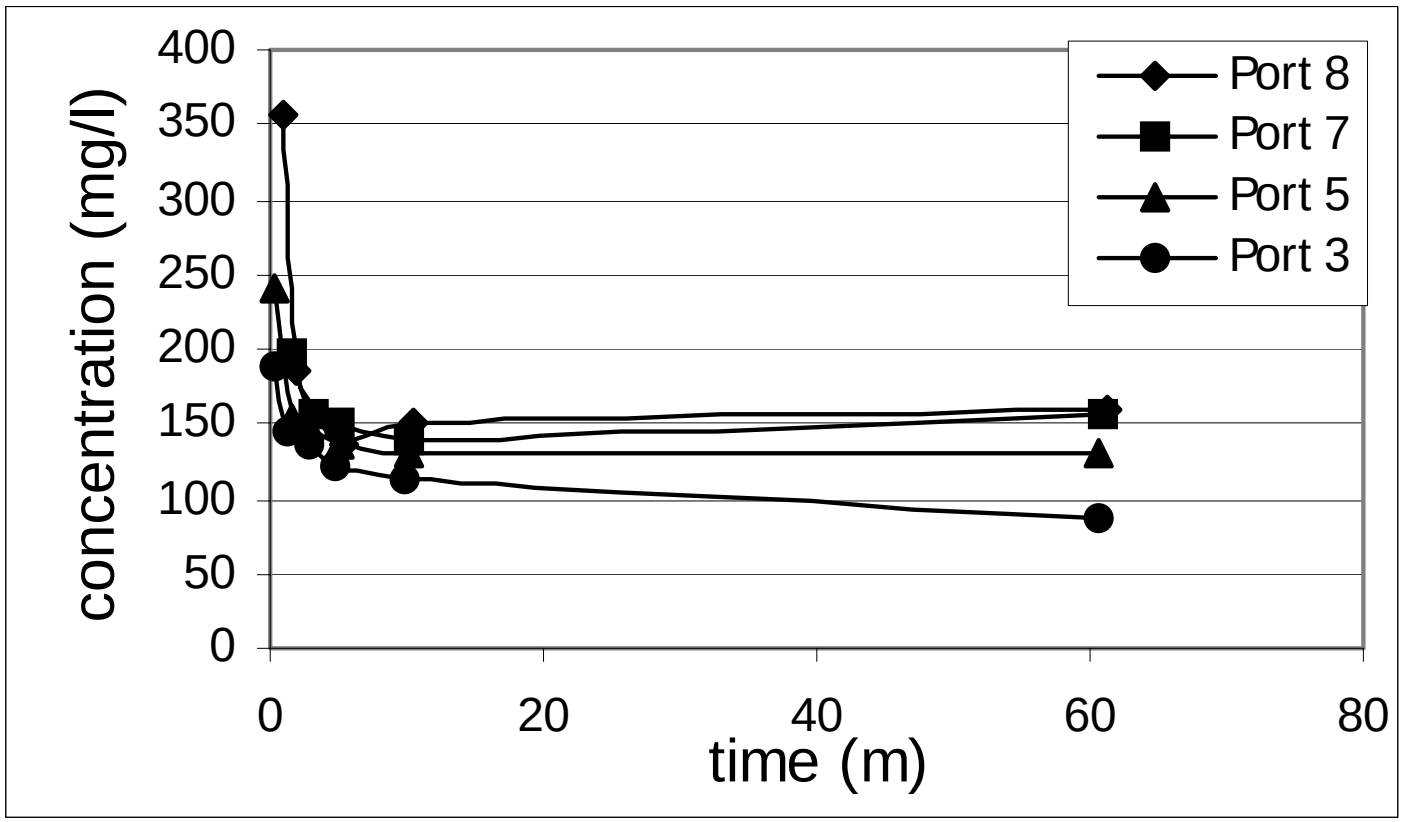


Figure B-13: Experiment 7, Long Column [18 cm, C/L, Mixture]

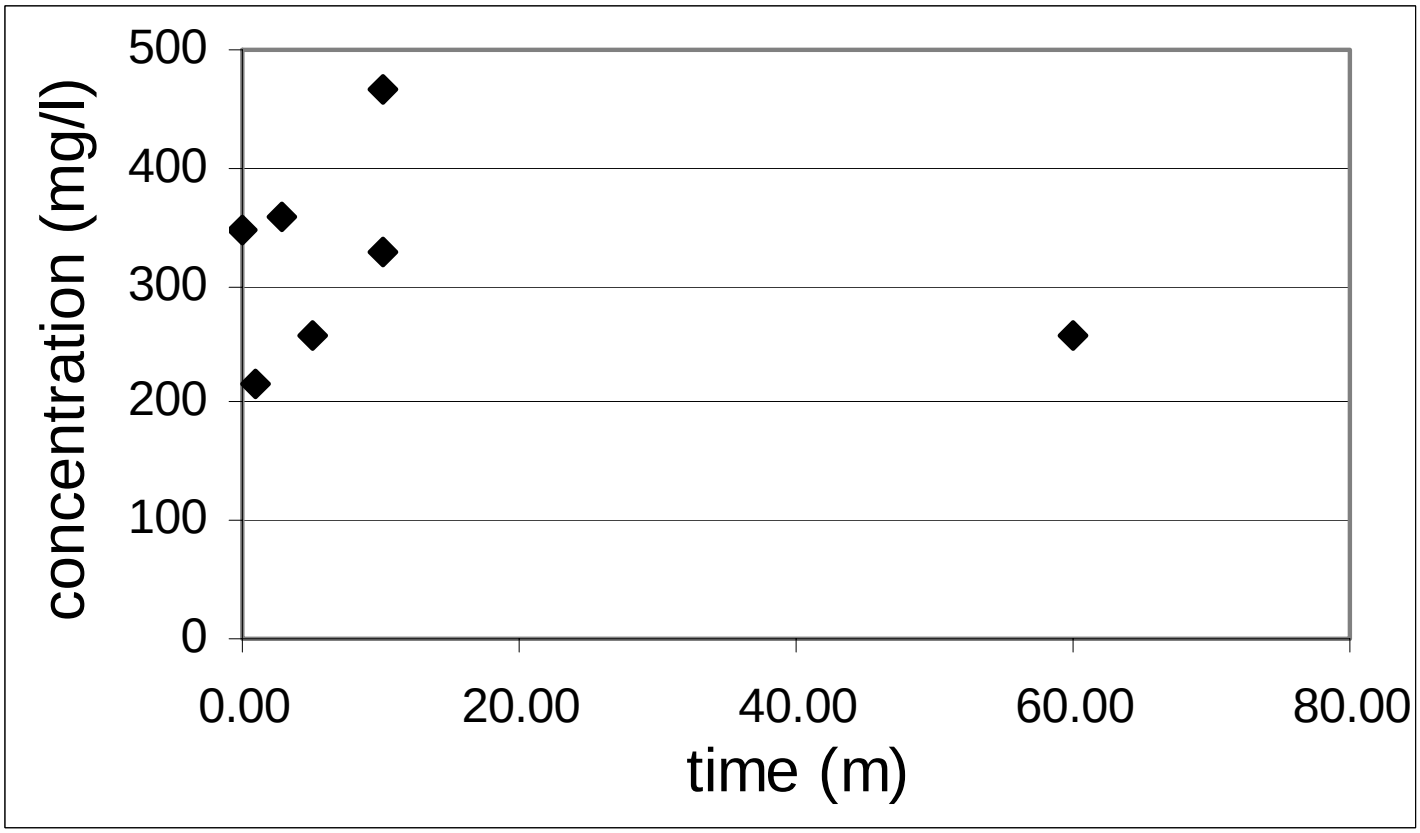


Figure B-14: Experiment 7, CERGRENE (multiple columns) [18 cm, C/L, Mixture]

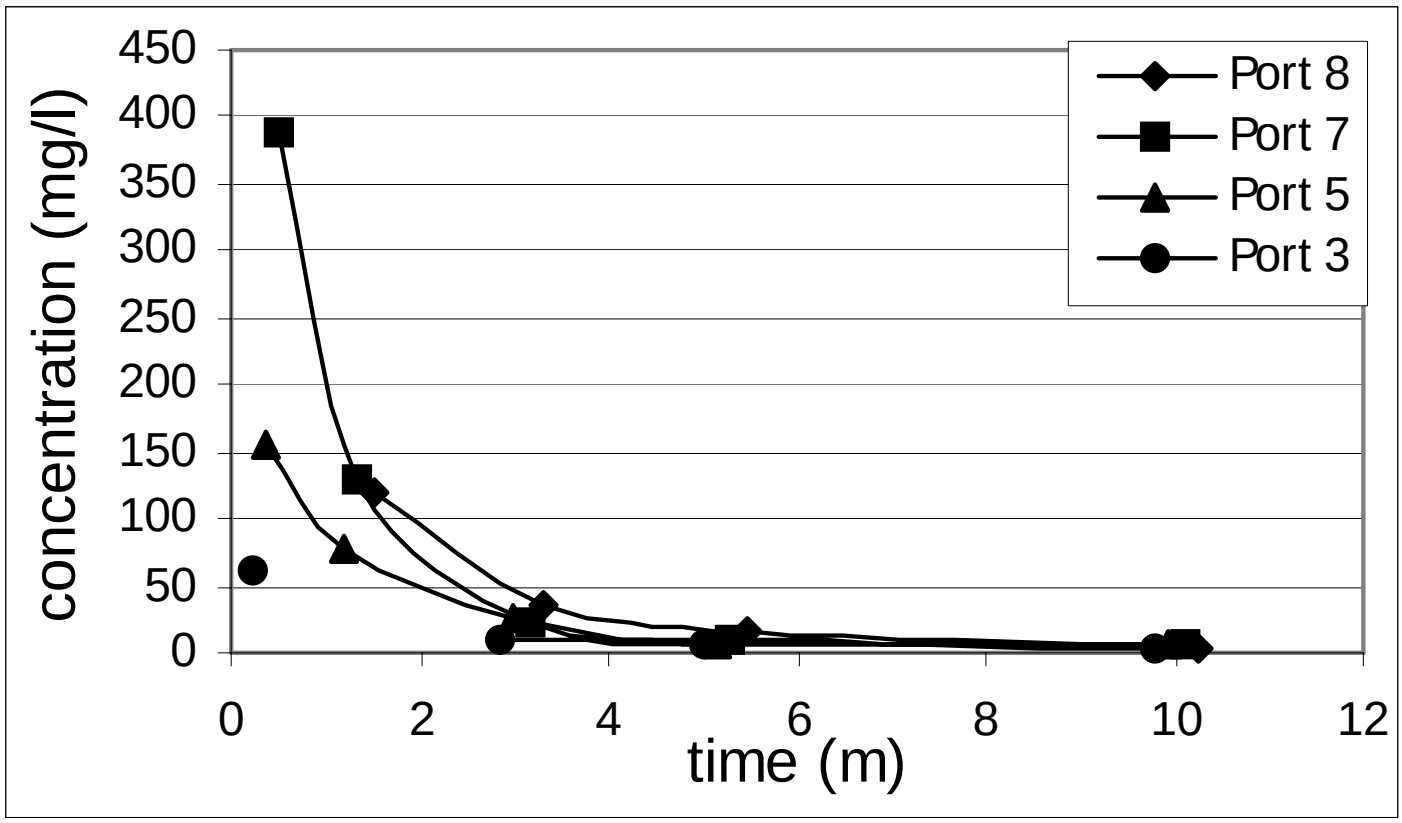


Figure B-15: Experiment 8, Long Column [18 cm, L/C, Microsand]

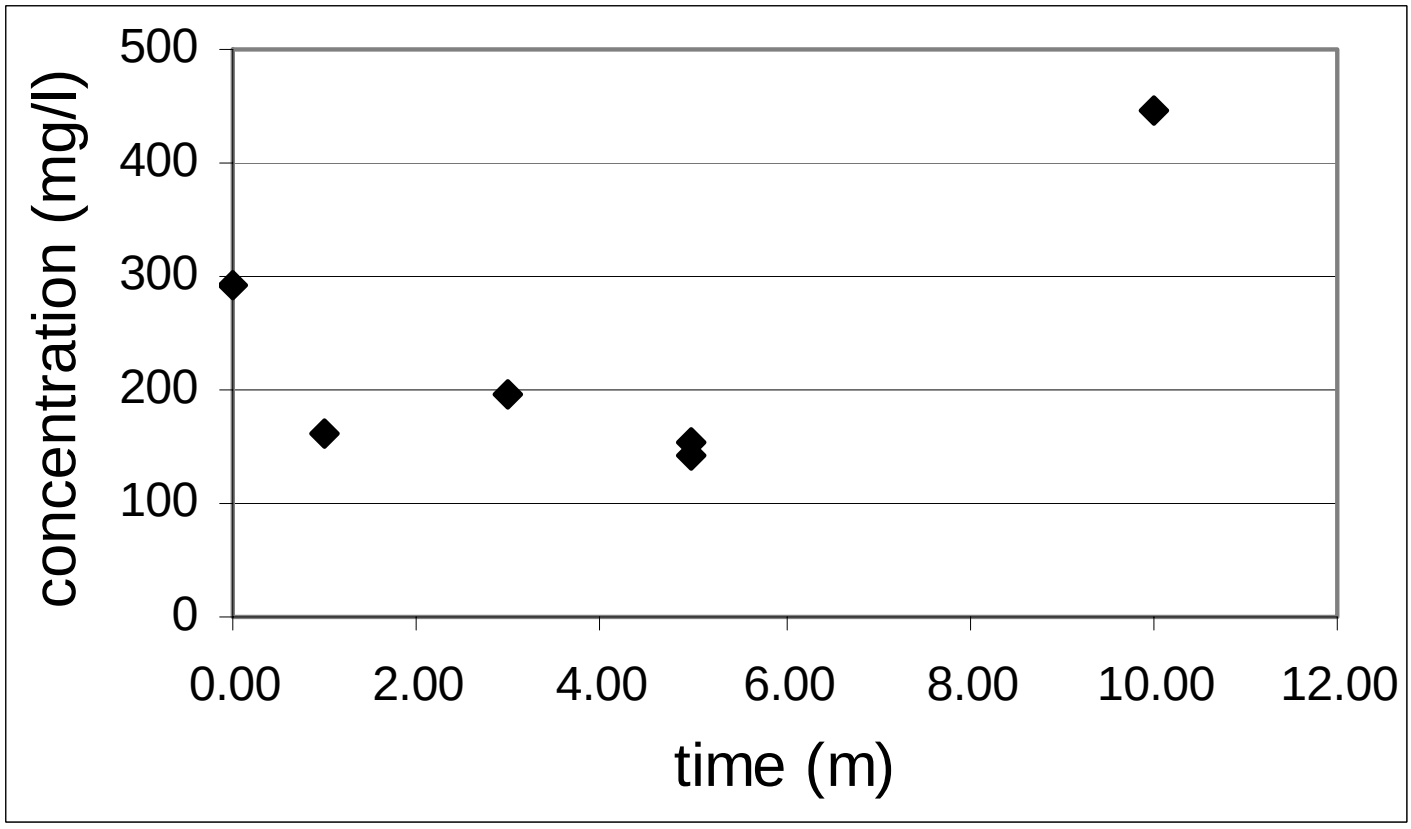


Figure B-16: Experiment 8, CERGRENE (multiple columns) [18 cm, L/C, Microsand]

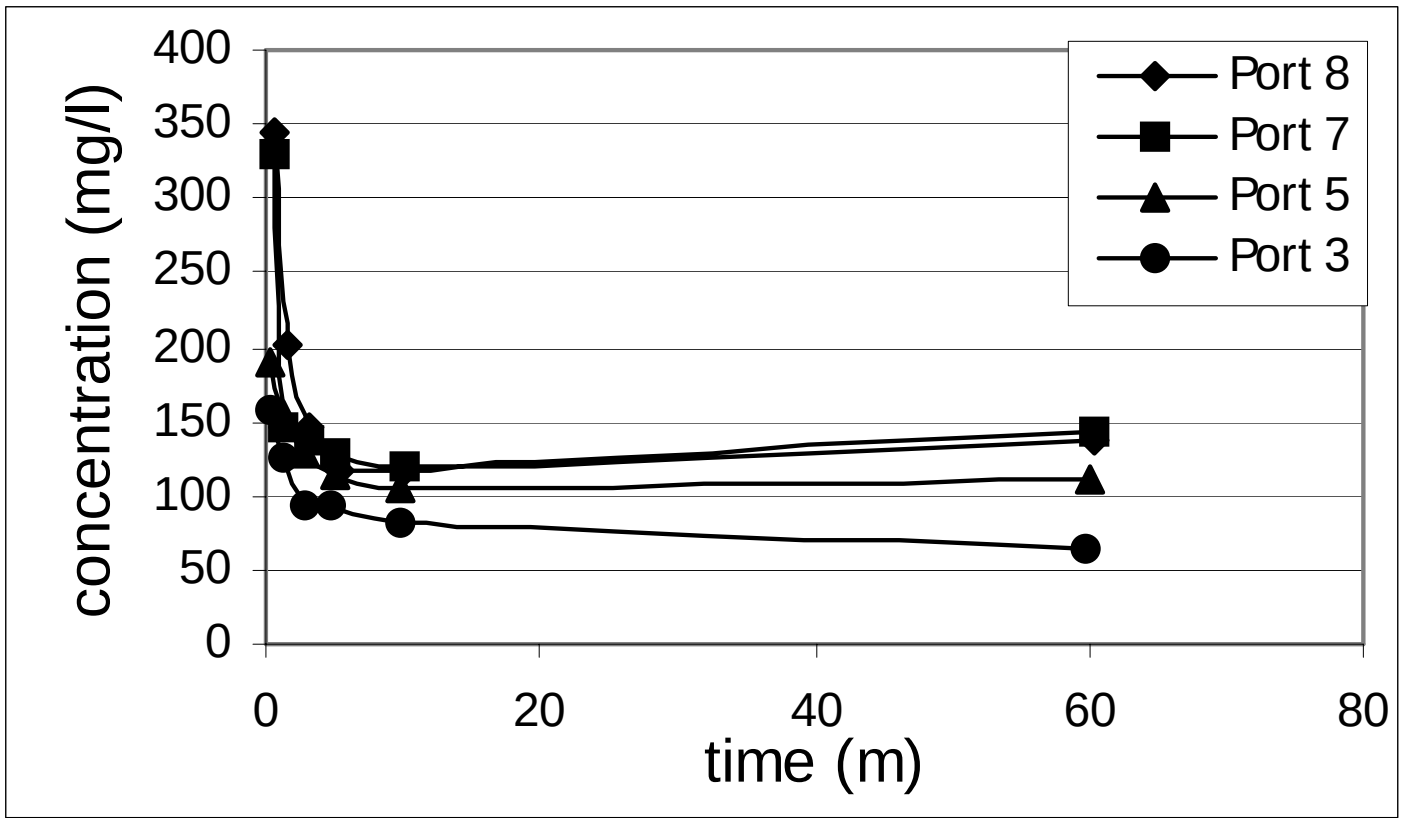


Figure B-17: Experiment 9, Long Column [18 cm, L/C, Mixture]

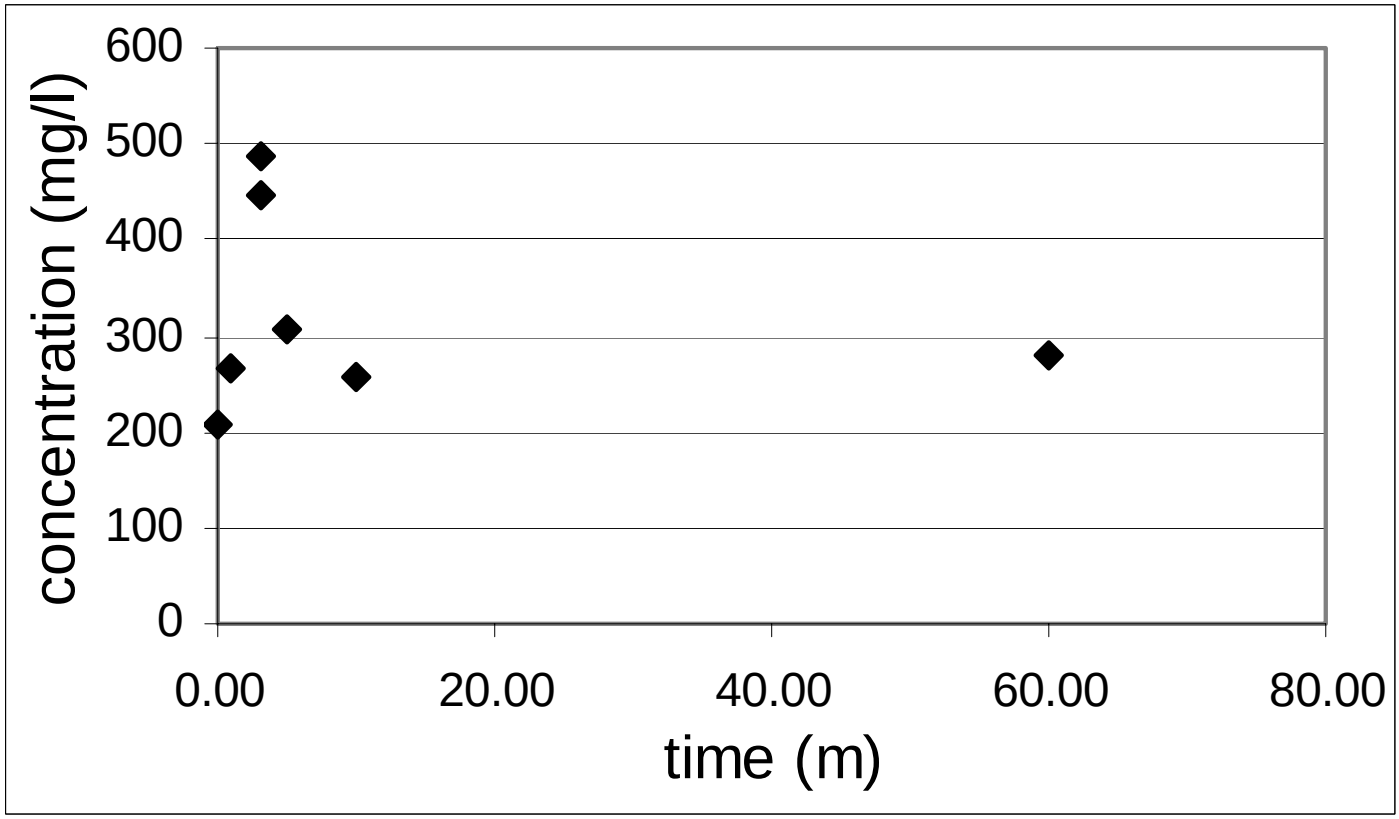


Figure B-18: Experiment 9, CERGRENE (multiple columns, randomized) [18 cm, L/C, Mixture]

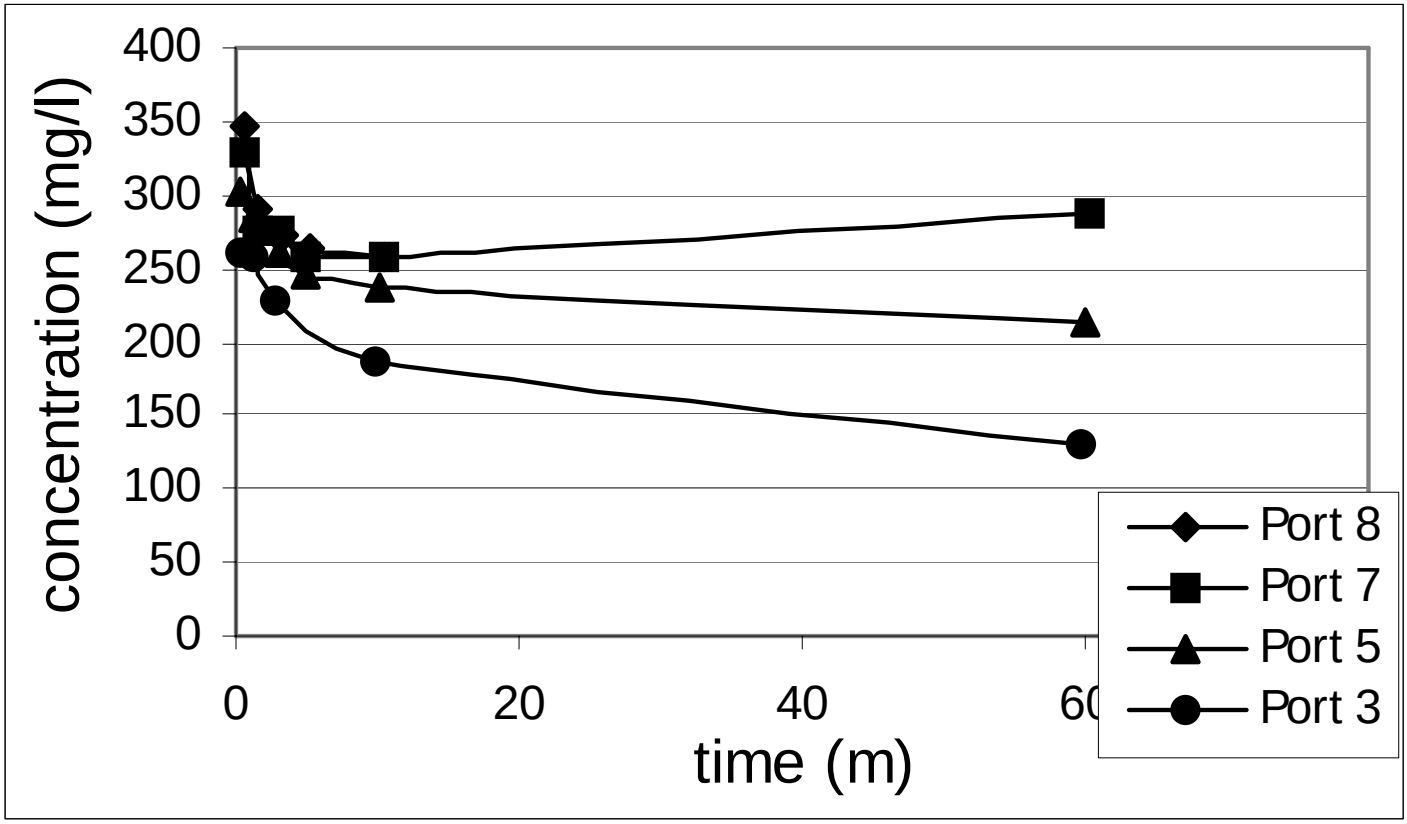


Figure B-19: Experiment 10, Long Column [36 cm, L/C, Neshaminy]

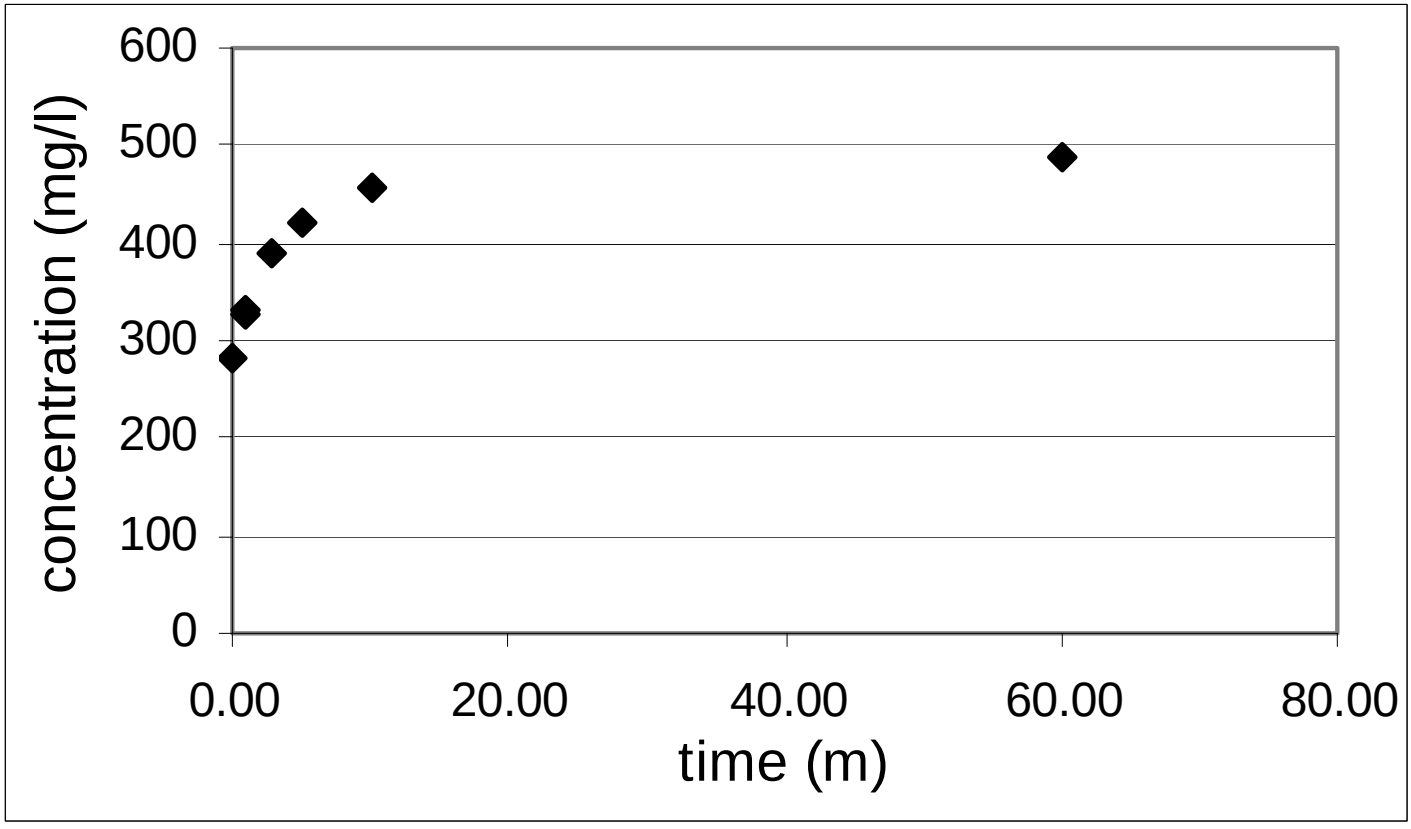


Figure B-20: Experiment 10, CERGRENE (one column) [36 cm, L/C, Neshaminy]

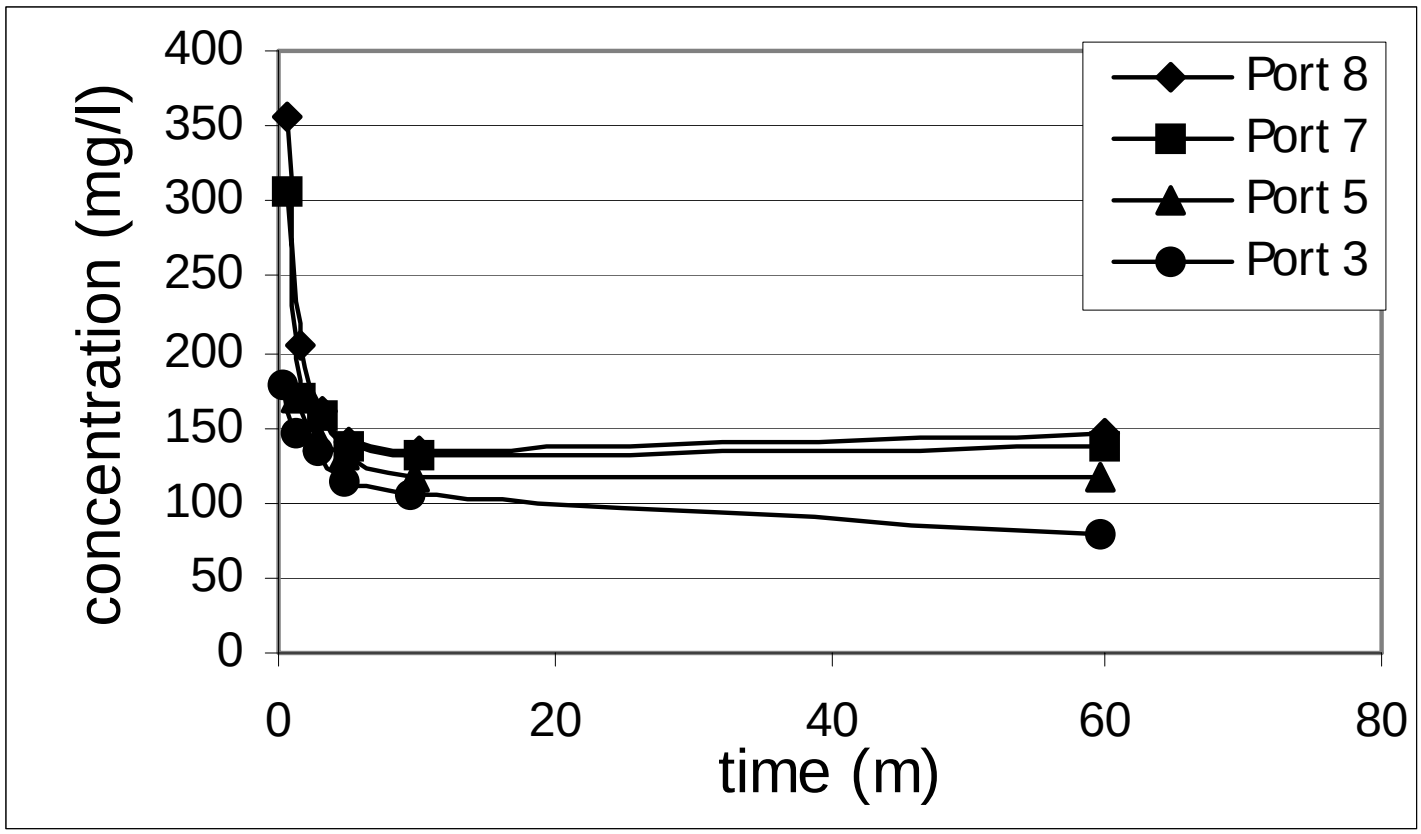


Figure B-21: Experiment 11, Long Column [36 cm, L/C, Mixture]

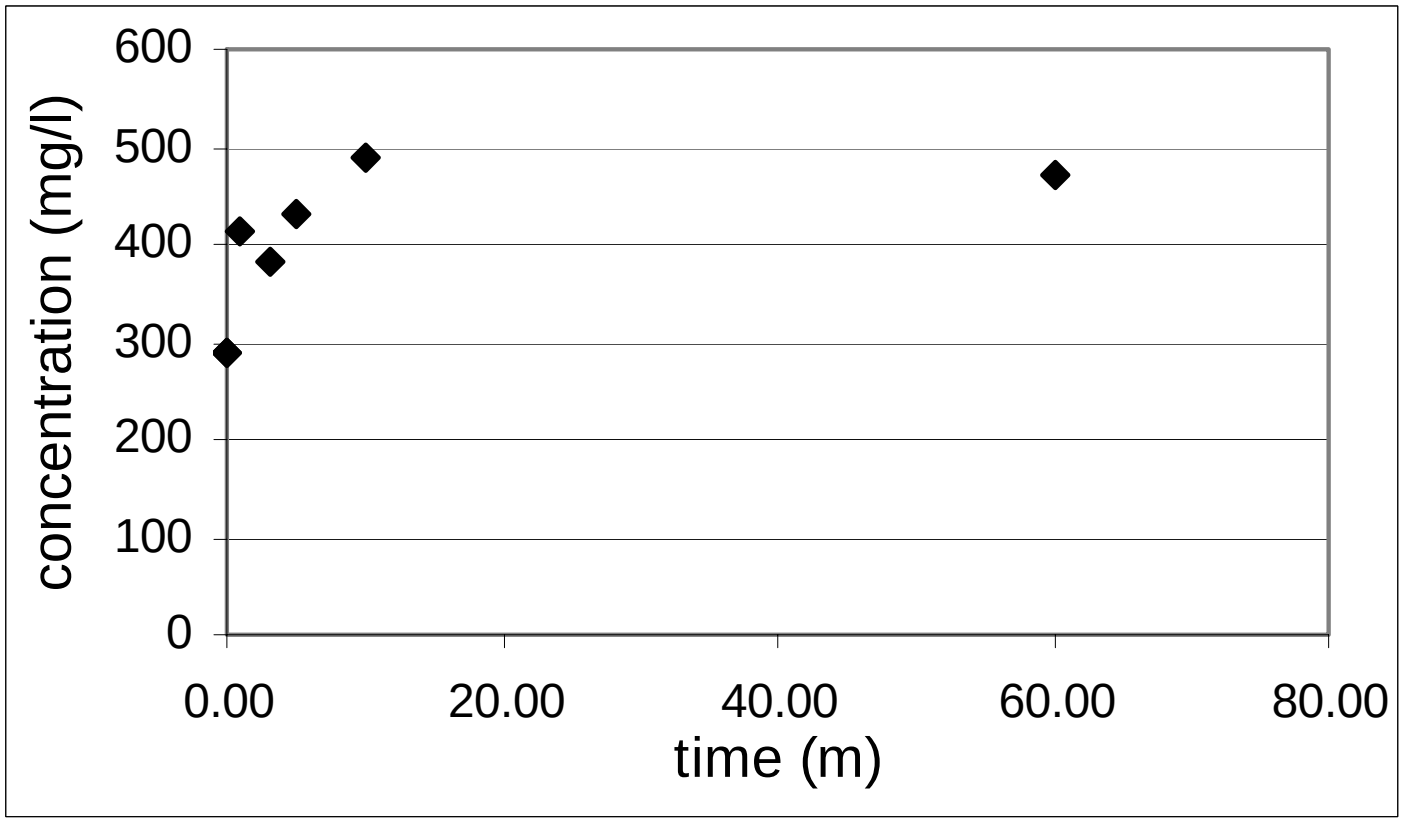


Figure B-22: Experiment 11, CERGRENE (one column) [36 cm, L/C, Mixture]

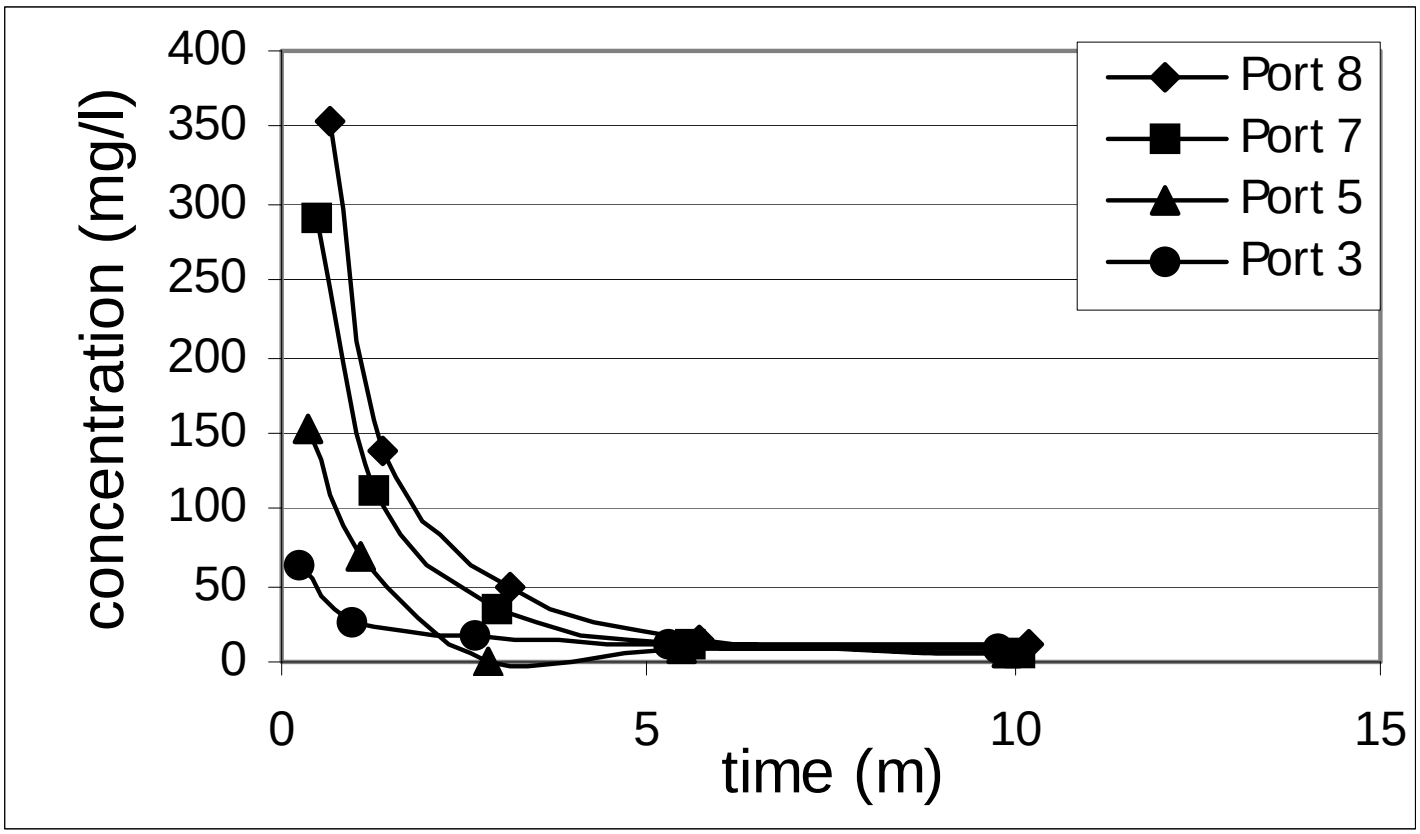


Figure B-23: Experiment 12, Long Column [18 cm, L/C, Microsand]

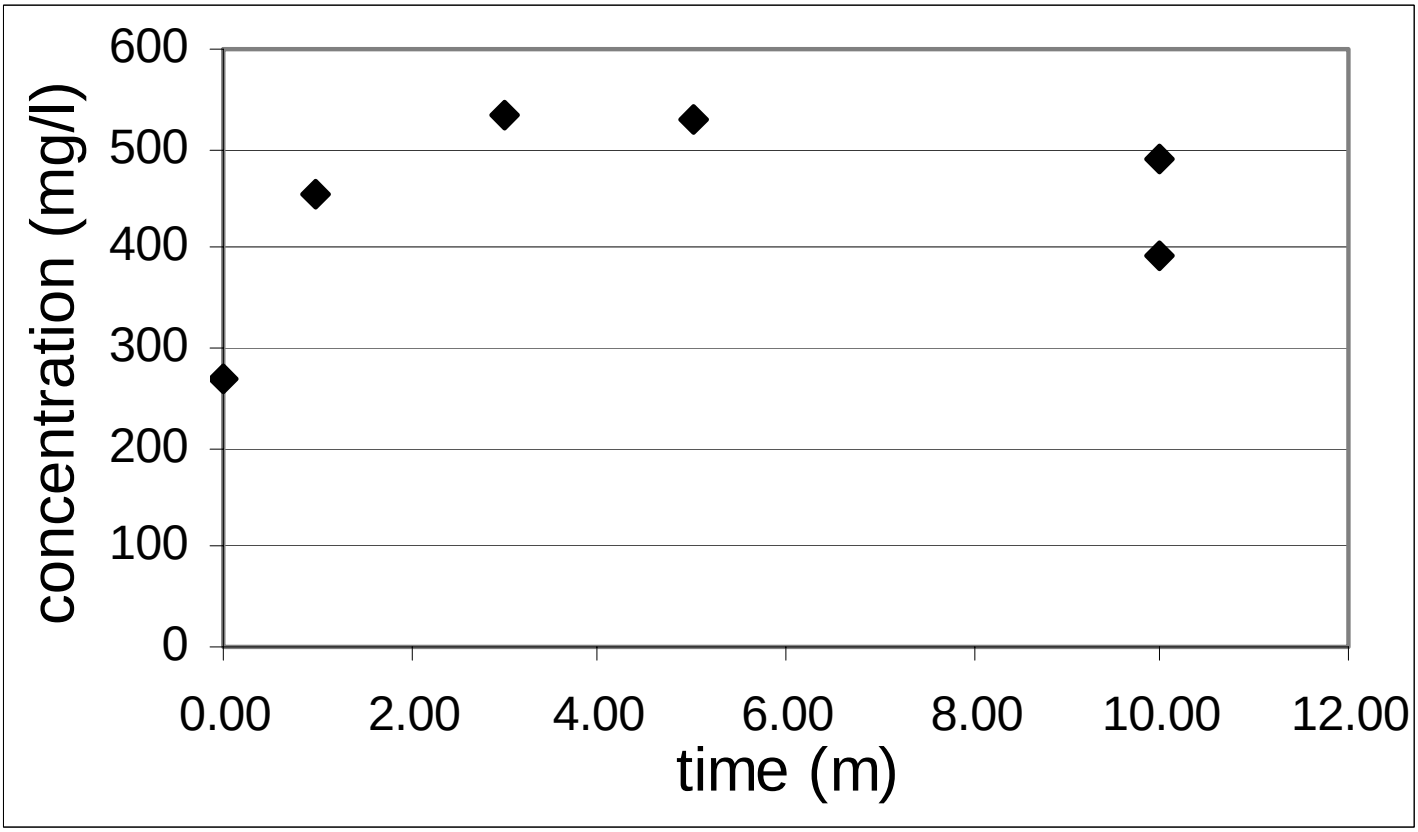


Figure B-24: Experiment 12, CERGRENE (one column) [18 cm, L/C, Microsand]

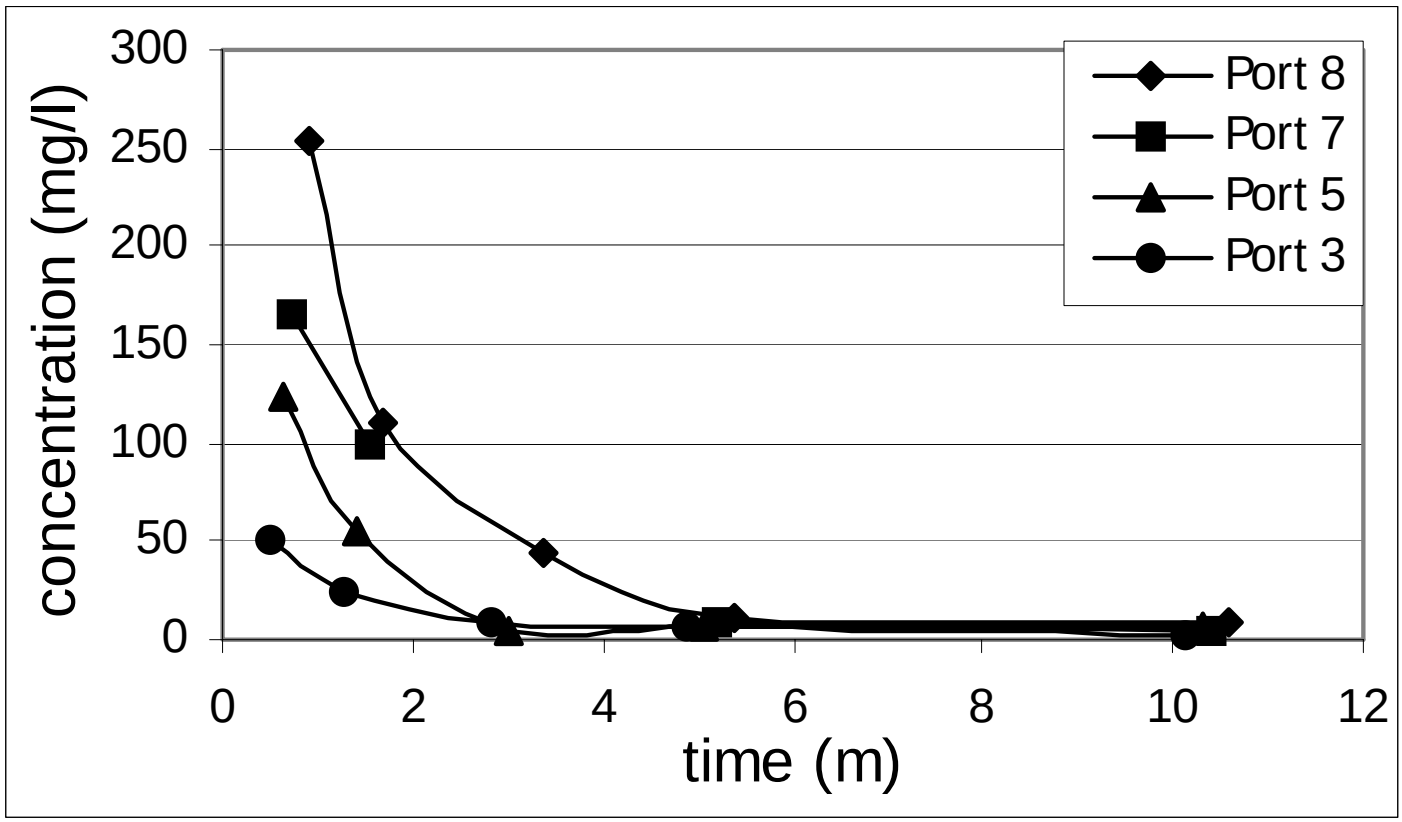


Figure B-25: Experiment 13, Long Column [36 cm, C/L, Microsand]

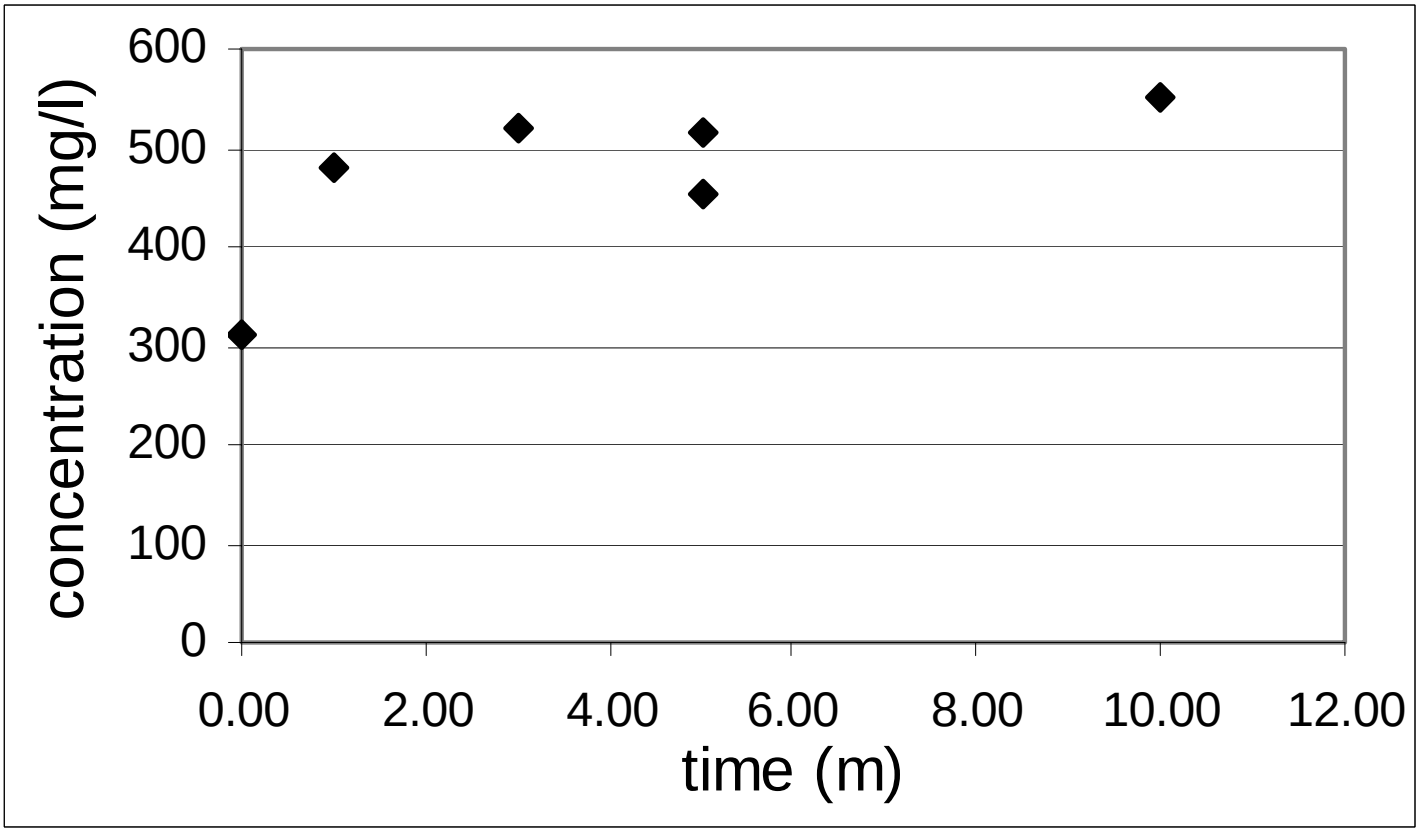


Figure B-26: Experiment 13, CERGRENE (one column) [36 cm, C/L, Microsand]

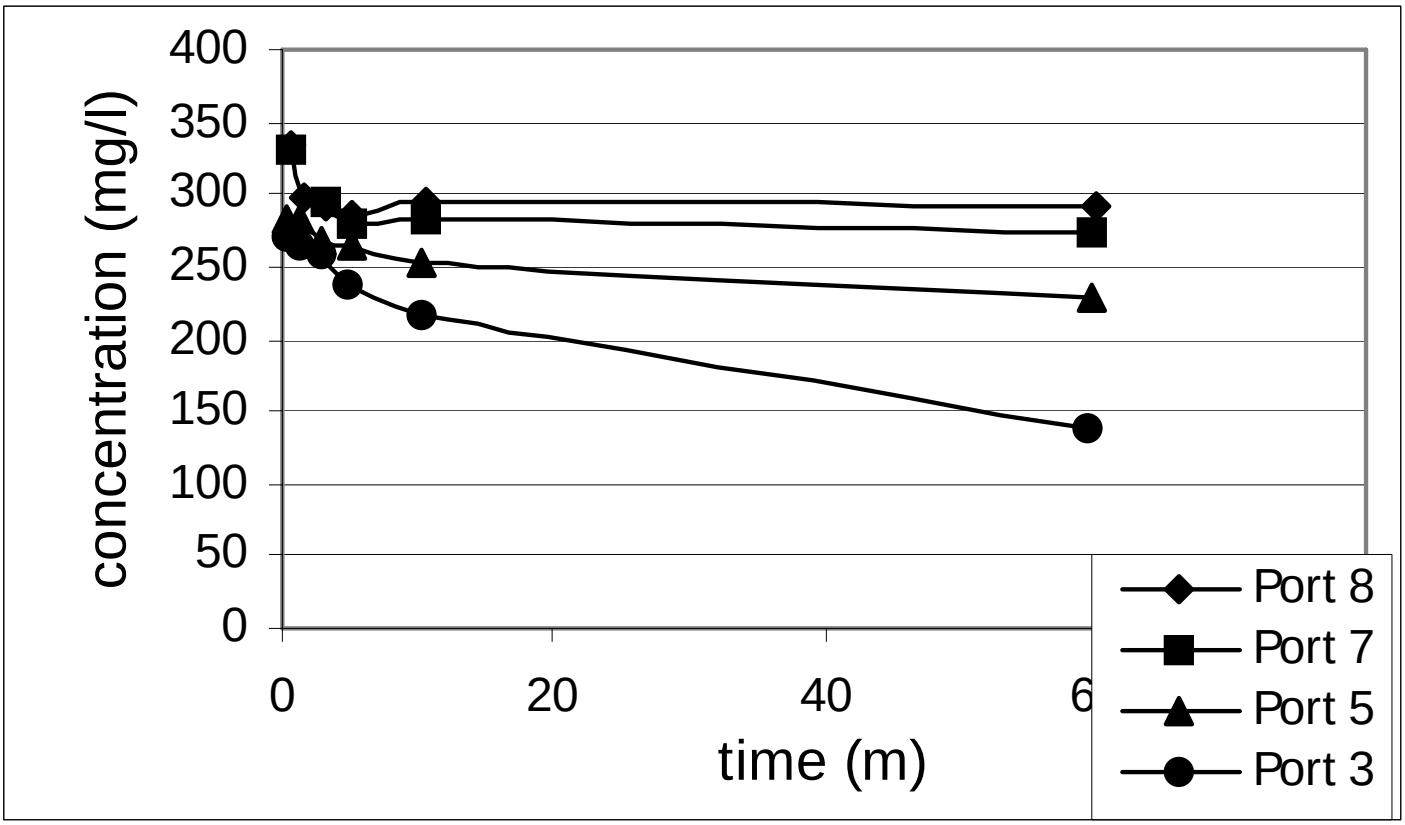


Figure B-27: Experiment 14, Long Column [18 cm, C/L, Neshaminy]

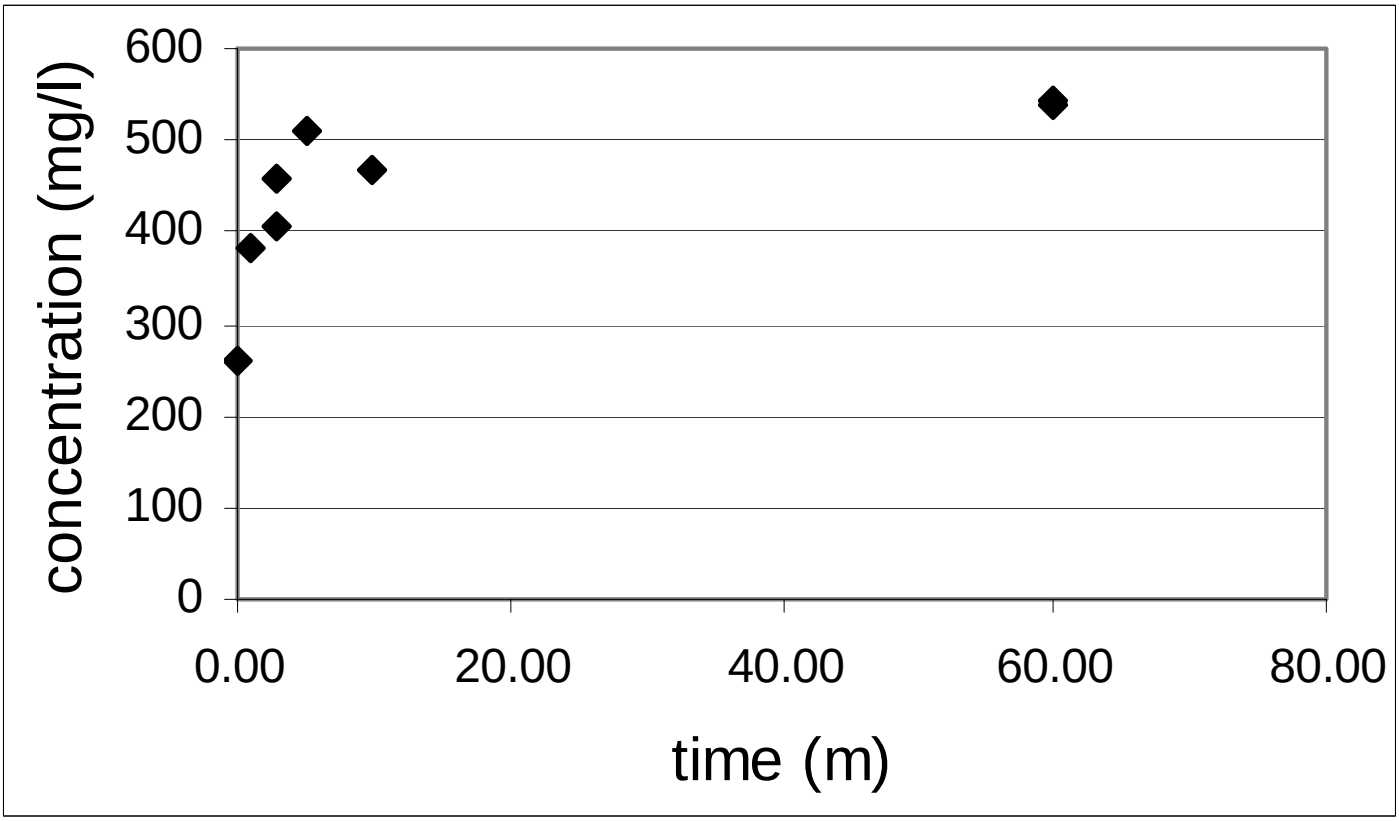


Figure B-28: Experiment 14, CERGRENE (one column) [18 cm, C/L, Neshaminy]

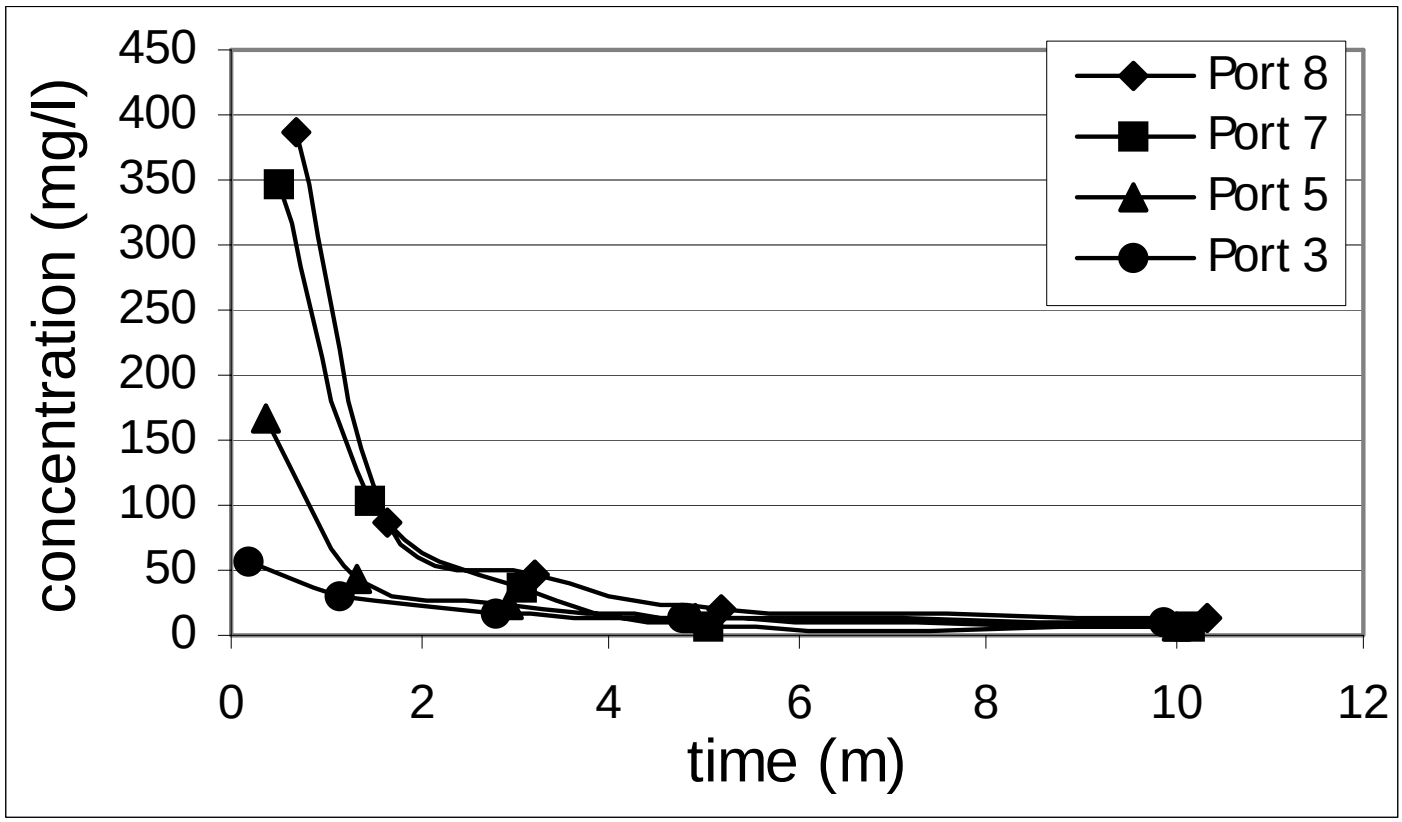


Figure B-29: Experiment 15, Long Column [36 cm, L/C, Microsand]

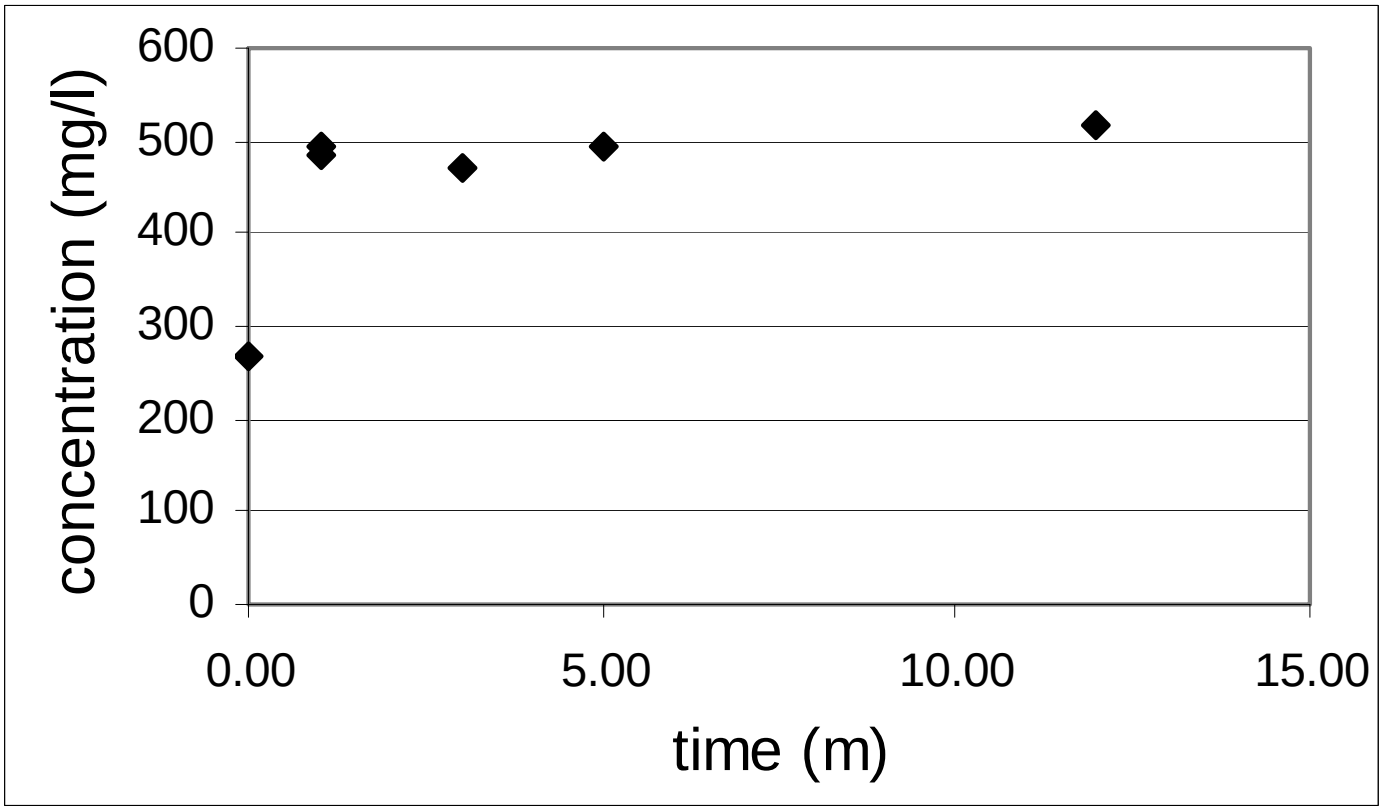


Figure B-30: Experiment 15, CERGRENE (one column) [36 cm, L/C, Microsand]

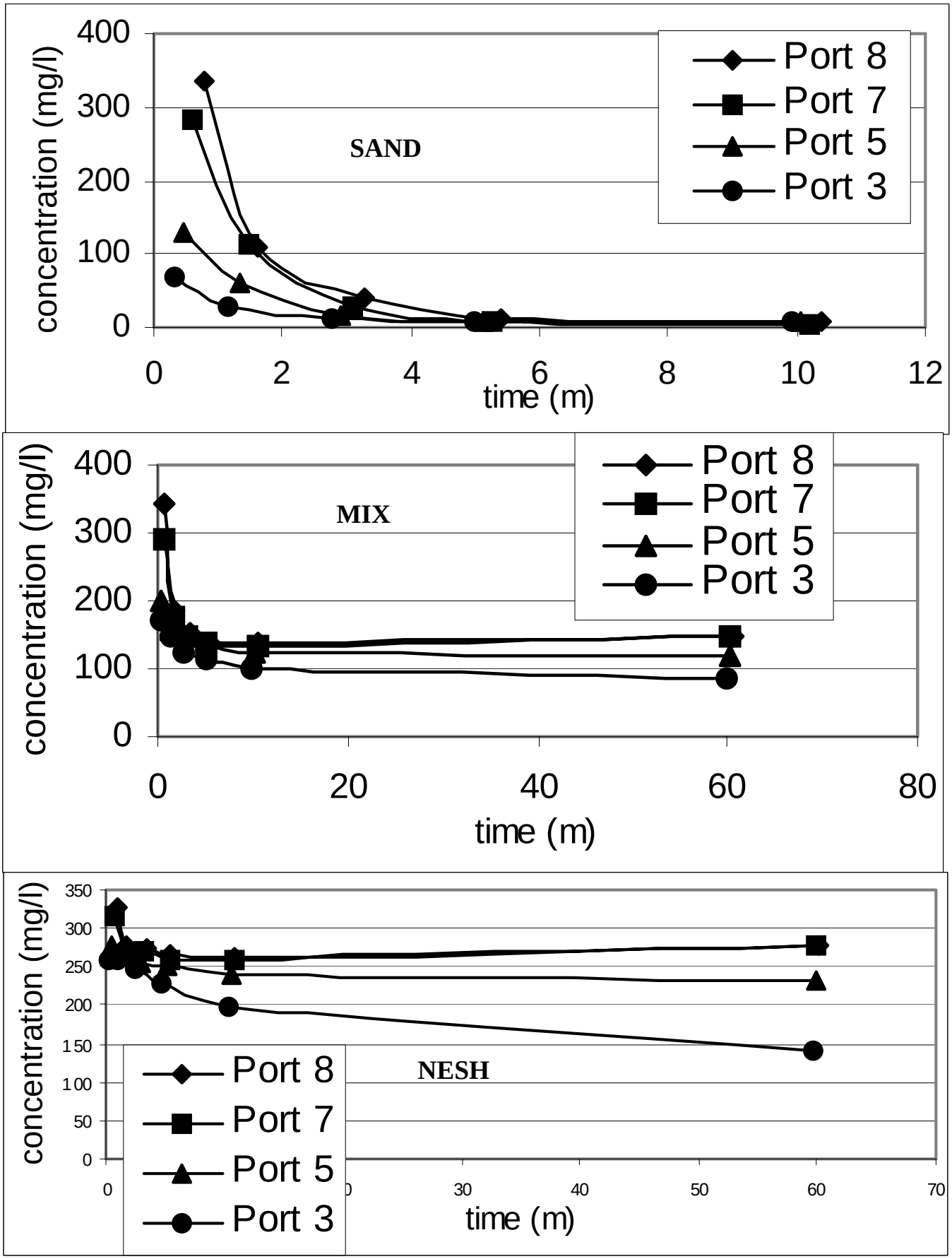


Figure B-31: Average of Long Column Concentrations by Soil Type

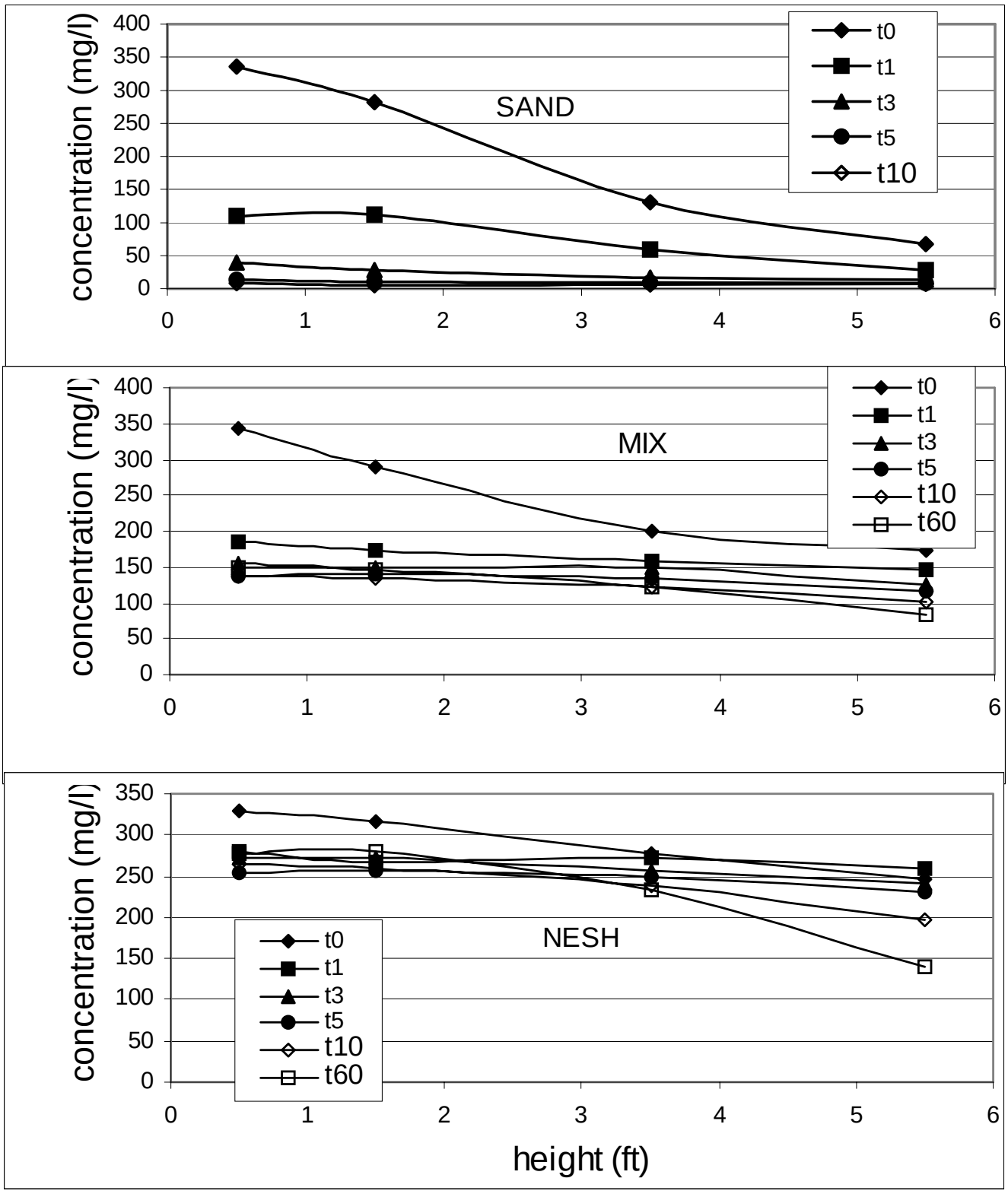


Figure B-32: Average Concentrations for Sand, Mix, and Neshaminy at Each Port and Time Interval

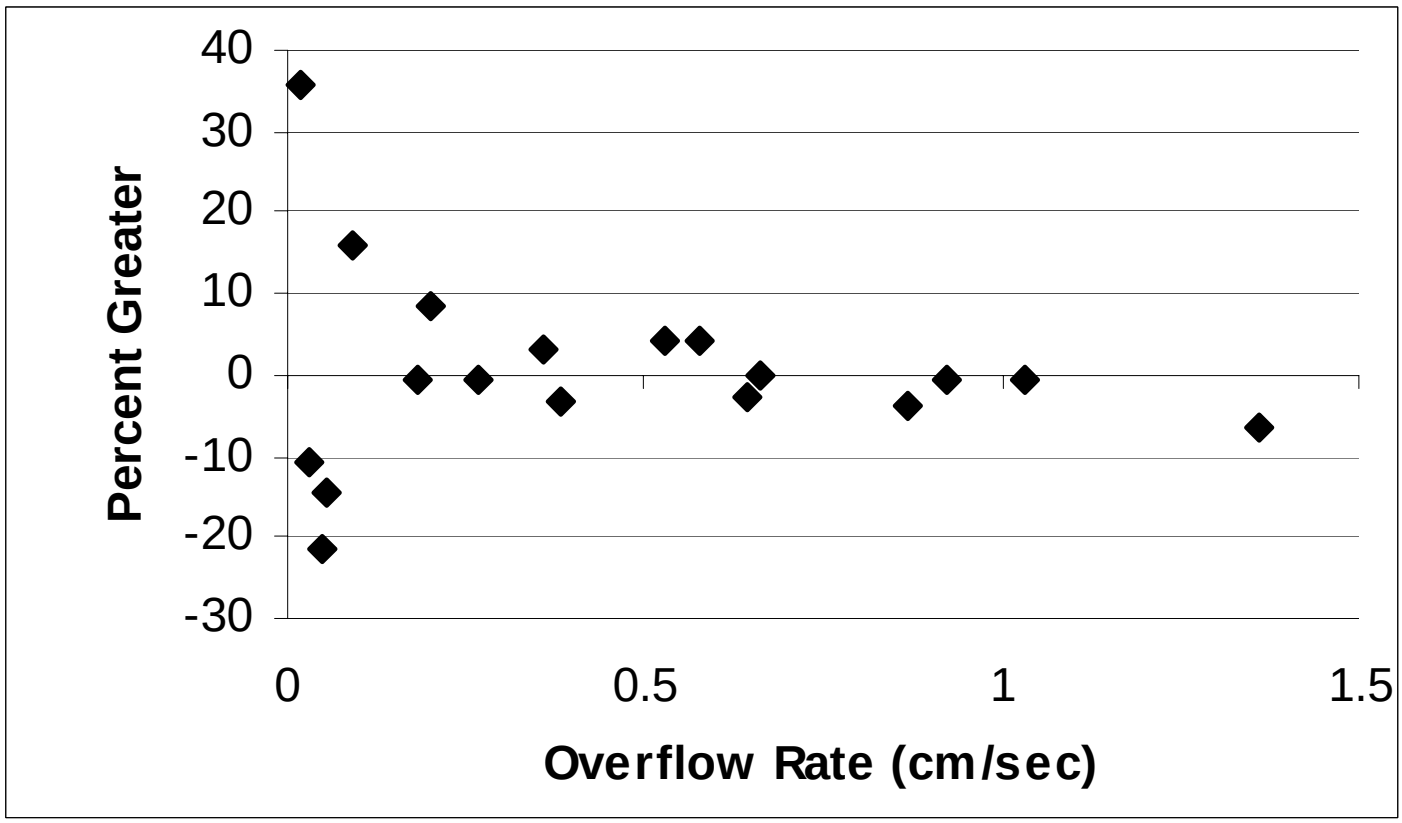


Figure C-1: Percent Removal versus Overflow Rate, Experiment 1, Long Column [36 cm, C/L, Neshaminy]

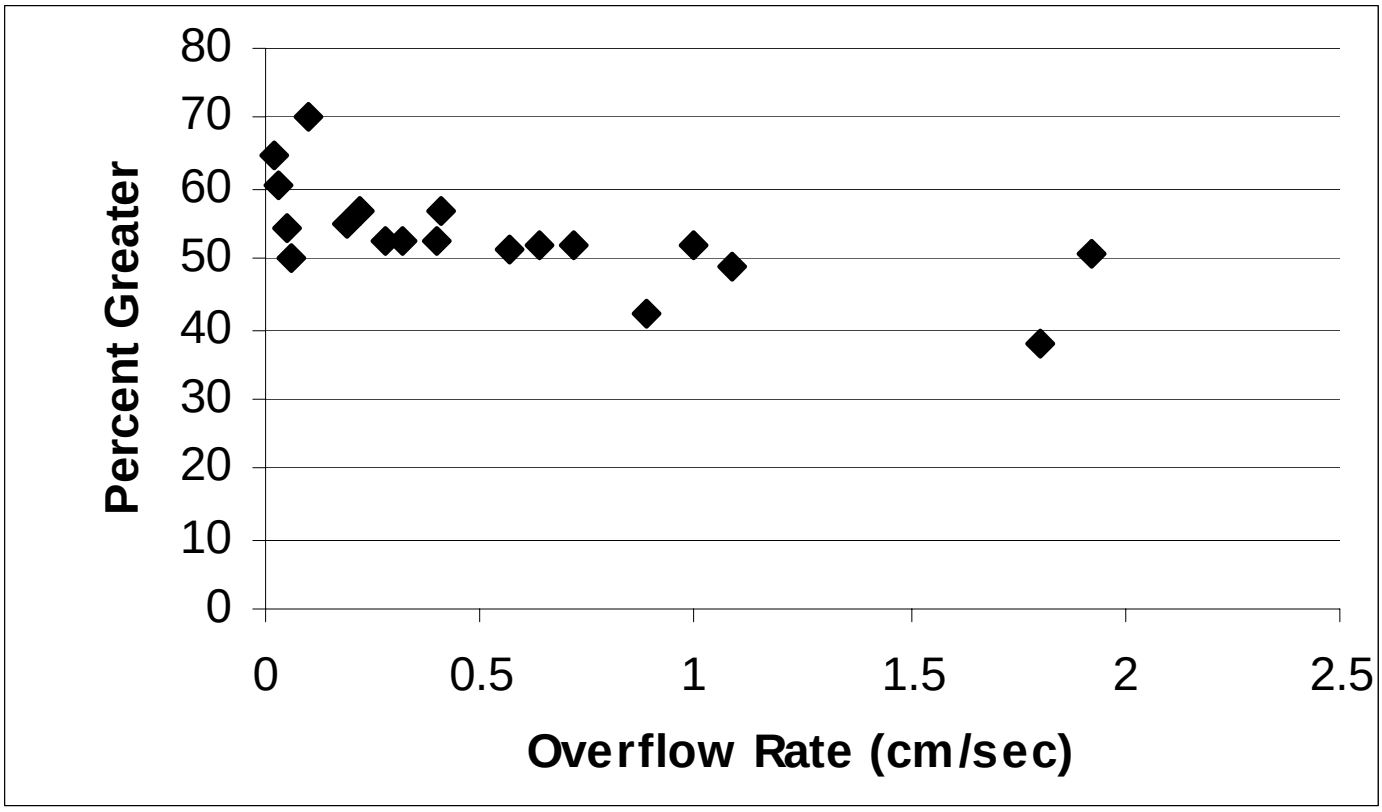


Figure C-2: Percent Removal versus Overflow Rate, Experiment 2, Long Column [36 cm, C/L, Mixture]

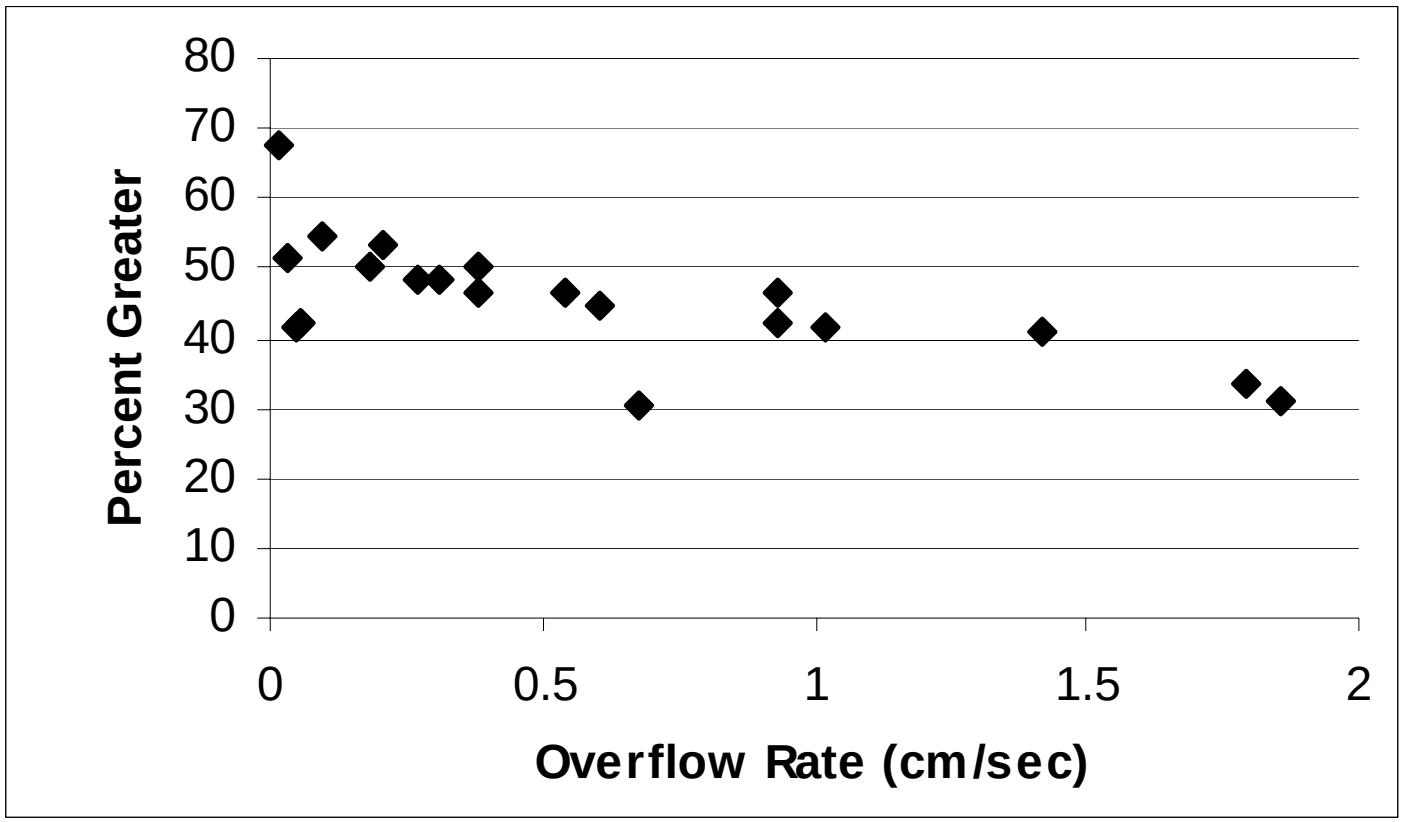


Figure C-3: Percent Removal versus Overflow Rate, Experiment 3, Long Column [18 cm, C/L, Mixture]

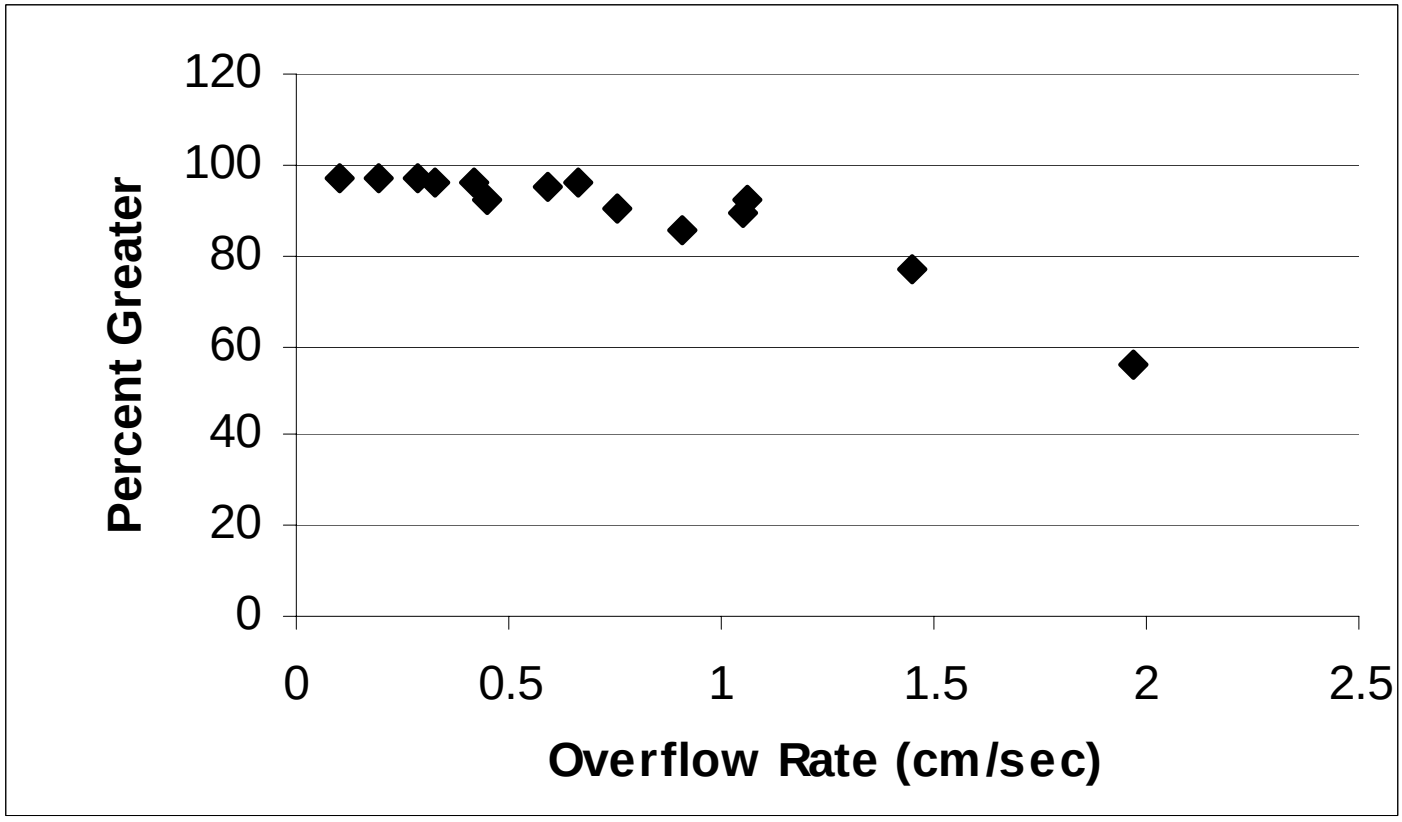


Figure C-4: Percent Removal versus Overflow Rate, Experiment 4, Long Column [18 cm, C/L, Microsand]

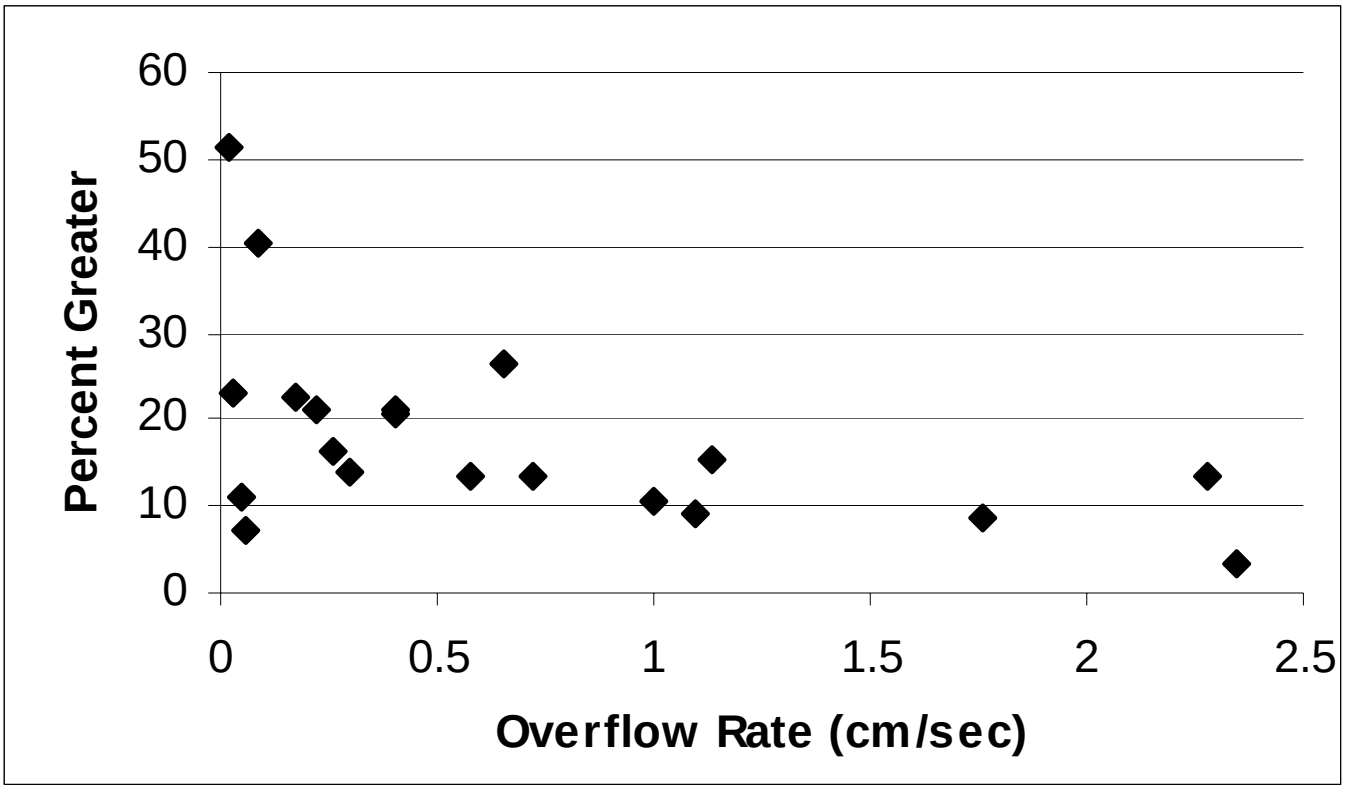


Figure C-5: Percent Removal versus Overflow Rate, Experiment 5, Long Column [18 cm, L/C, Neshaminy]

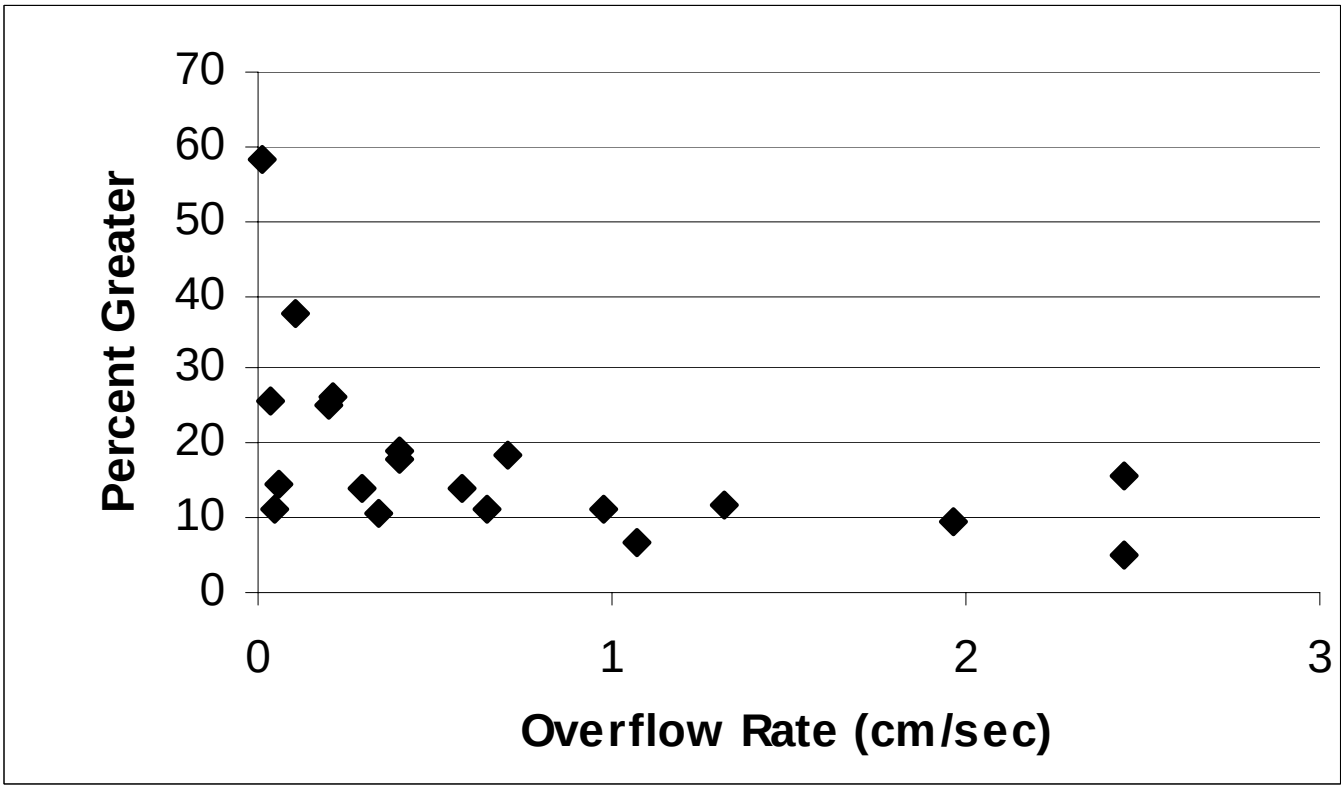


Figure C-6: Percent Removal versus Overflow Rate, Experiment 6, Long Column [36 cm, L/C, Neshaminy]

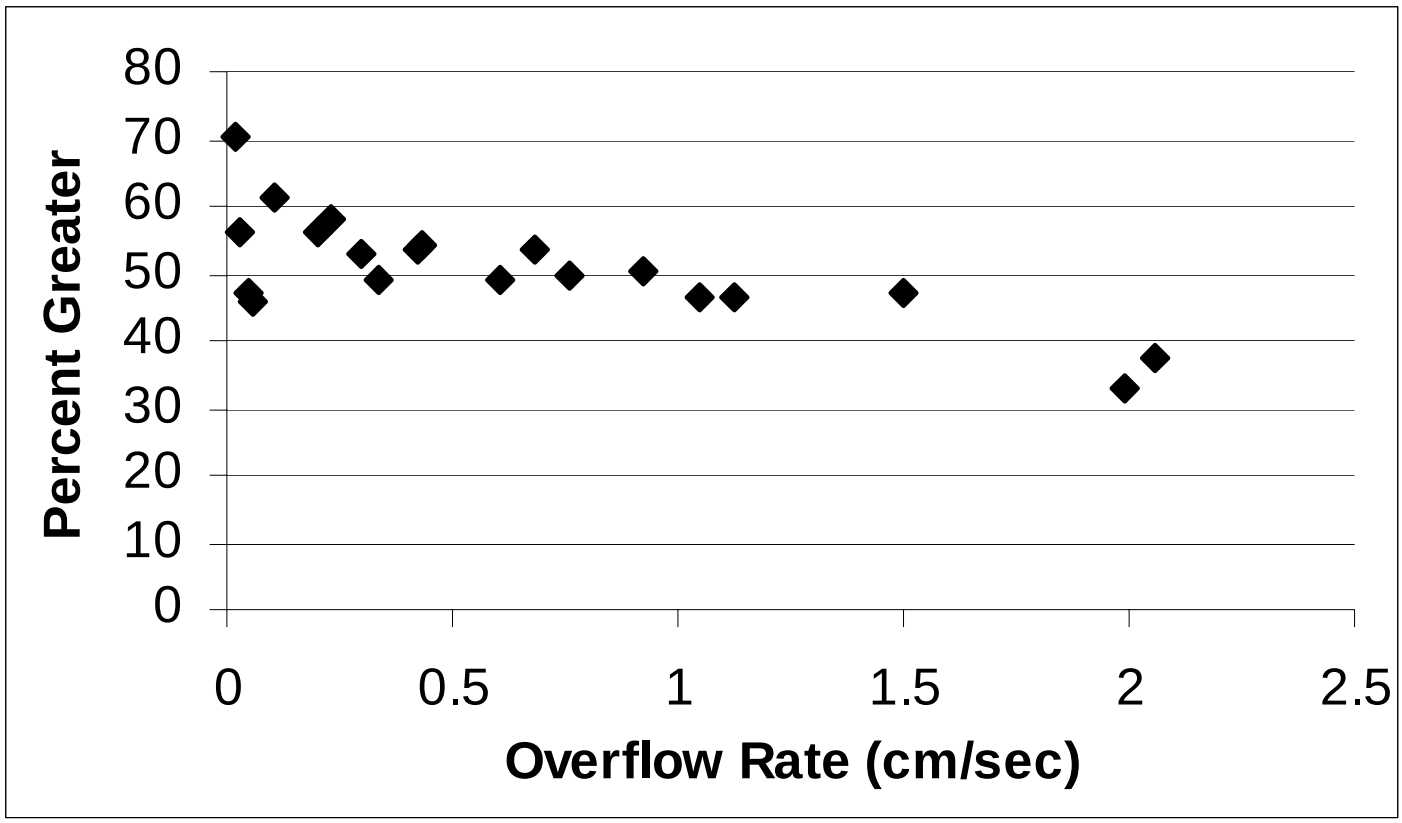


Figure C-7: Percent Removal versus Overflow Rate, Experiment 7, Long Column [18cm, C/L, Mixture]

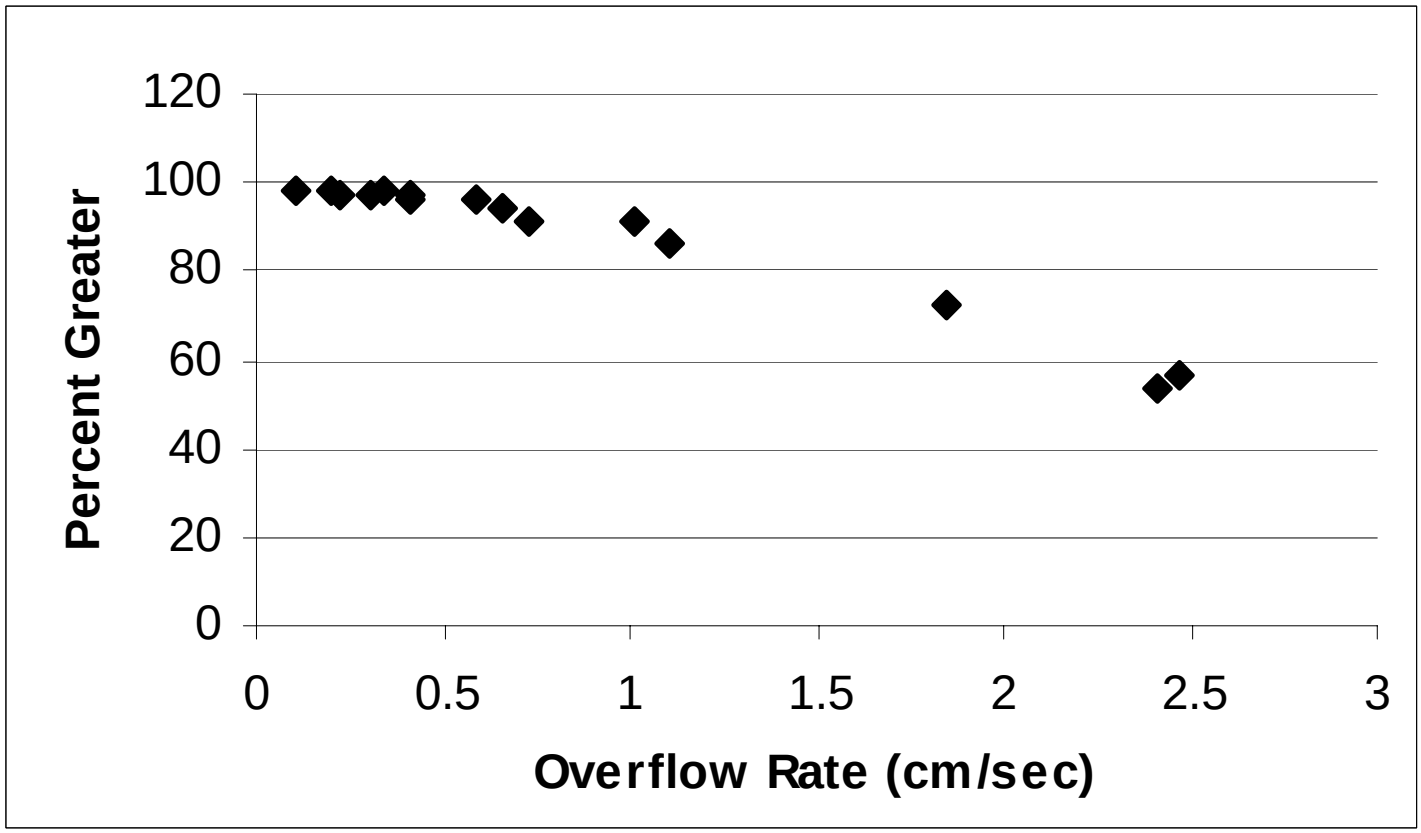


Figure C-8: Percent Removal versus Overflow Rate, Experiment 8, Long Column [18 cm, L/C, Microsand]

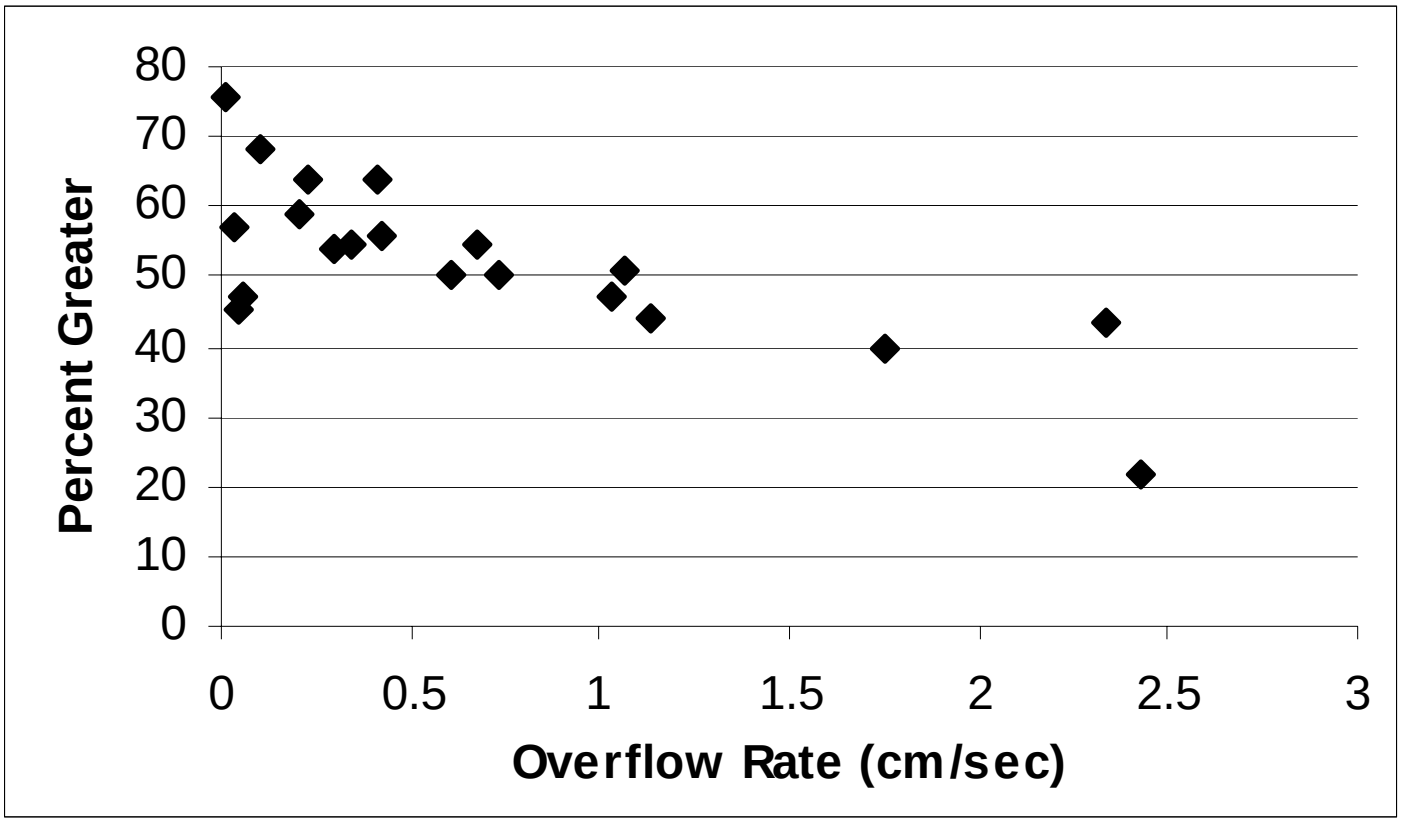


Figure C-9: Percent Removal versus Overflow Rate, Experiment 9, Long Column [18 cm, L/C, Mixture]

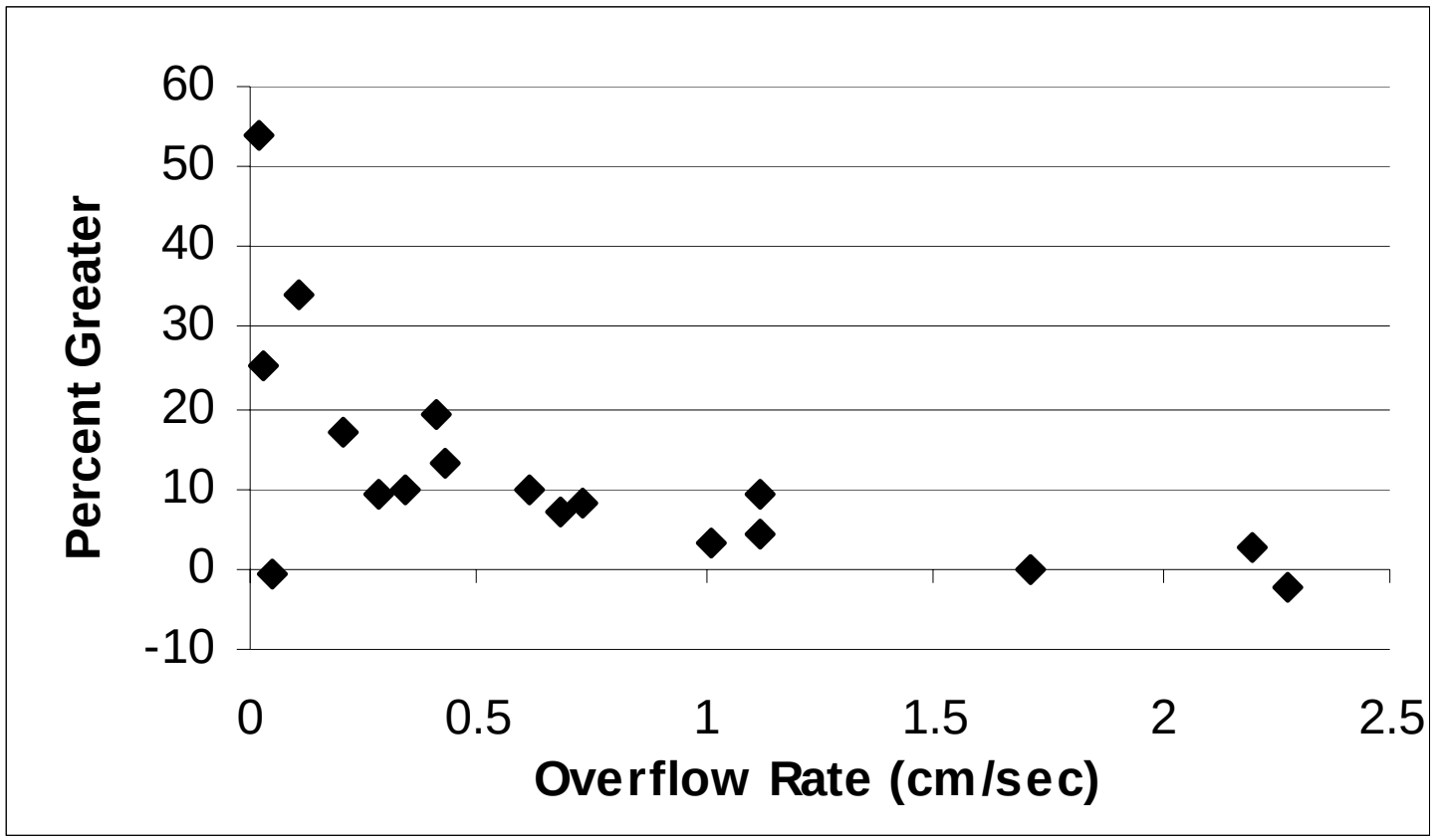


Figure C-10: Percent Removal versus Overflow Rate, Experiment 10, Long Column [36 cm, L/C, Neshaminy]

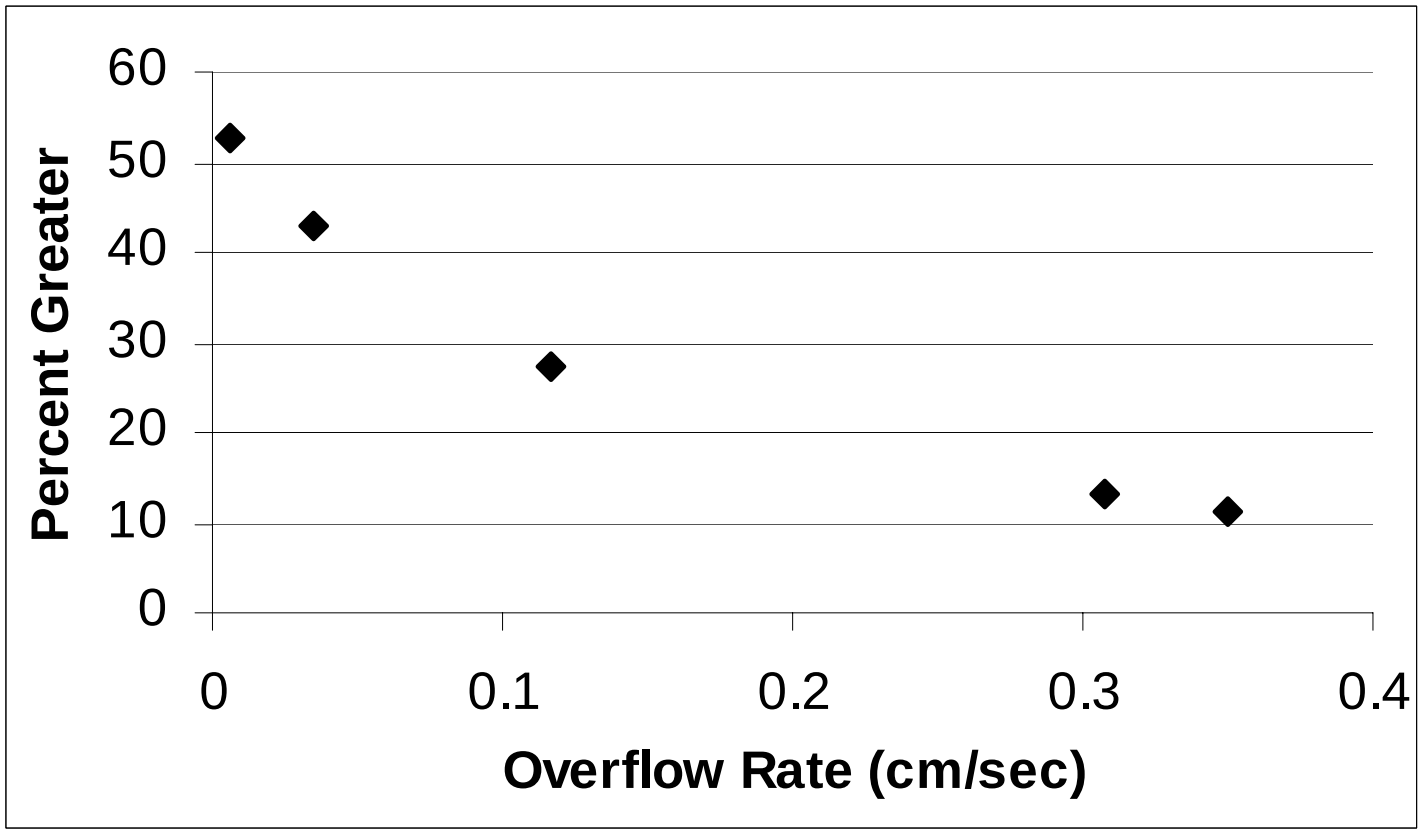


Figure C-11: Percent Removal versus Overflow Rate, Experiment 10, CERGRENE Column [36 cm, L/C, Neshaminy]

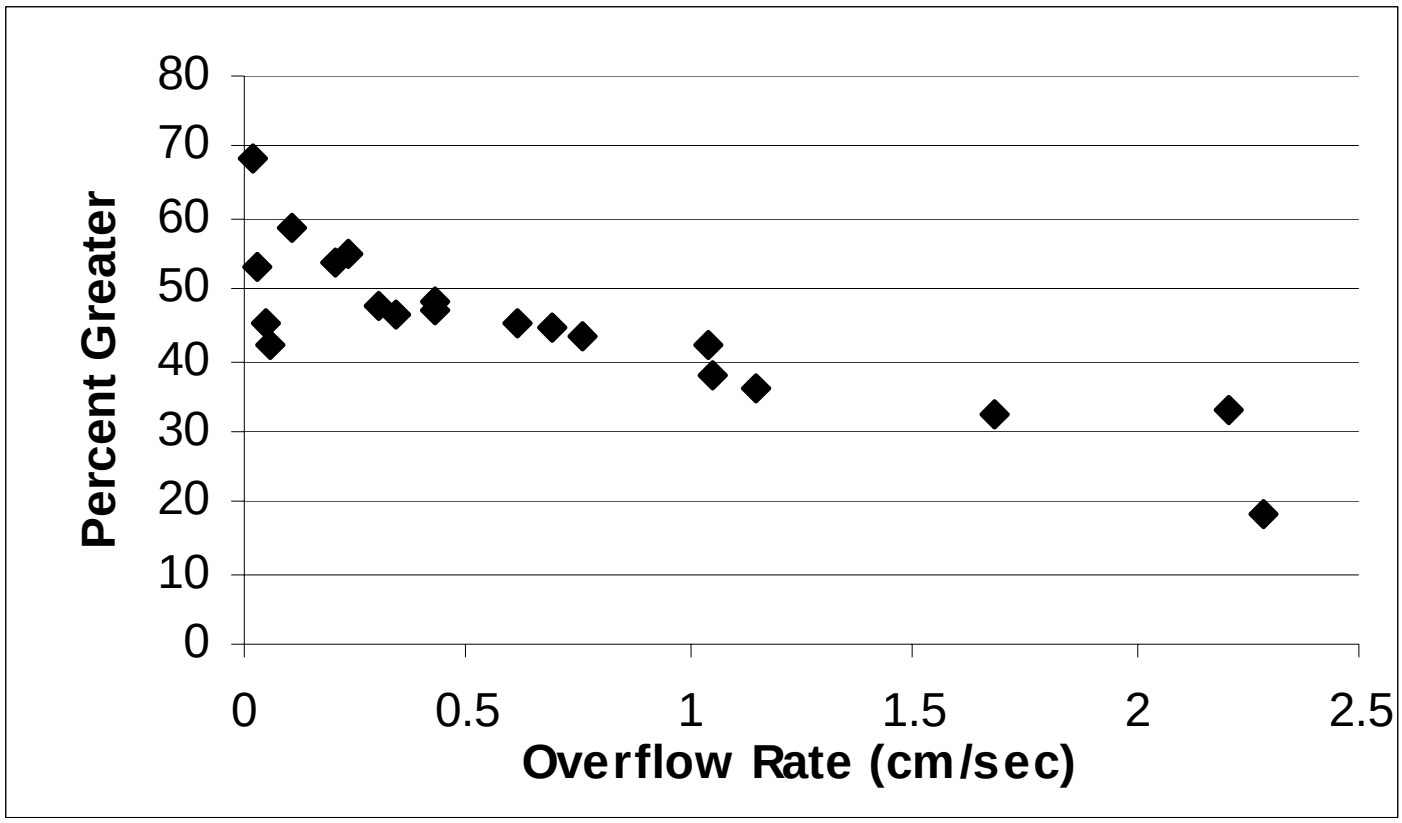


Figure C-12: Percent Removal versus Overflow Rate, Experiment 11, Long Column [36 cm, L/C, Mixture]

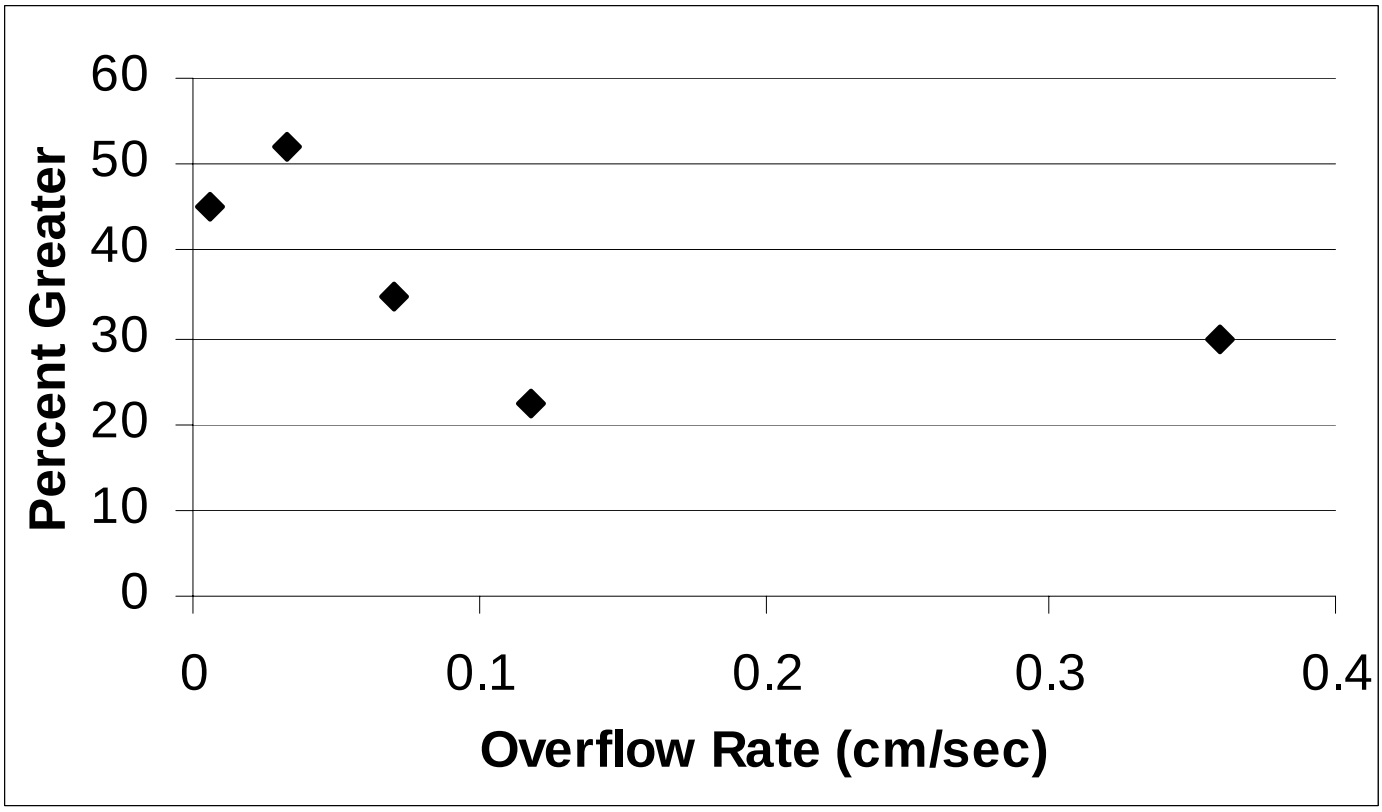


Figure C-13: Percent Removal versus Overflow Rate, Experiment 11, CERGRENE Column [36 cm, L/C, Mixture]

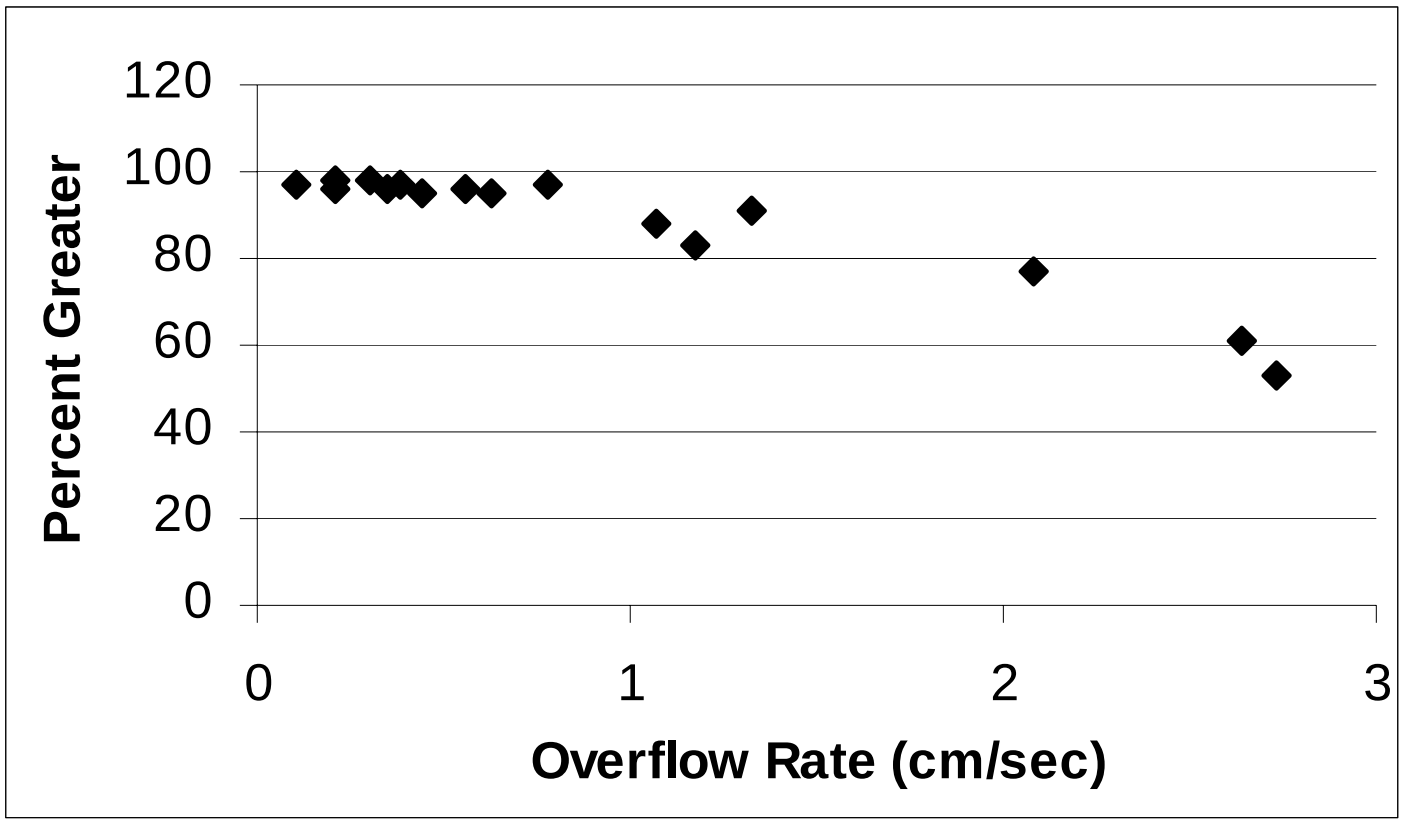


Figure C-14: Percent Removal versus Overflow Rate, Experiment 12, Long Column [18 cm, L/C, Microsand]

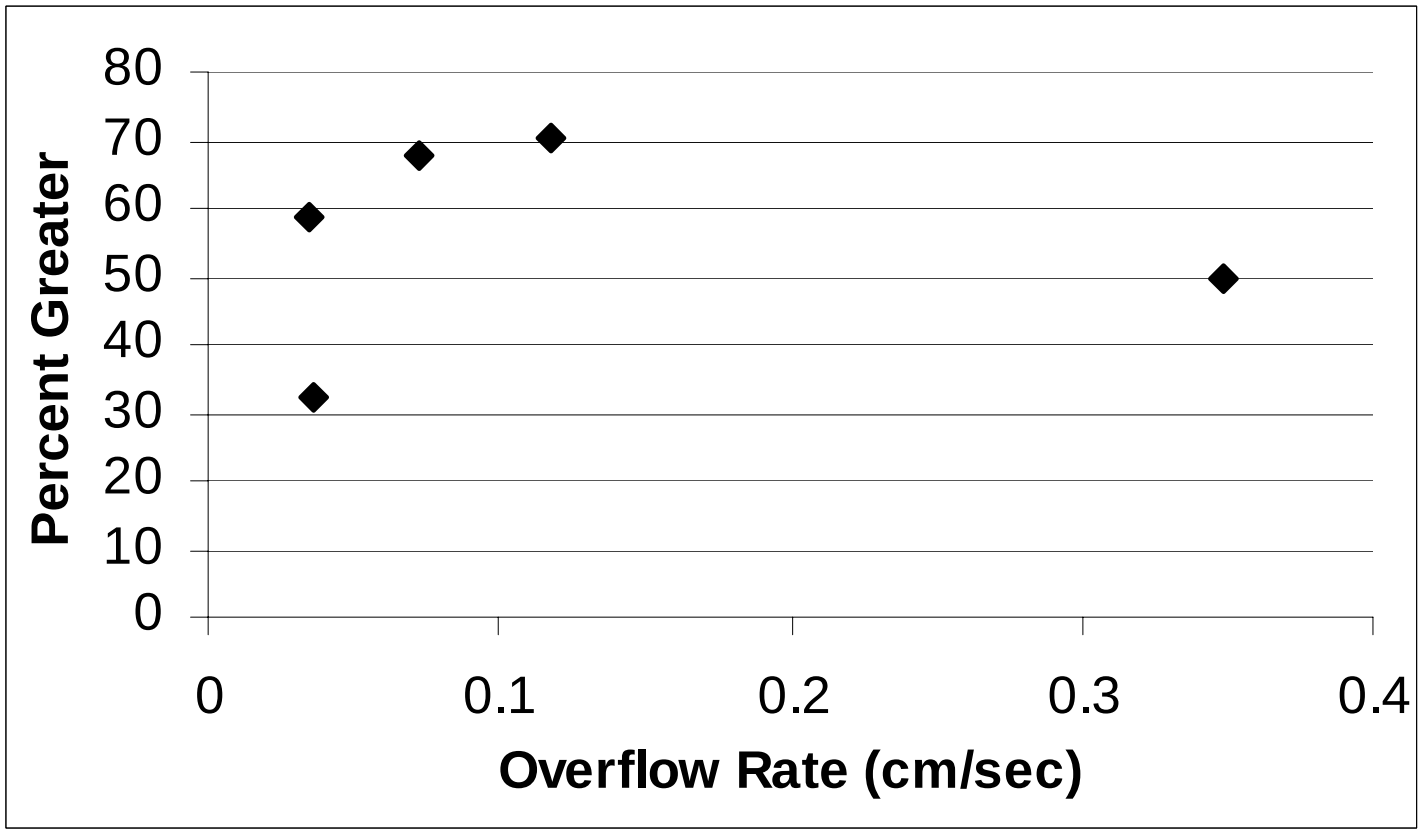


Figure C-15: Percent Removal versus Overflow Rate, Experiment 12, CERGRENE Column [18 cm, L/C, Microsand]

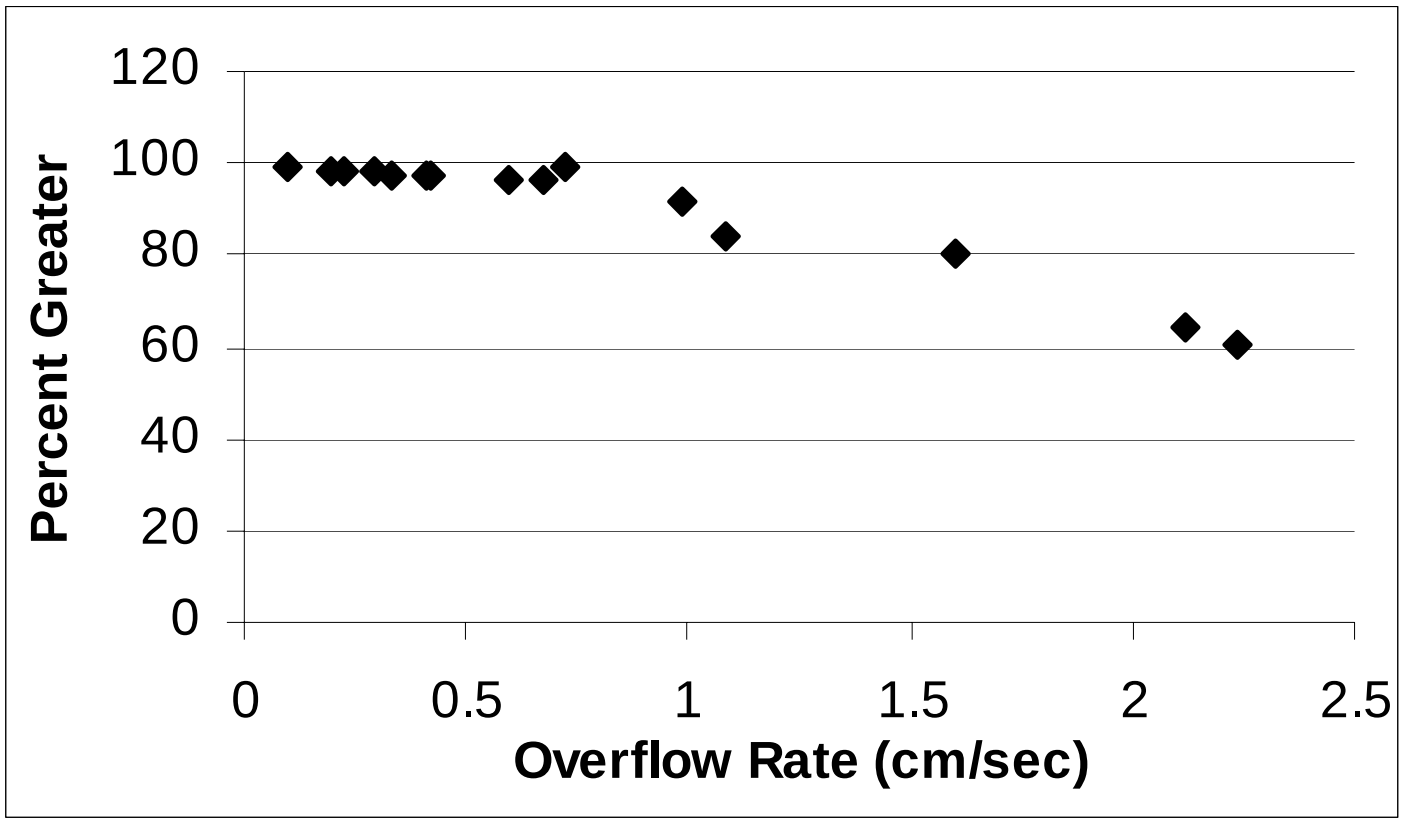


Figure C-16: Percent Removal versus Overflow Rate, Experiment 13, Long Column [36 cm, C/L, Microsand]

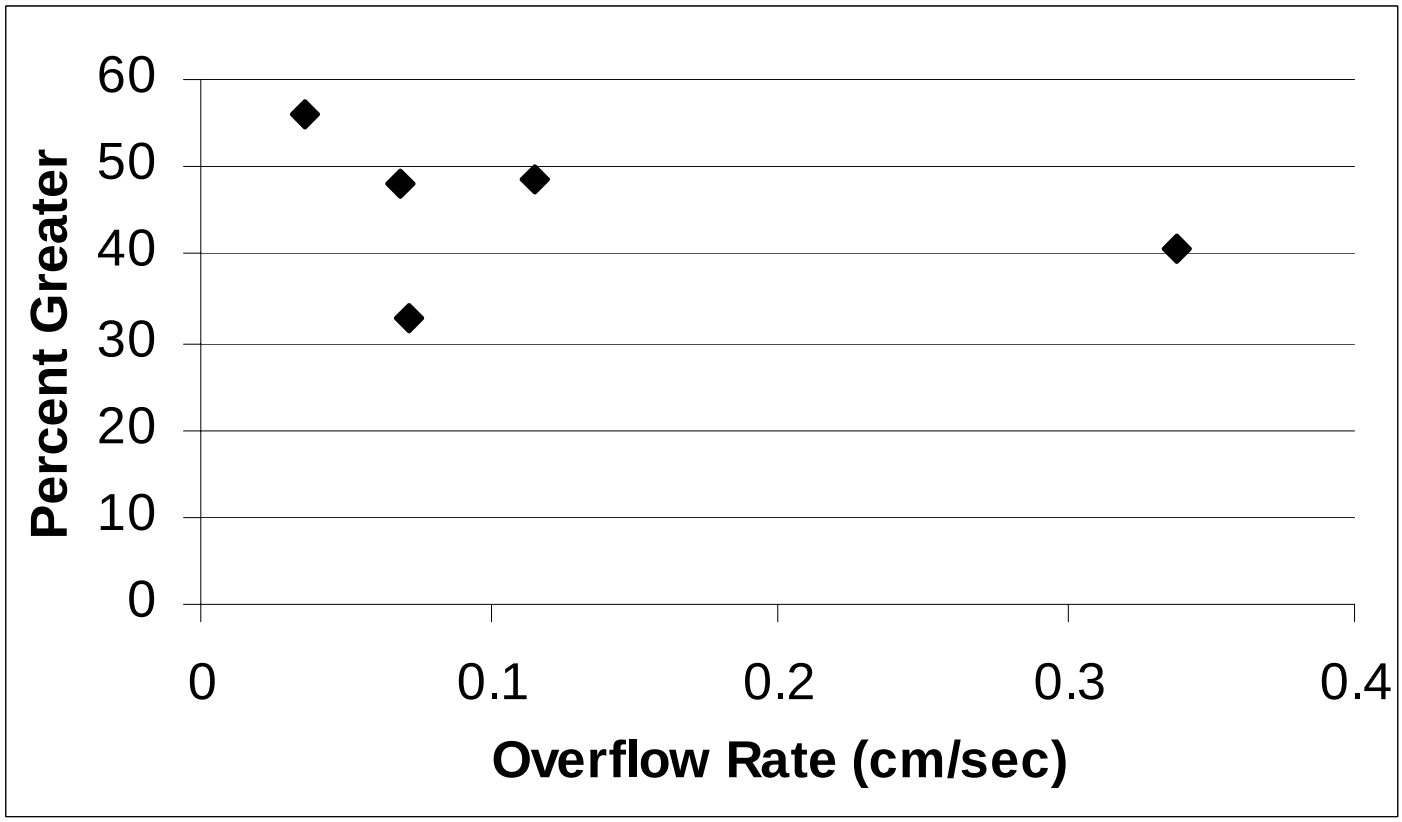


Figure C-17: Percent Removal versus Overflow Rate, Experiment 13, CERGRENE Column [36 cm, C/L, Microsand]

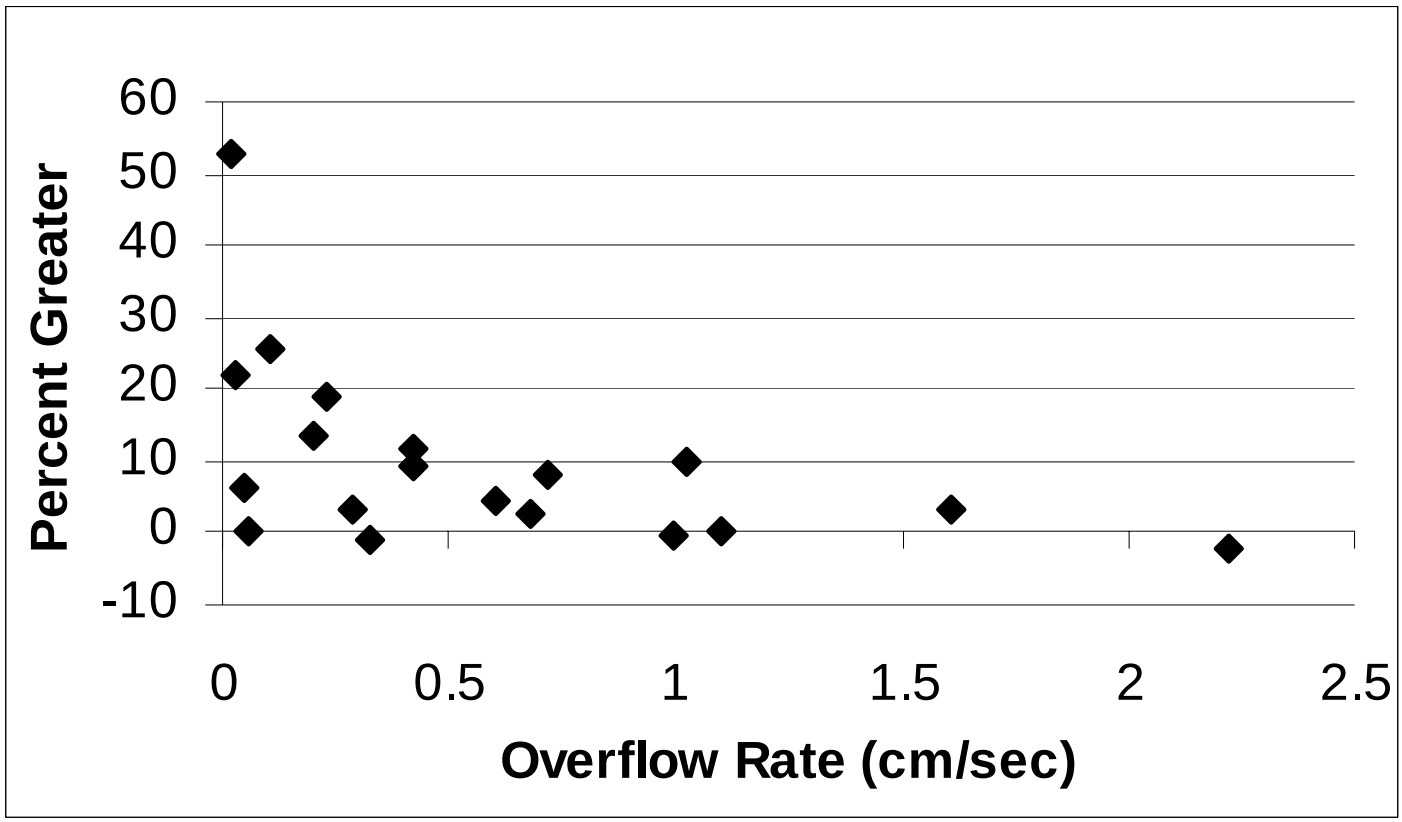


Figure C-18: Percent Removal versus Overflow Rate, Experiment 14, Long Column [18 cm, C/L, Neshaminy]

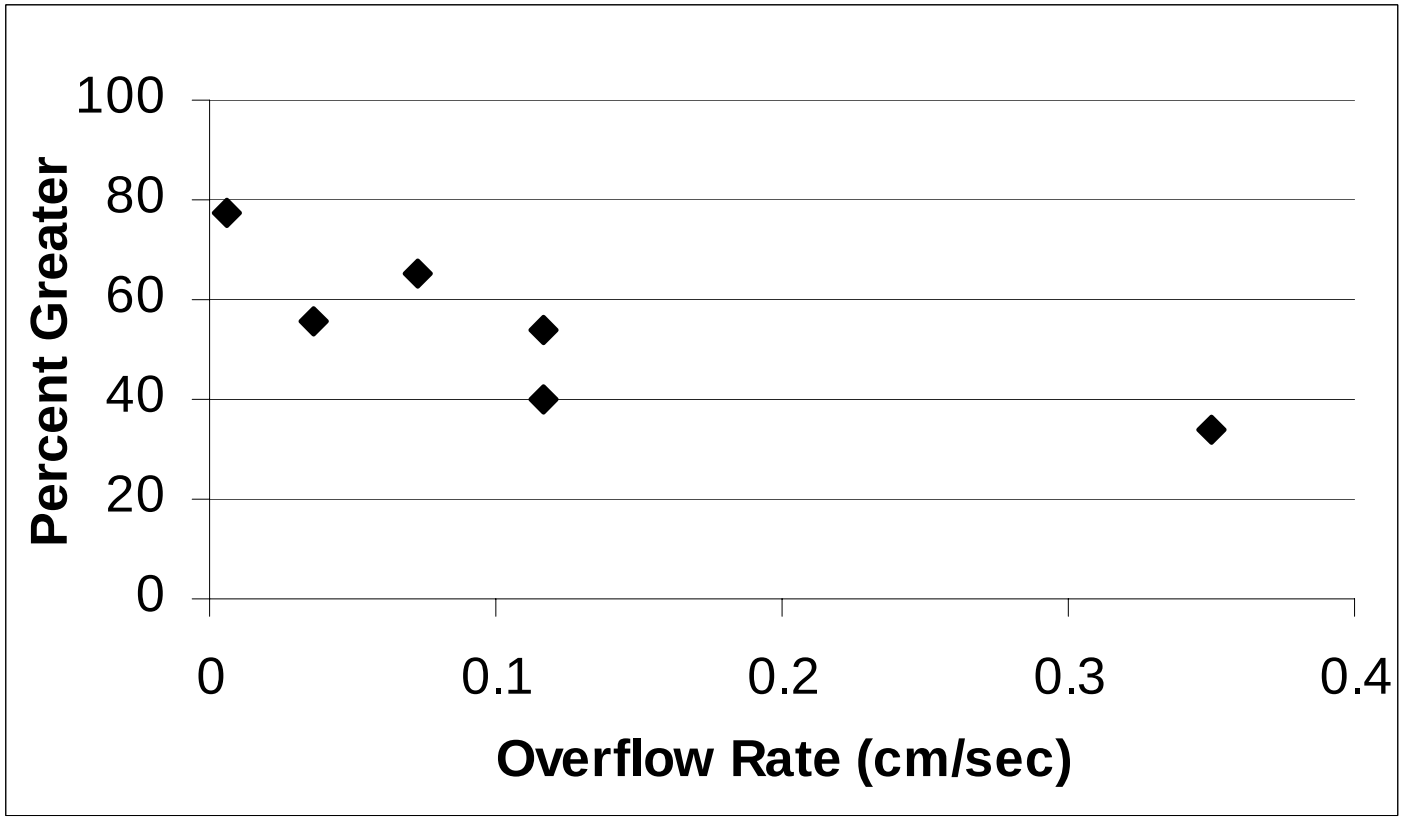


Figure C-19: Percent Removal versus Overflow Rate, Experiment 14, CERGRENE Column [18 cm, C/L, Neshaminy]

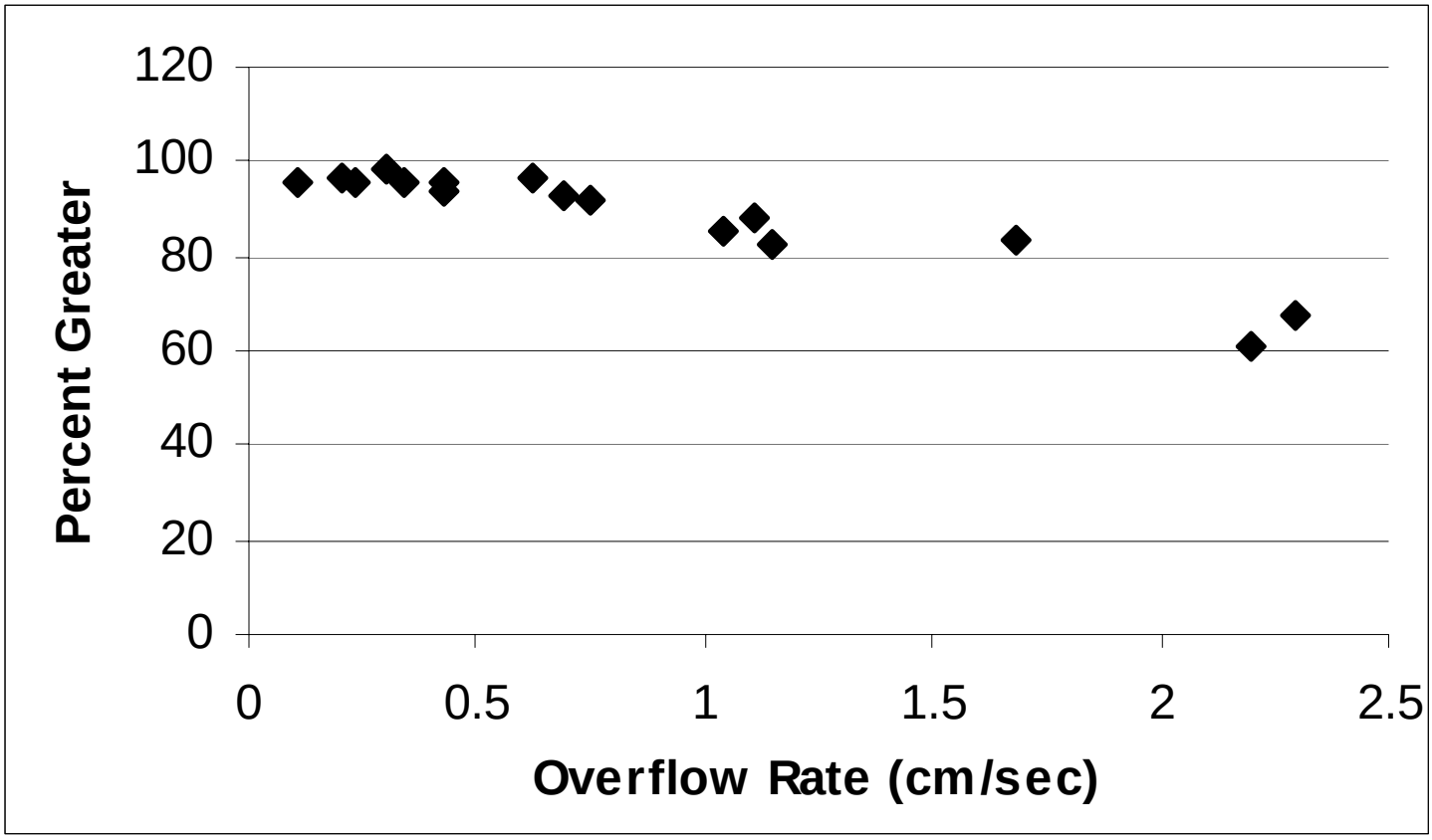


Figure C-20: Percent Removal versus Overflow Rate, Experiment 15, Long Column [36cm, L/C, Microsand]

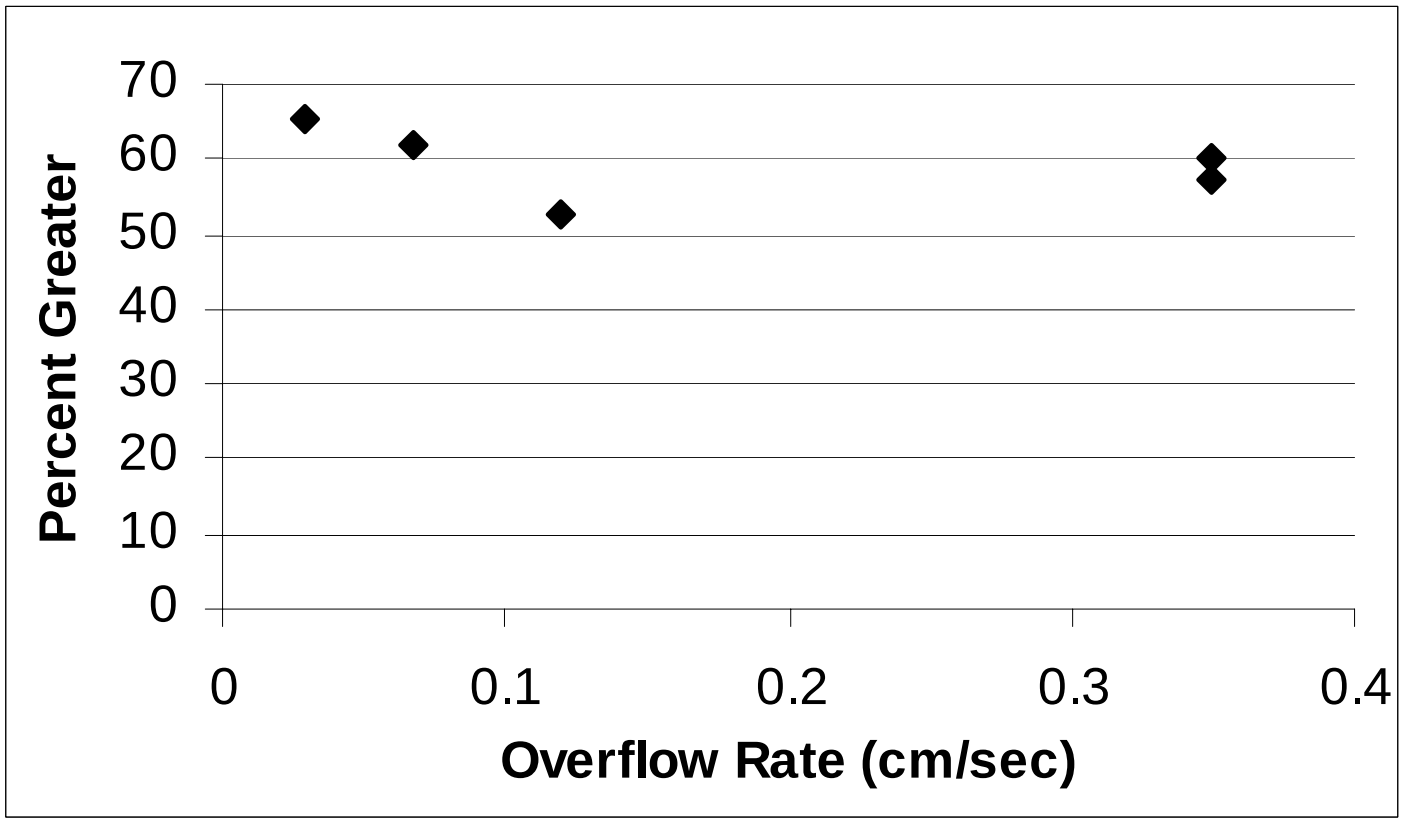


Figure C-21: Percent Removal versus Overflow Rate, Experiment 15, CERGRENE Column [36cm, L/C, Microsand]

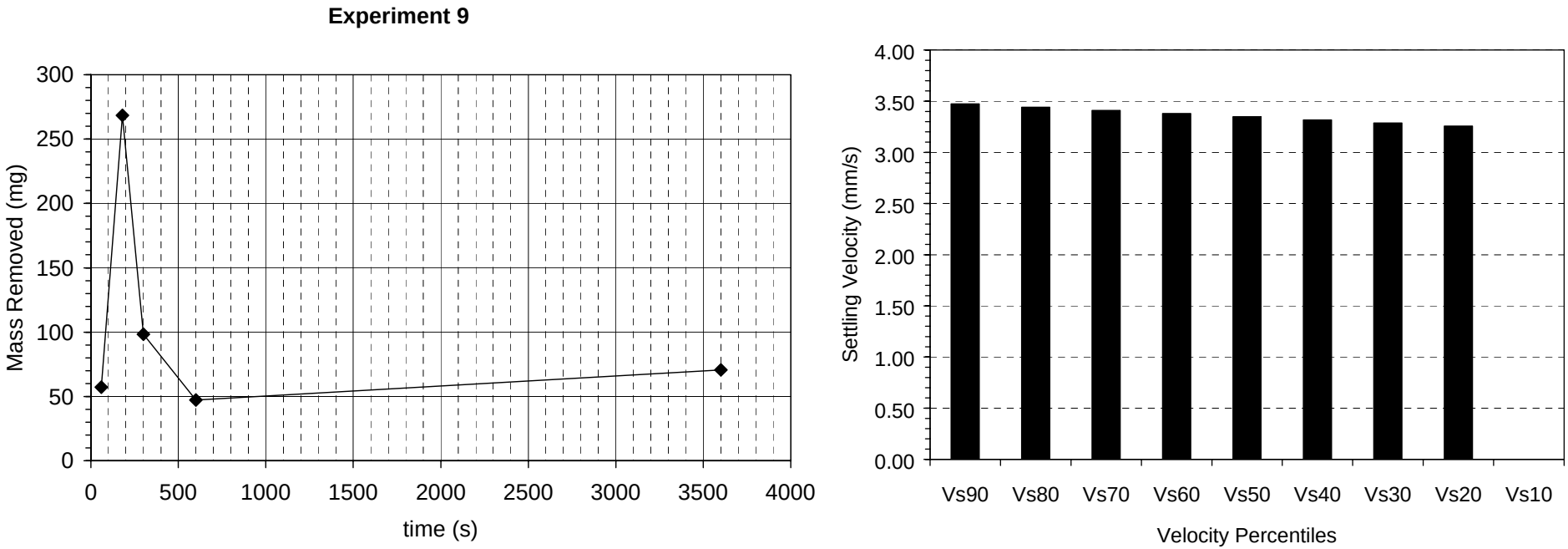


Figure D-1

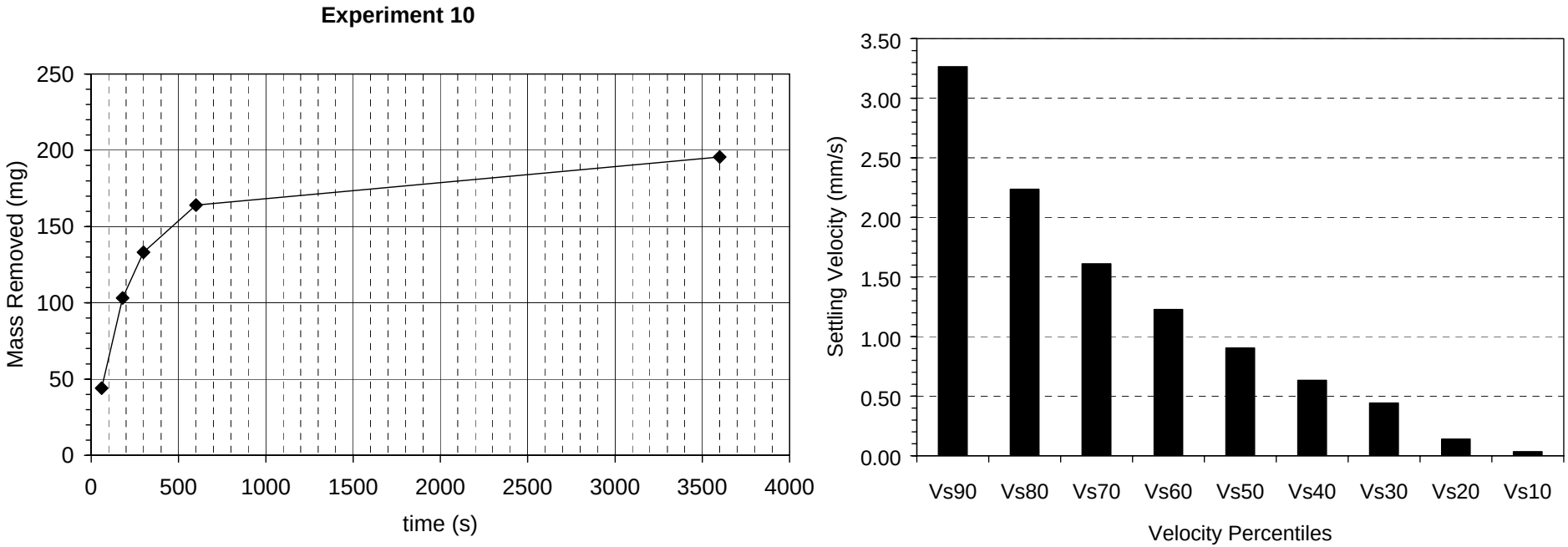
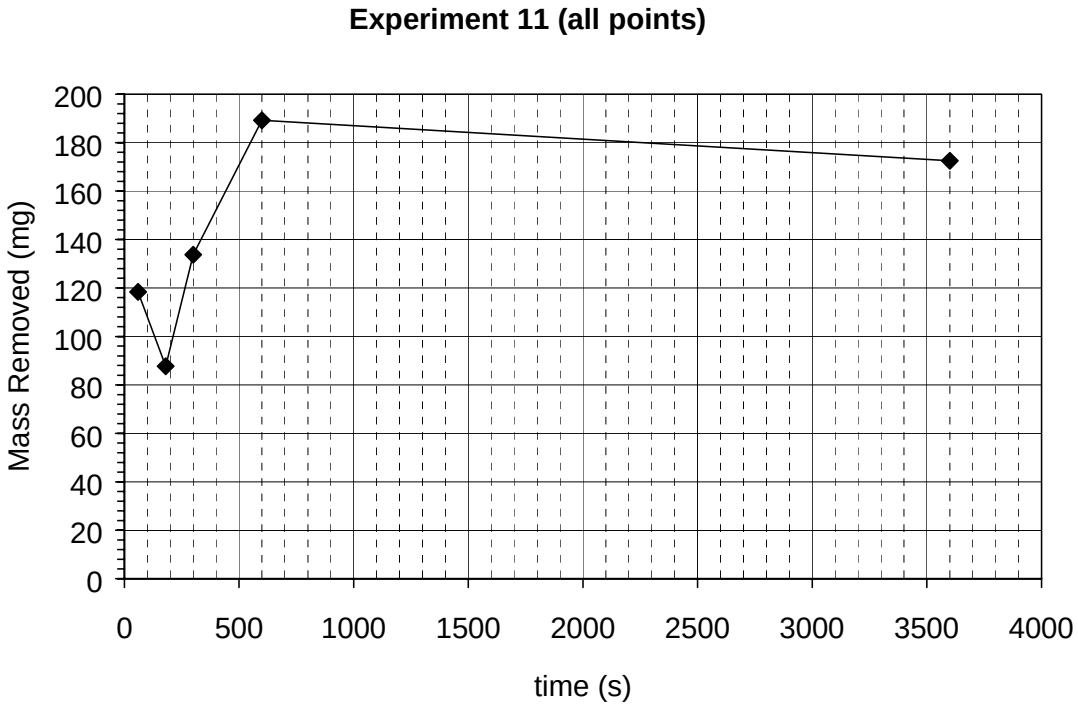


Figure D-2



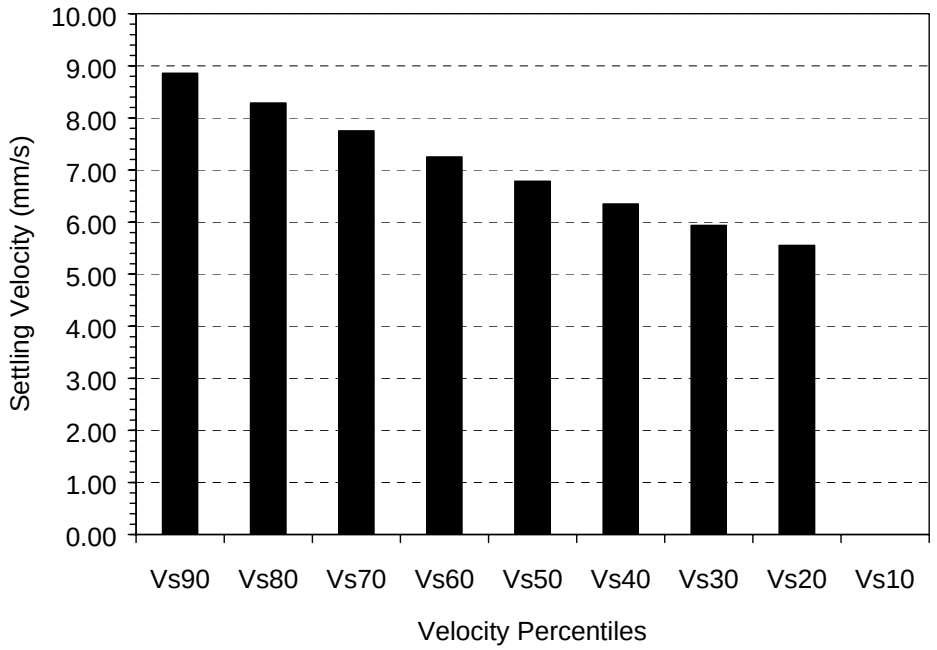
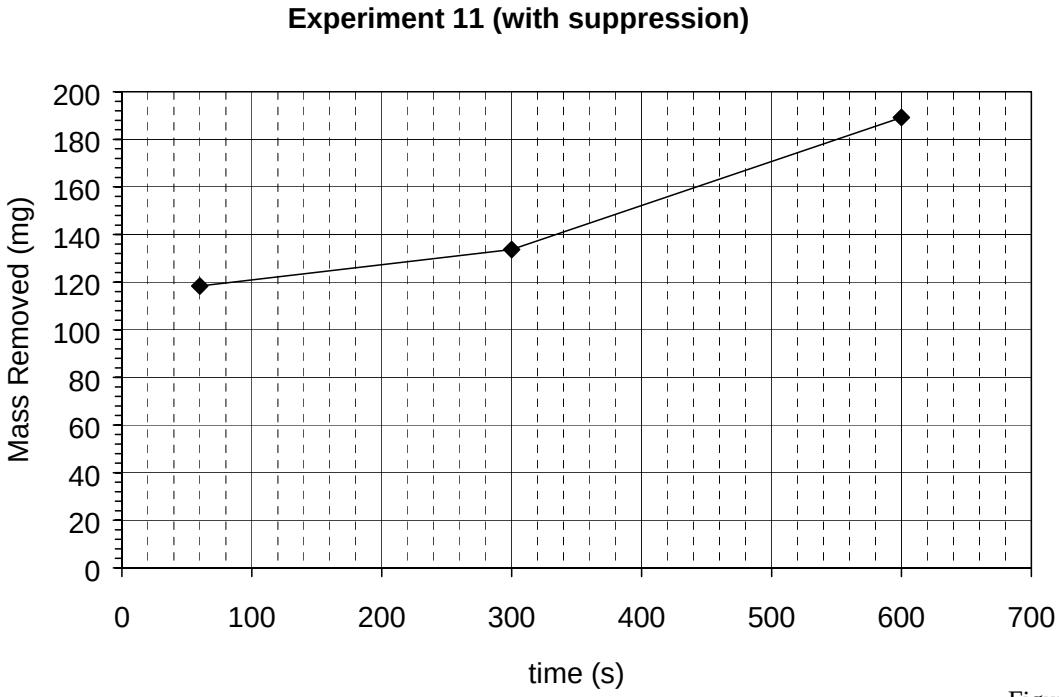


Figure D-3



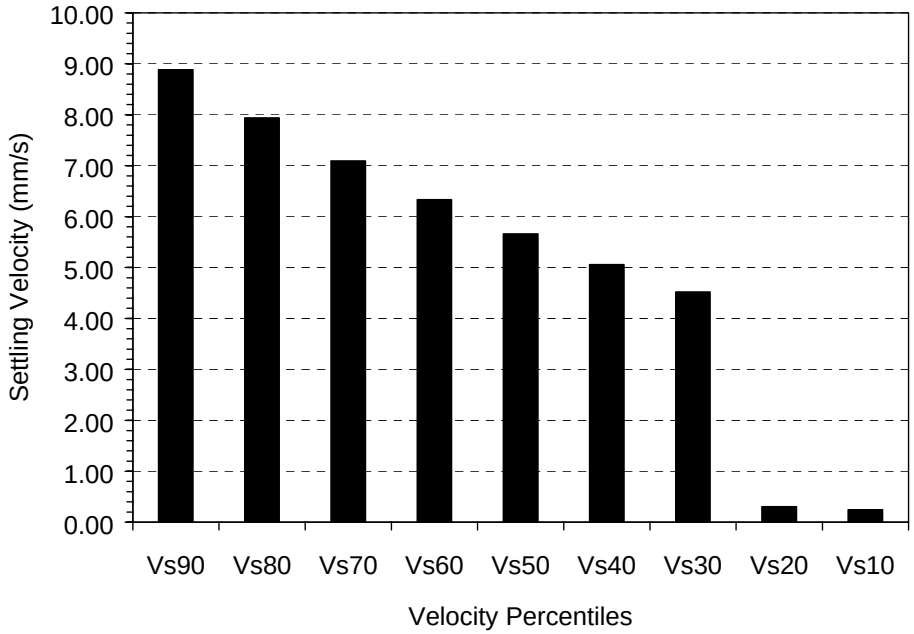


Figure D-4

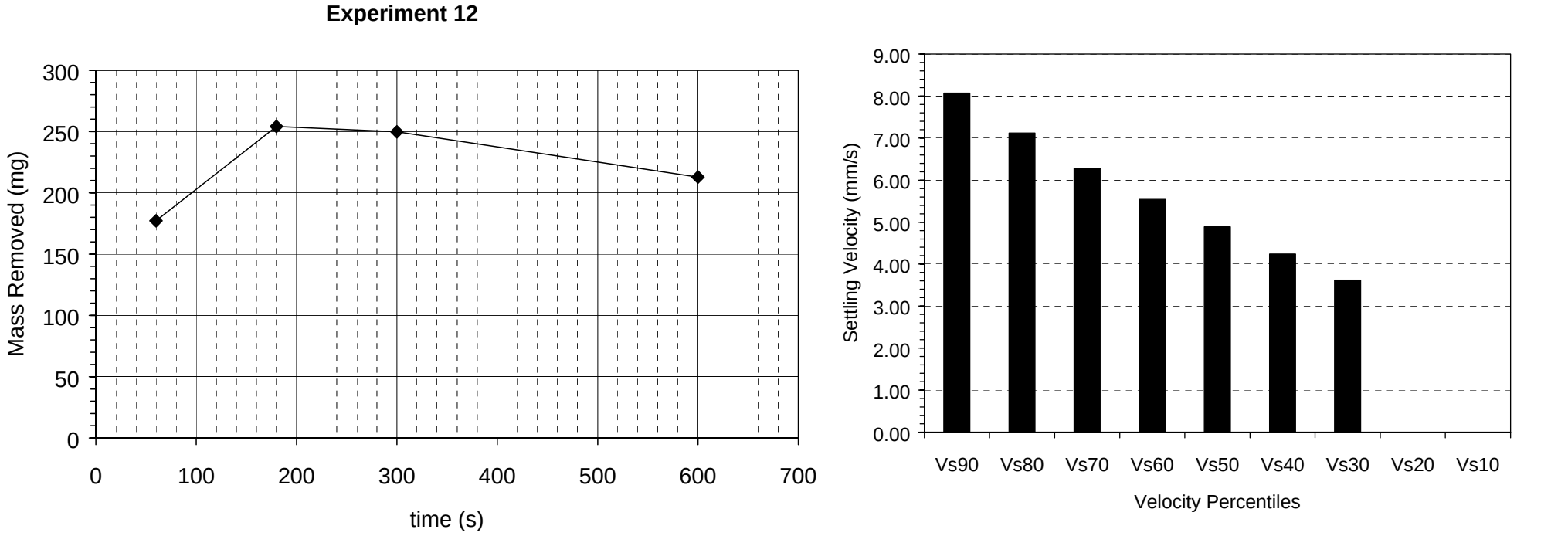


Figure D-5

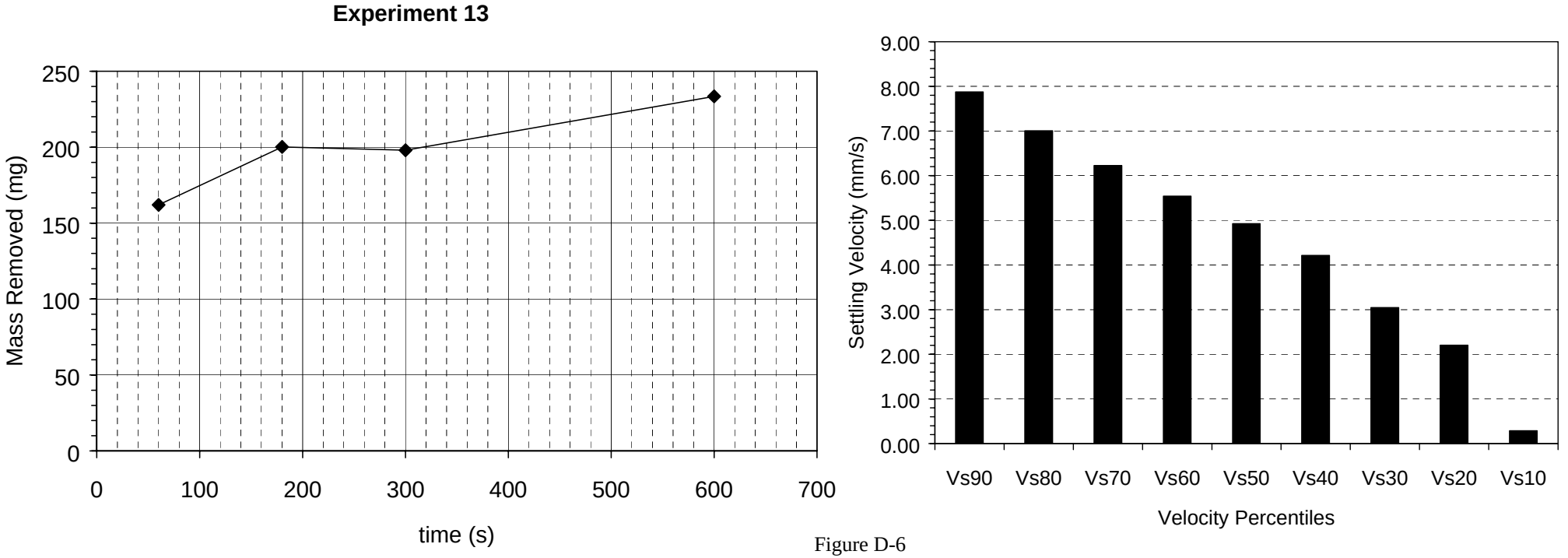
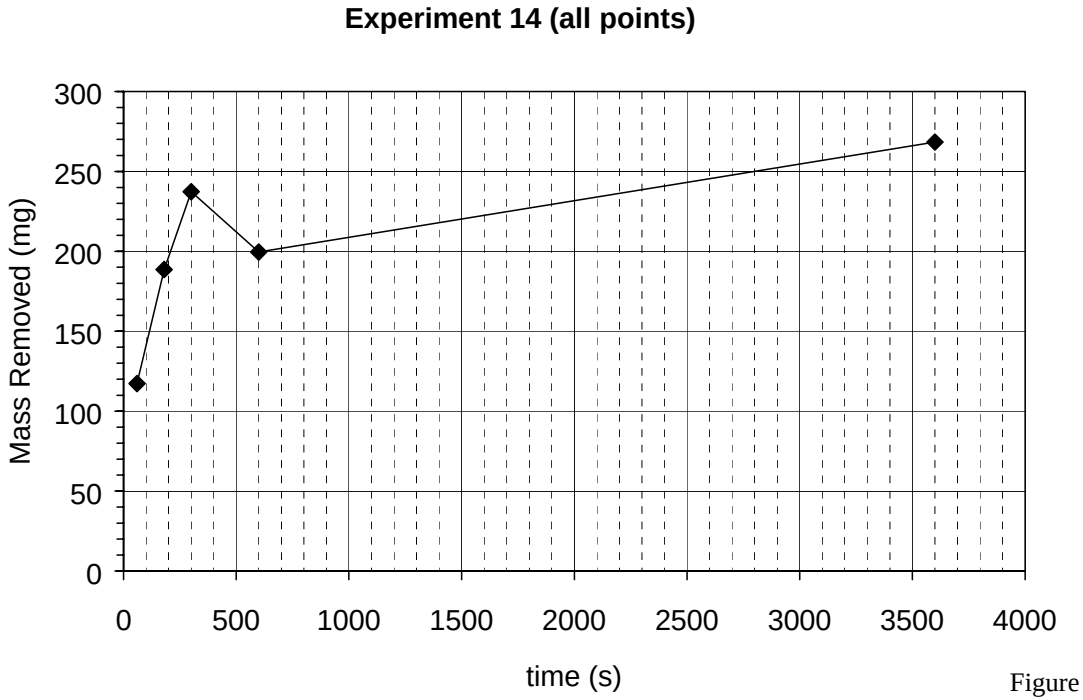


Figure D-6



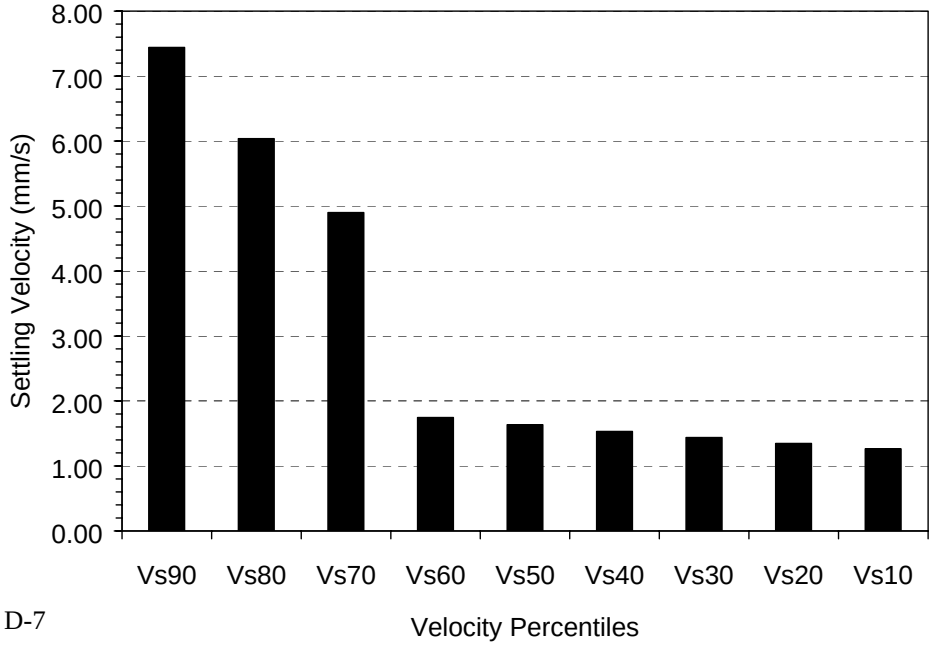
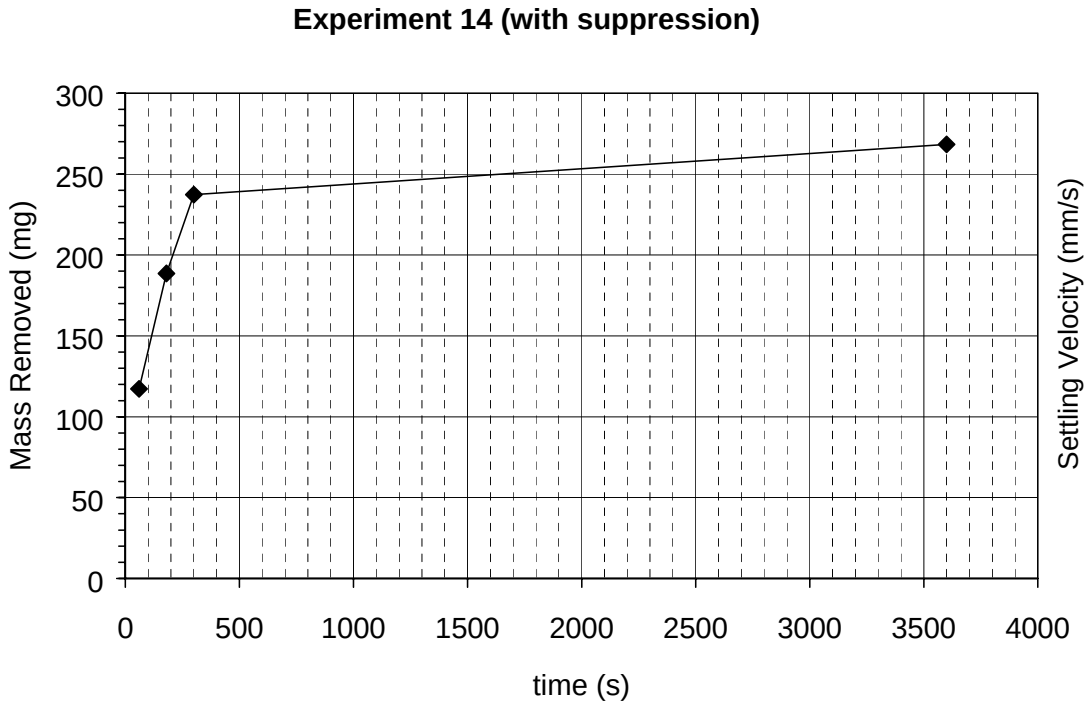


Figure D-7



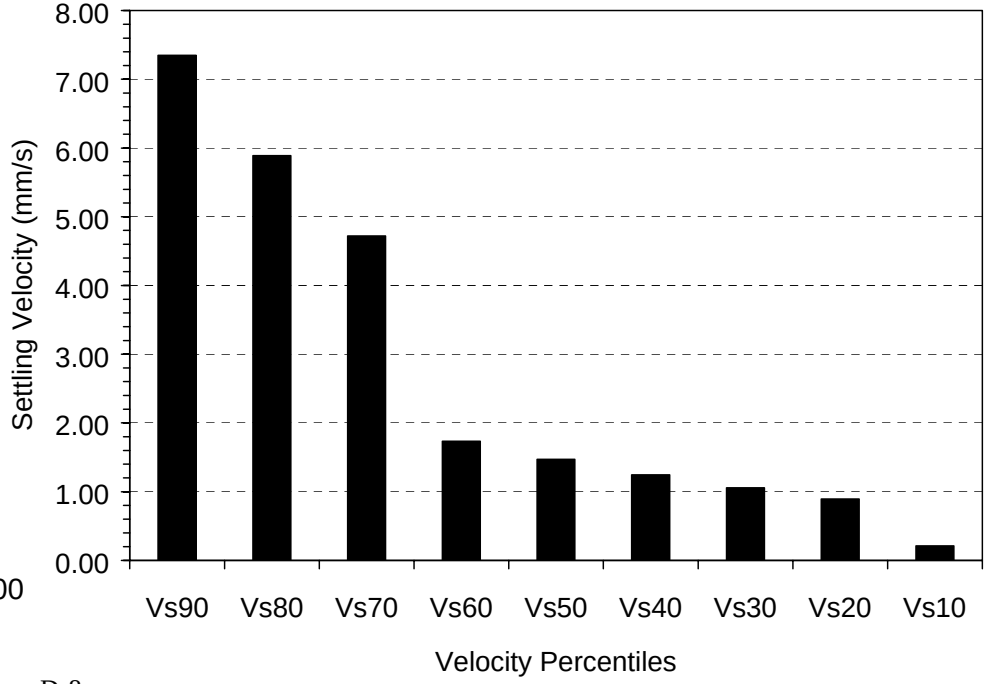
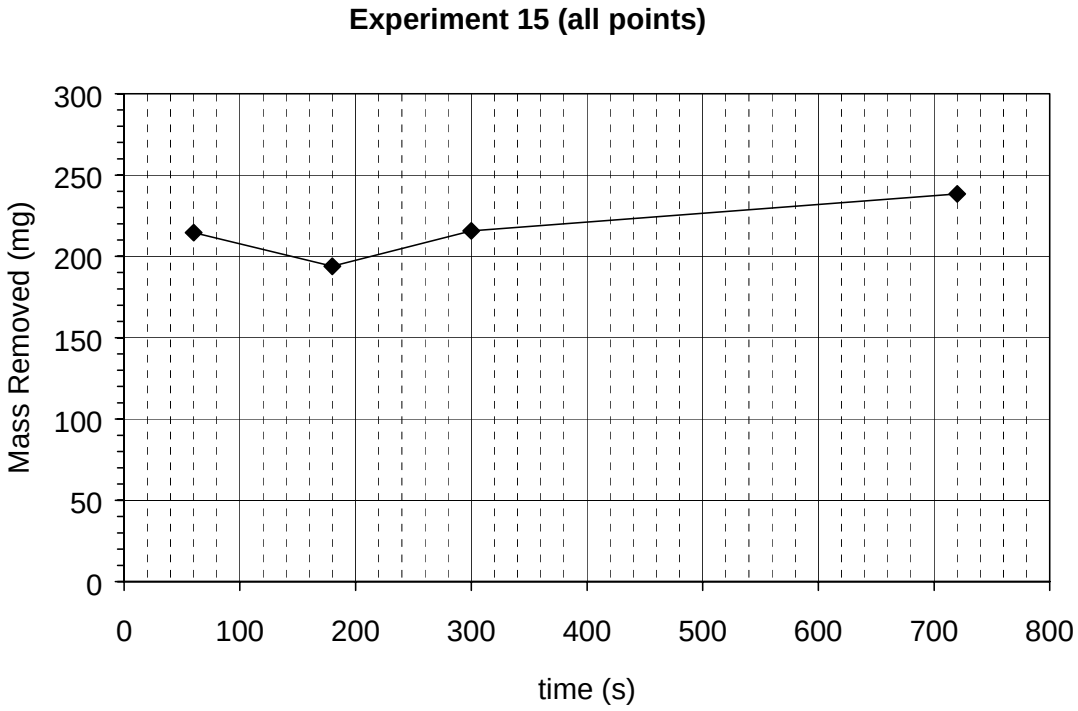


Figure D-8



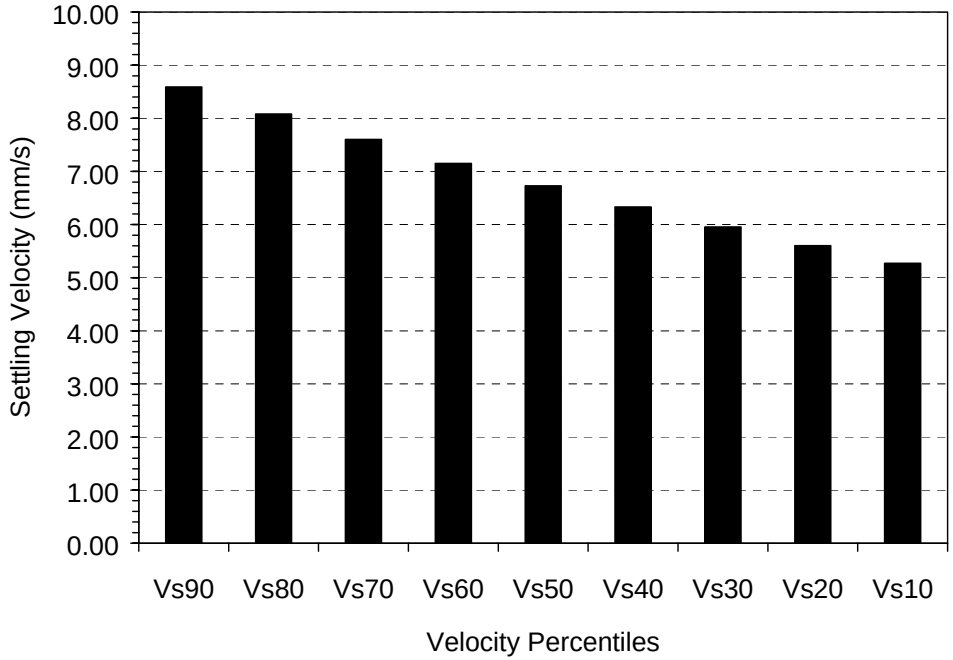
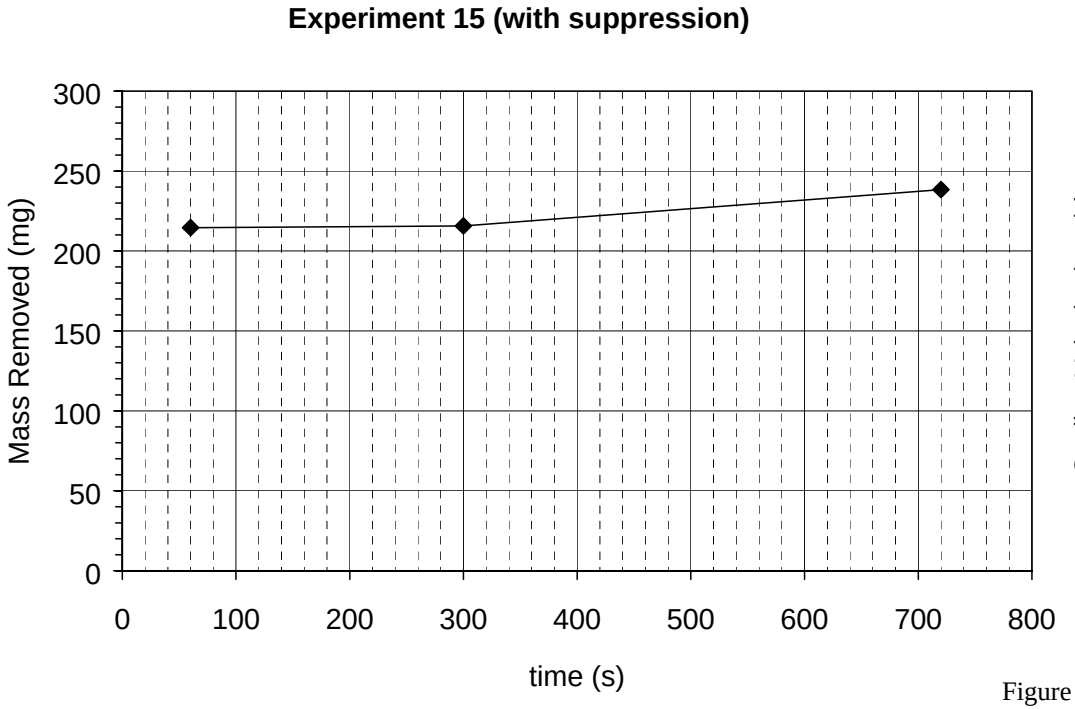


Figure D-9



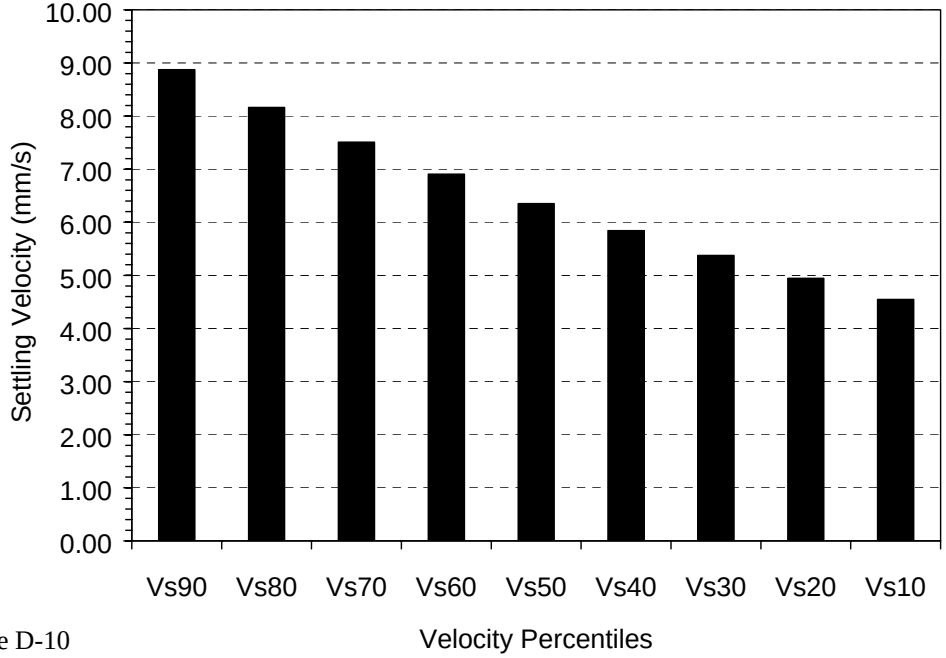


Figure D-10

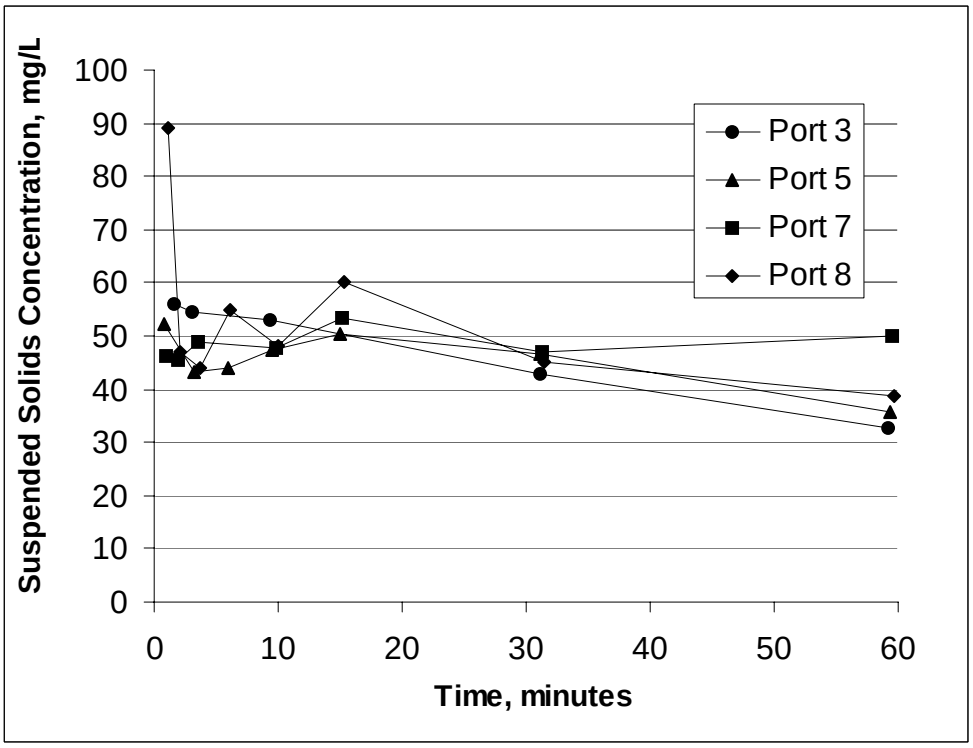


Figure E-1: Experiment 1, Long Column, Suspended Solids

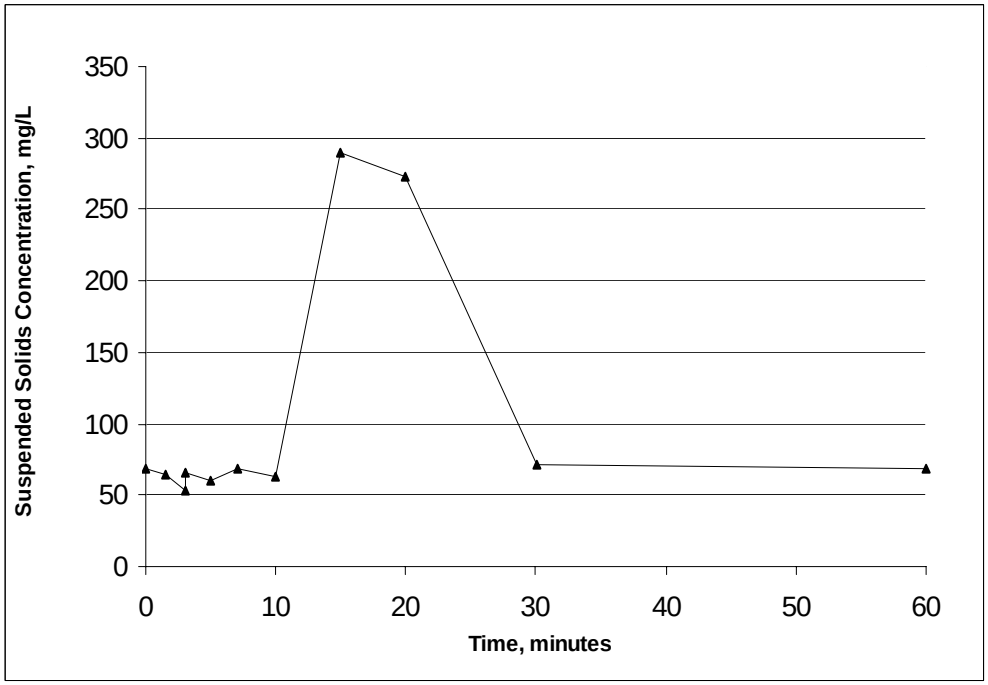


Figure E-2: Experiment 1, CERGRENE Column, Suspended Solids

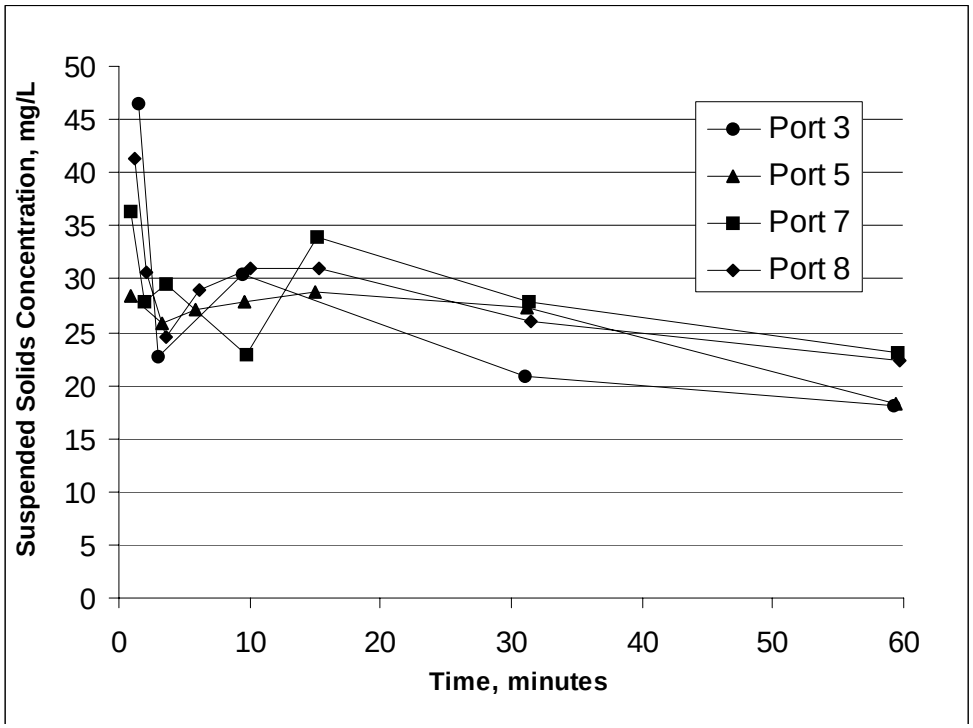


Figure E-3: Experiment 1, Long Column, Volatile Suspended Solids

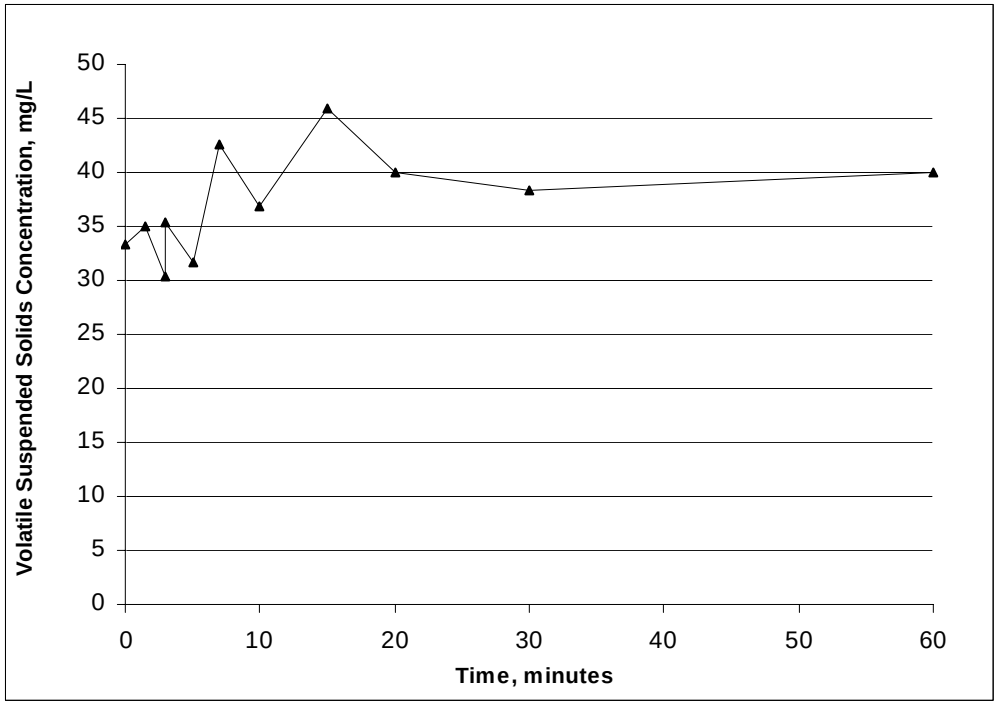


Figure E-4: Experiment 1, CERGRENE Column, Volatile Suspended Solids

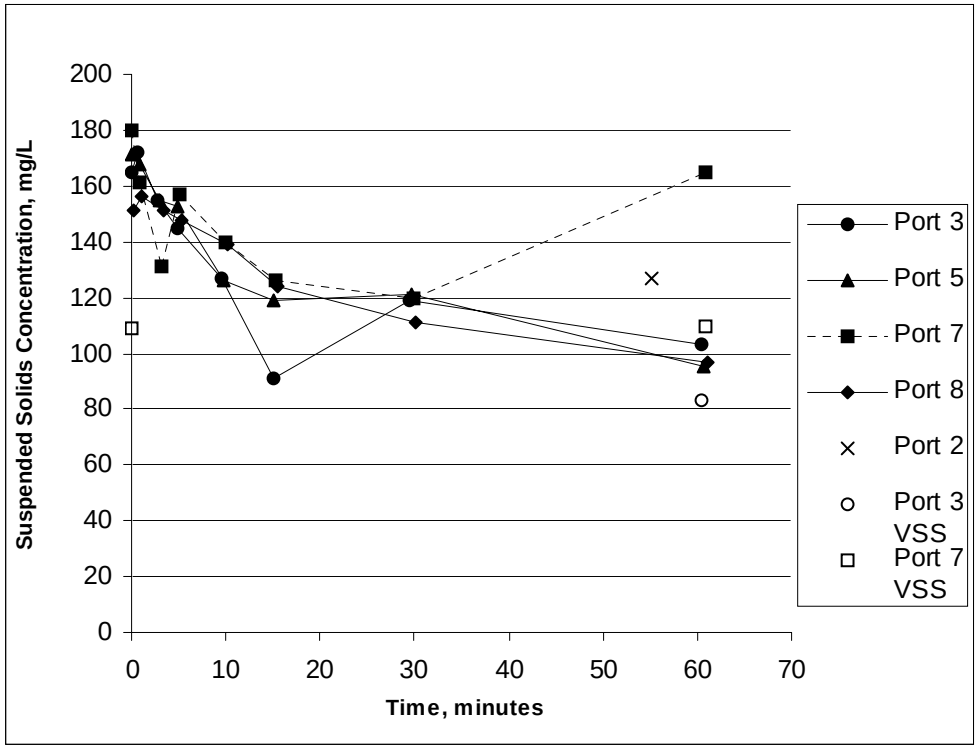


Figure E-5: Experiment 2, Long Column, Suspended Solids (with several Volatile Suspended Solid measurements)

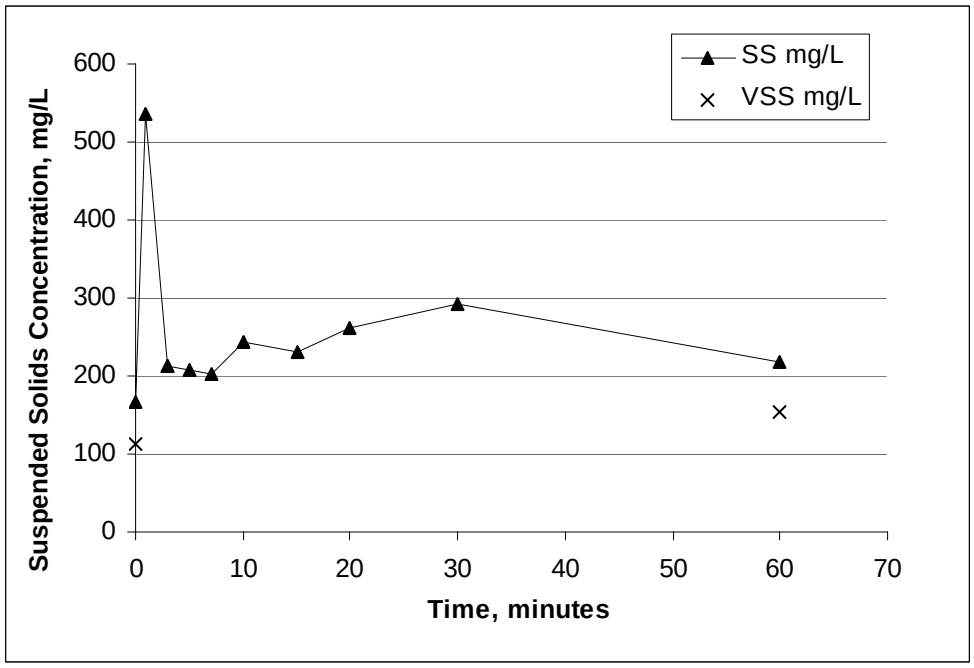


Figure E-6: Experiment 2, CERGRENE Column, Suspended Solids (with two Volatile Suspended Solid measurements)

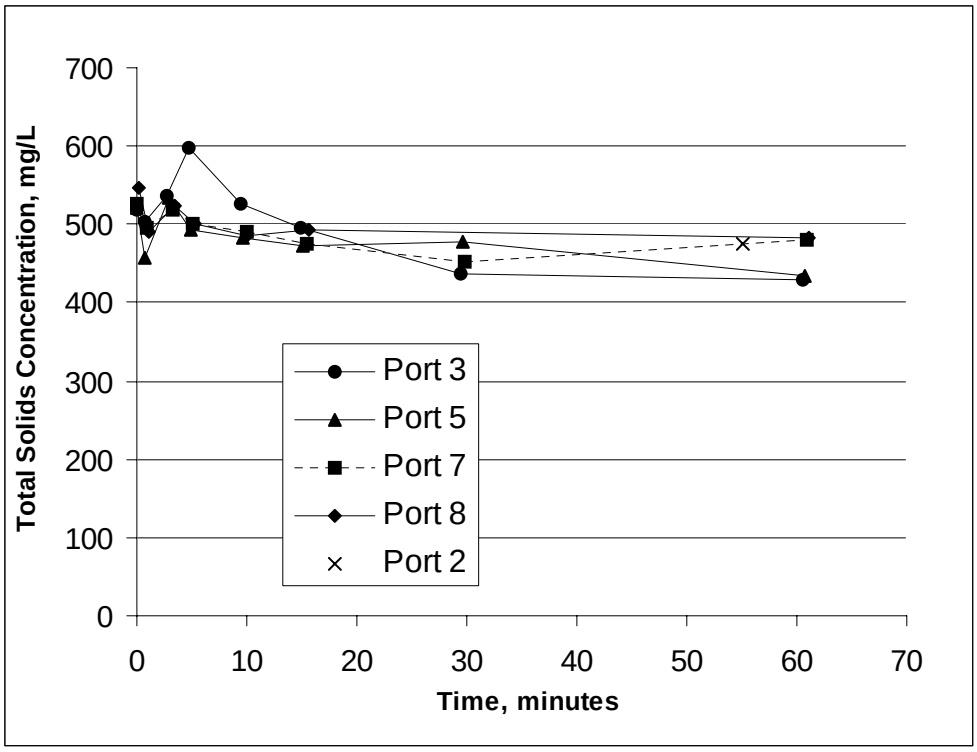


Figure E-7: Experiment 2, Long Column, Total Solids

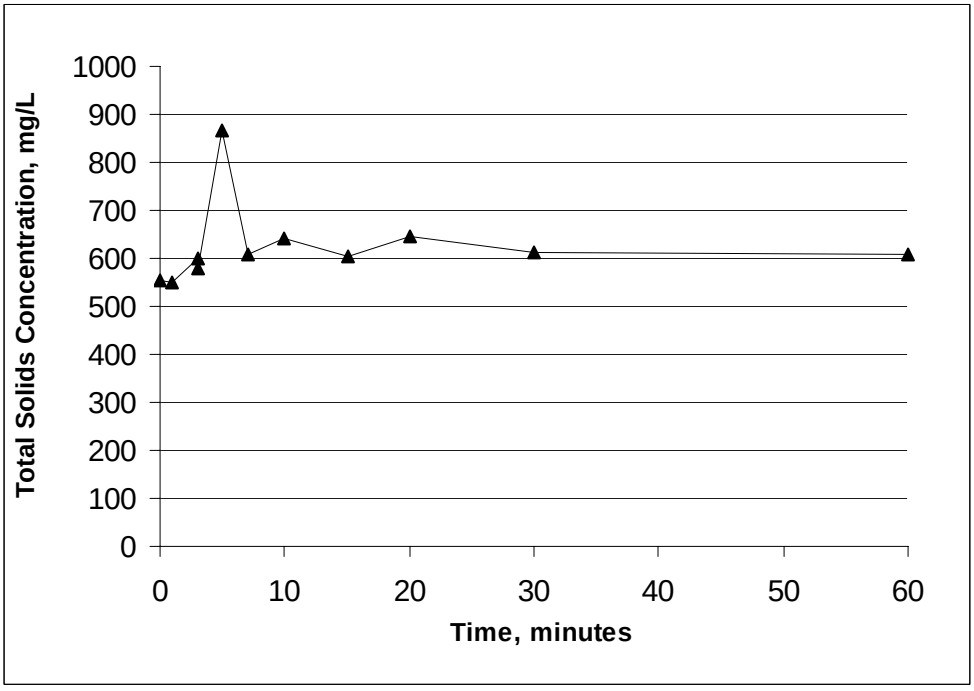


Figure E-8: Experiment 2, CERGRENE Column, Total Solids

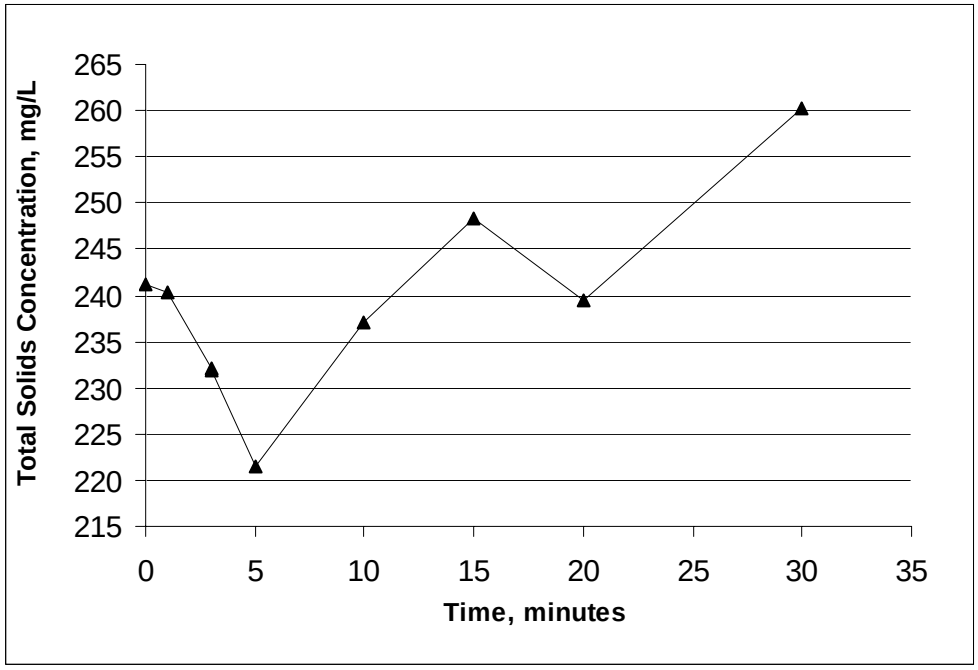


Figure E-9: Experiment 3, CERGRENE Column, Total Solids

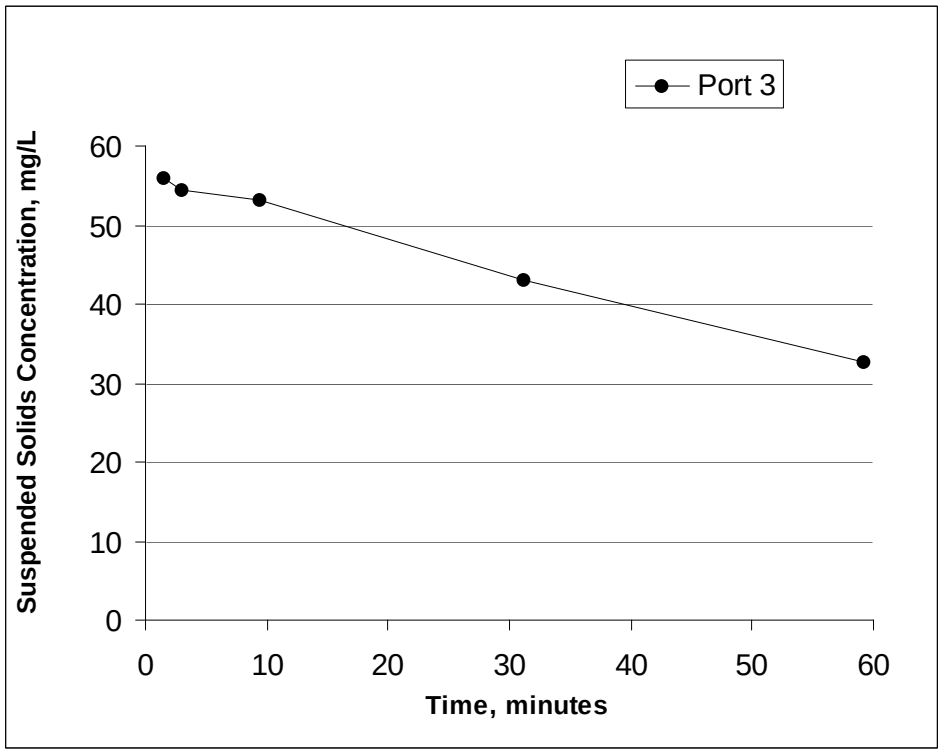


Figure E-10: Experiment 1, Long Column, Suspended Solids, Port 3 Only

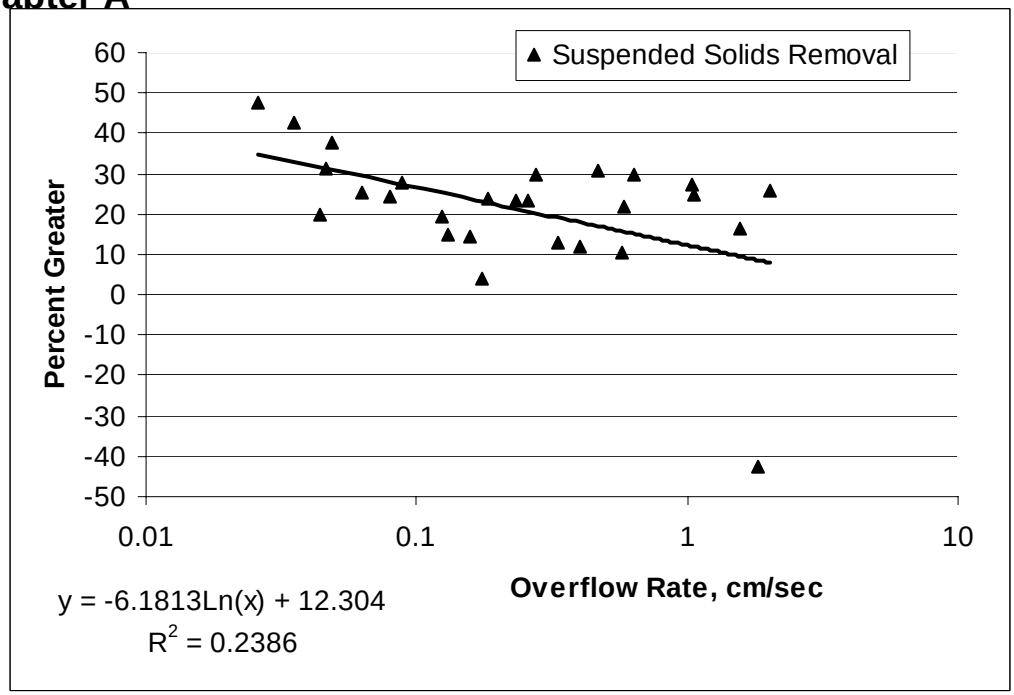


Figure F-1: Experiment 1, Percent Removal vs. Overflow Rate, Long Column, Suspended Solids

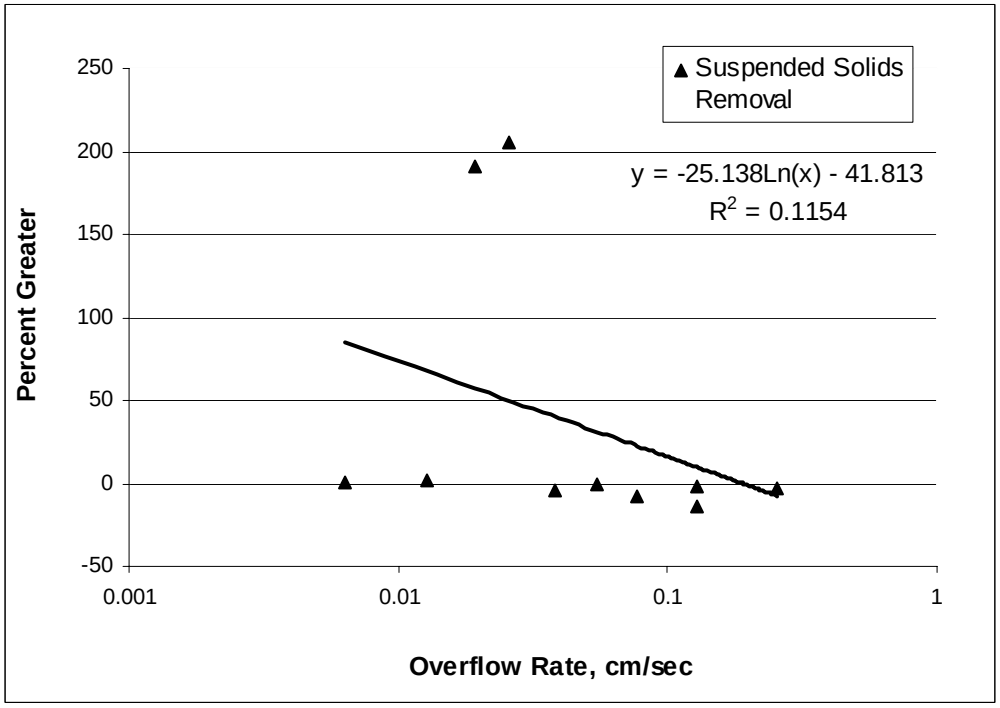


Figure F-2: Experiment 1, Percent Removal vs. Overflow Rate, CERGRENE Column, Suspended Solids

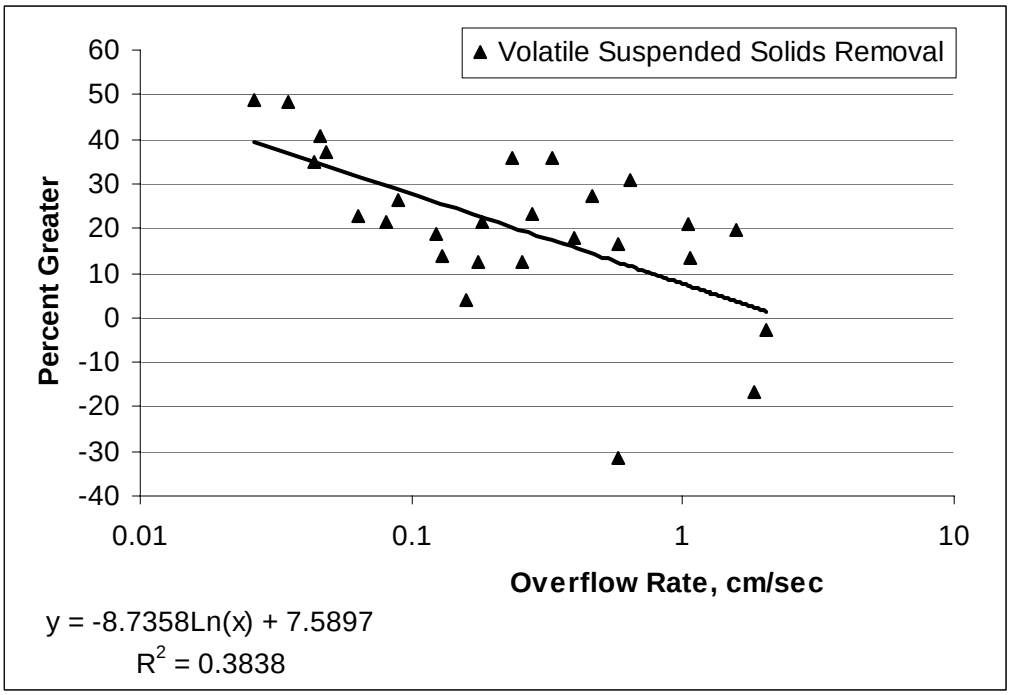


Figure F-3: Experiment 1, Percent Removal vs. Overflow Rate, Long Column, Volatile Suspended Solids

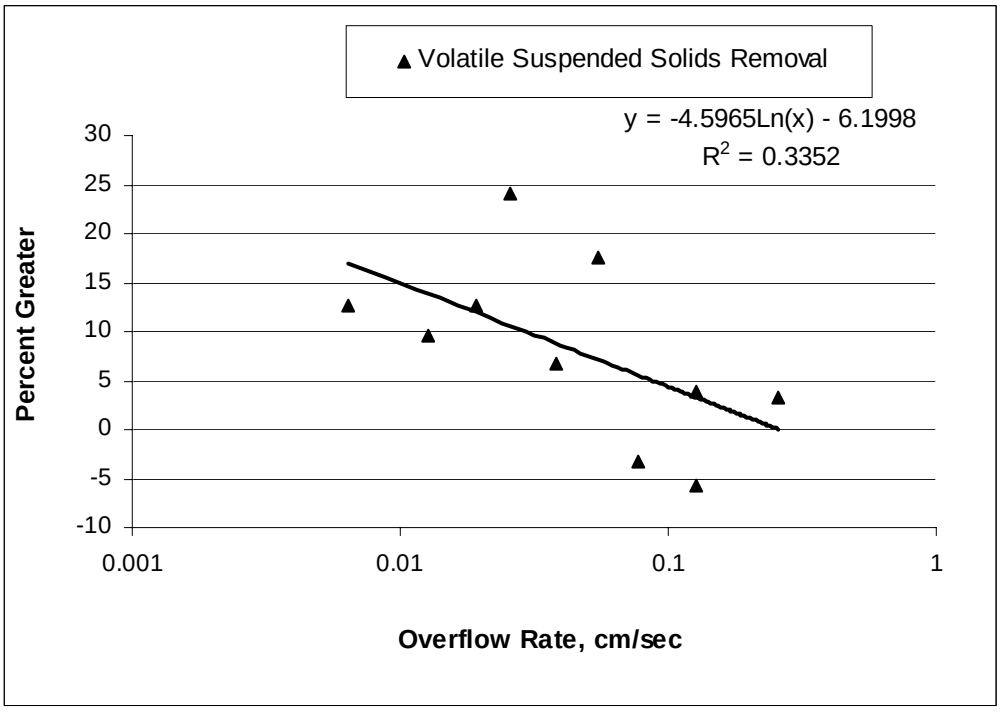


Figure F-4: Experiment 1, Percent Removal vs. Overflow Rate, CERGRENE Column, Volatile Suspended Solids

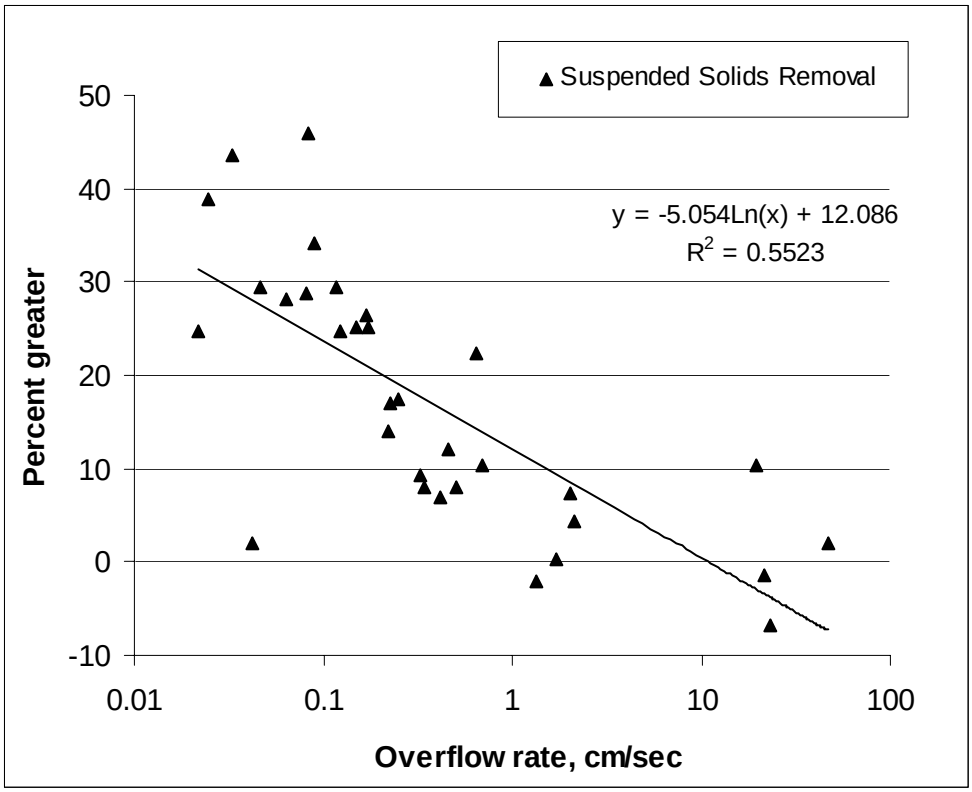


Figure F-5: Experiment 2, Percent Removal vs. Overflow Rate, Long Column, Suspended Solids

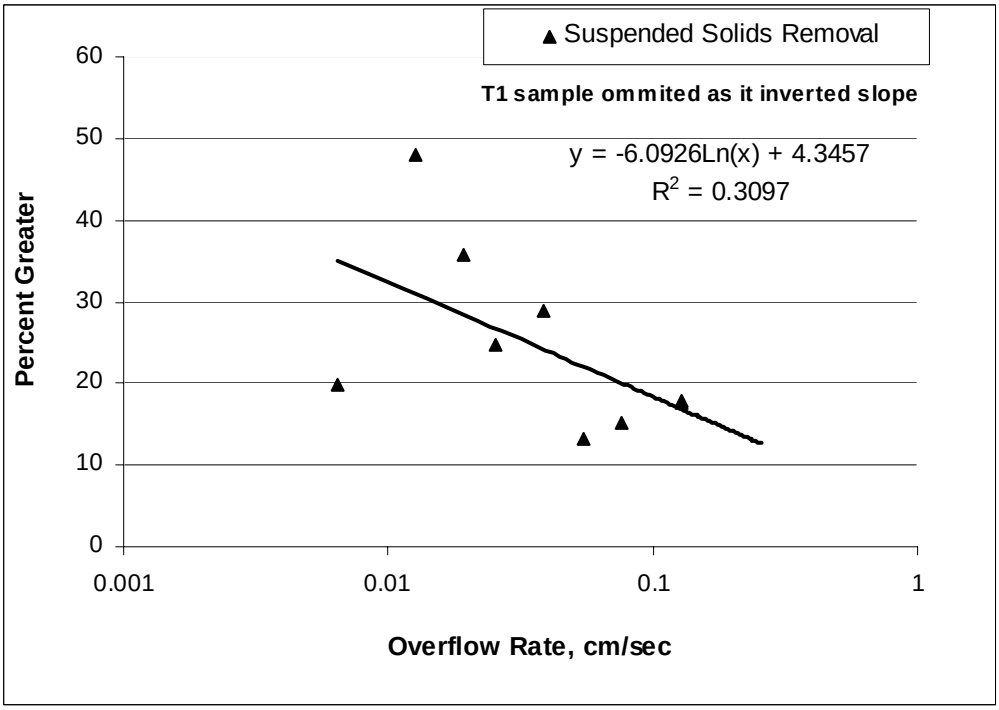


Figure F-6: Experiment 2, Percent Removal vs. Overflow Rate, CERGRENE Column, Suspended Solids

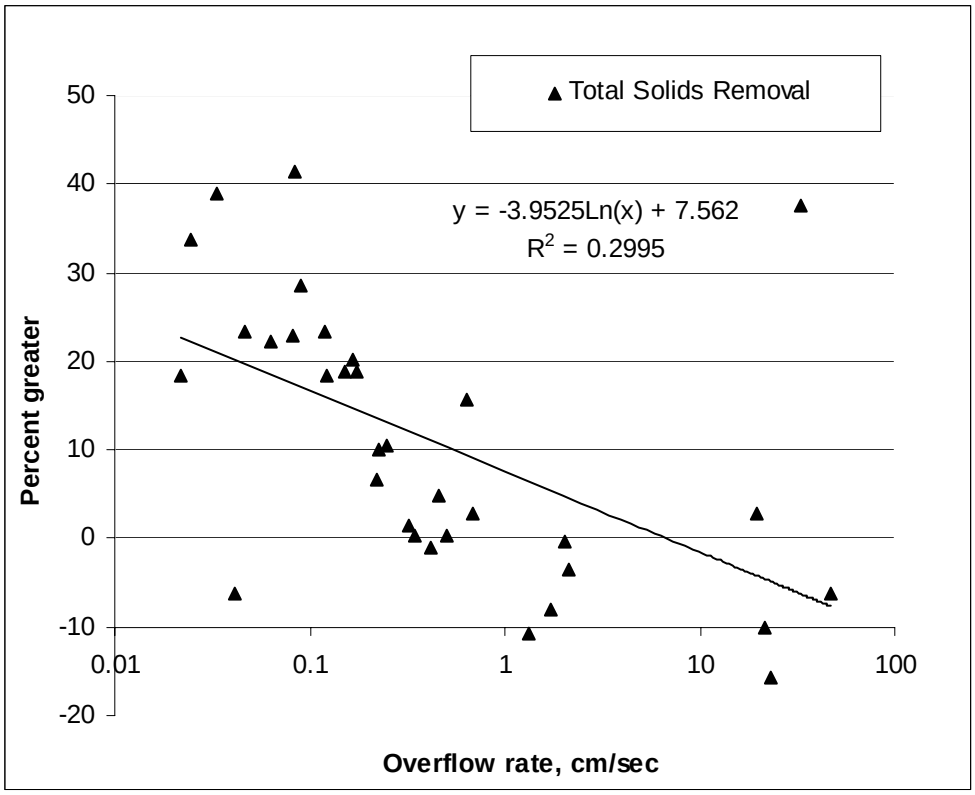


Figure F-7: Experiment 2, Percent Removal vs. Overflow Rate, Long Column, Total Solids

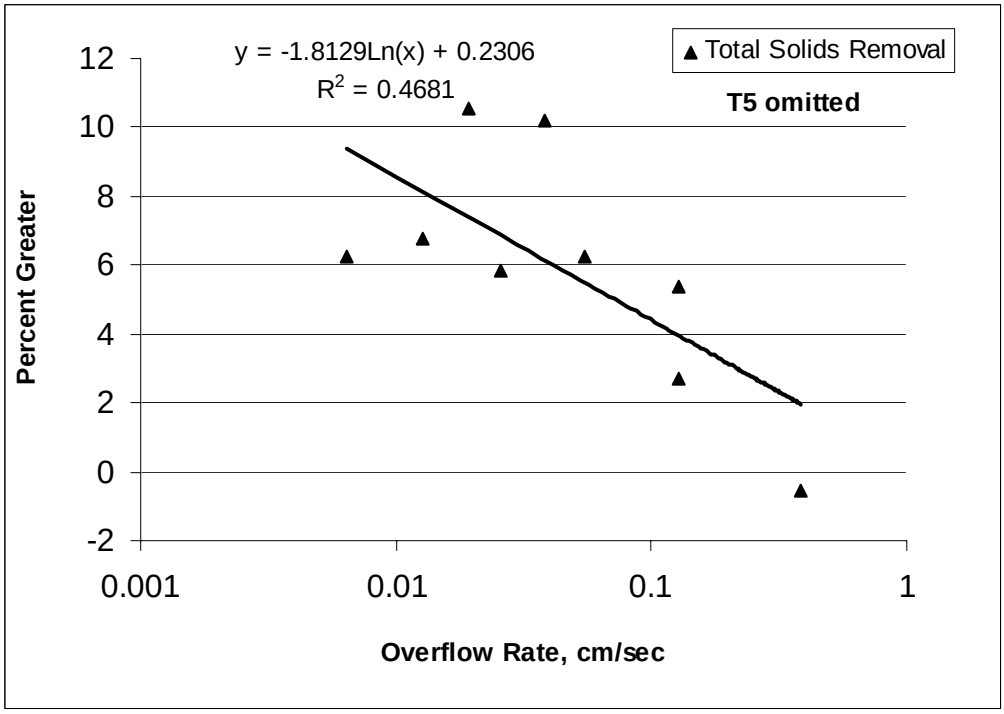


Figure F-8: Experiment 2, Percent Removal vs. Overflow Rate, CERGRENE Column, Total Solids

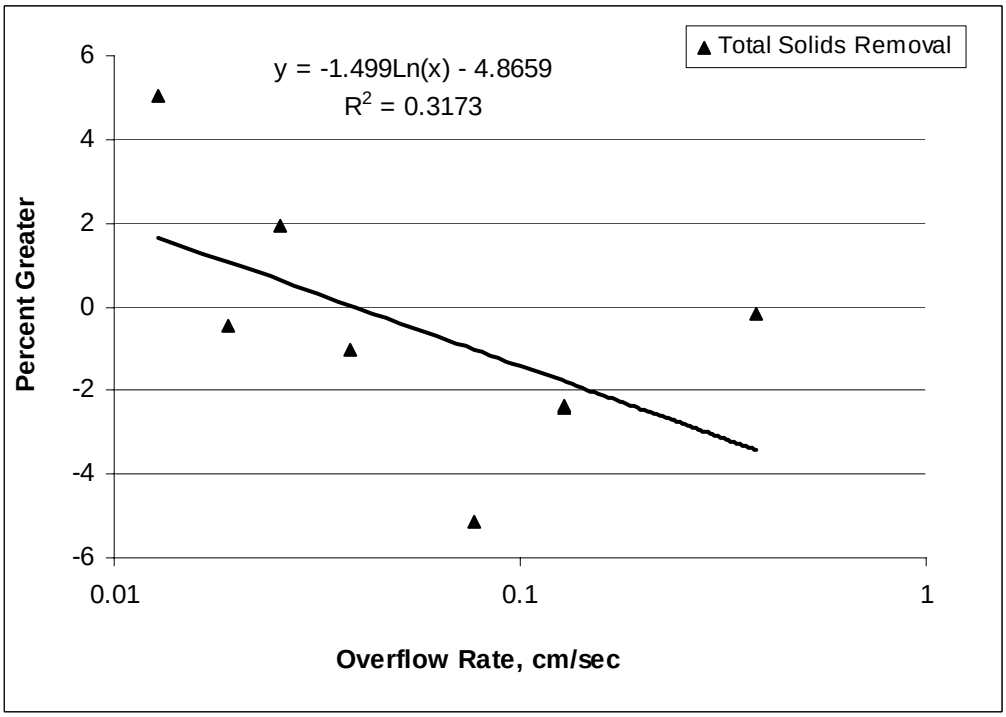


Figure F-9: Experiment 3, Percent Removal vs. Overflow Rate, CERGRENE Column, Total Solids

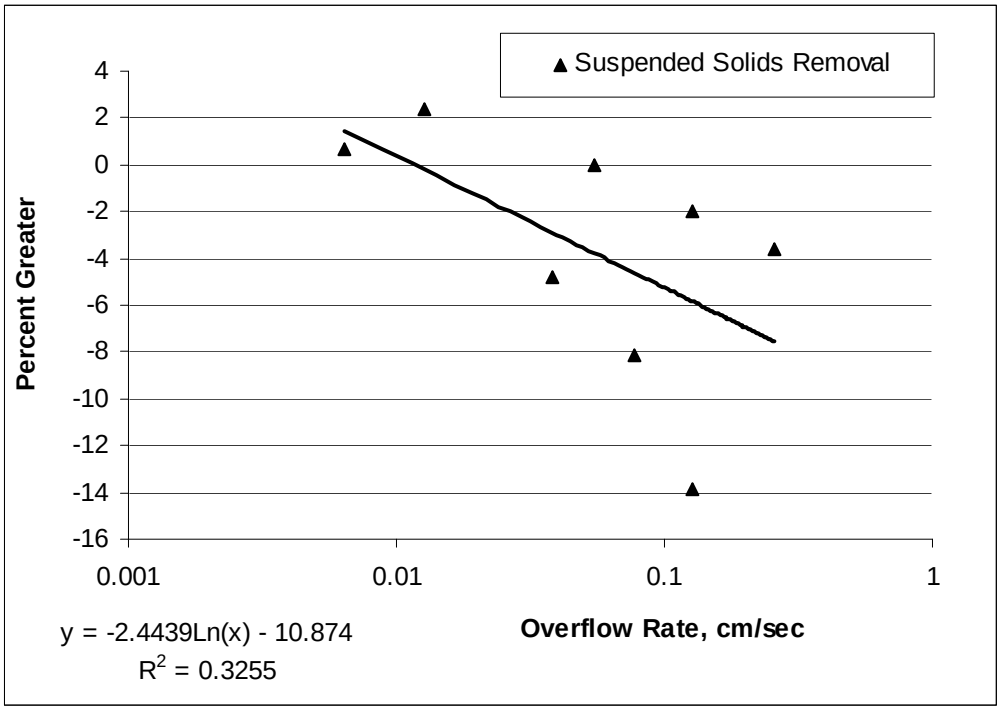
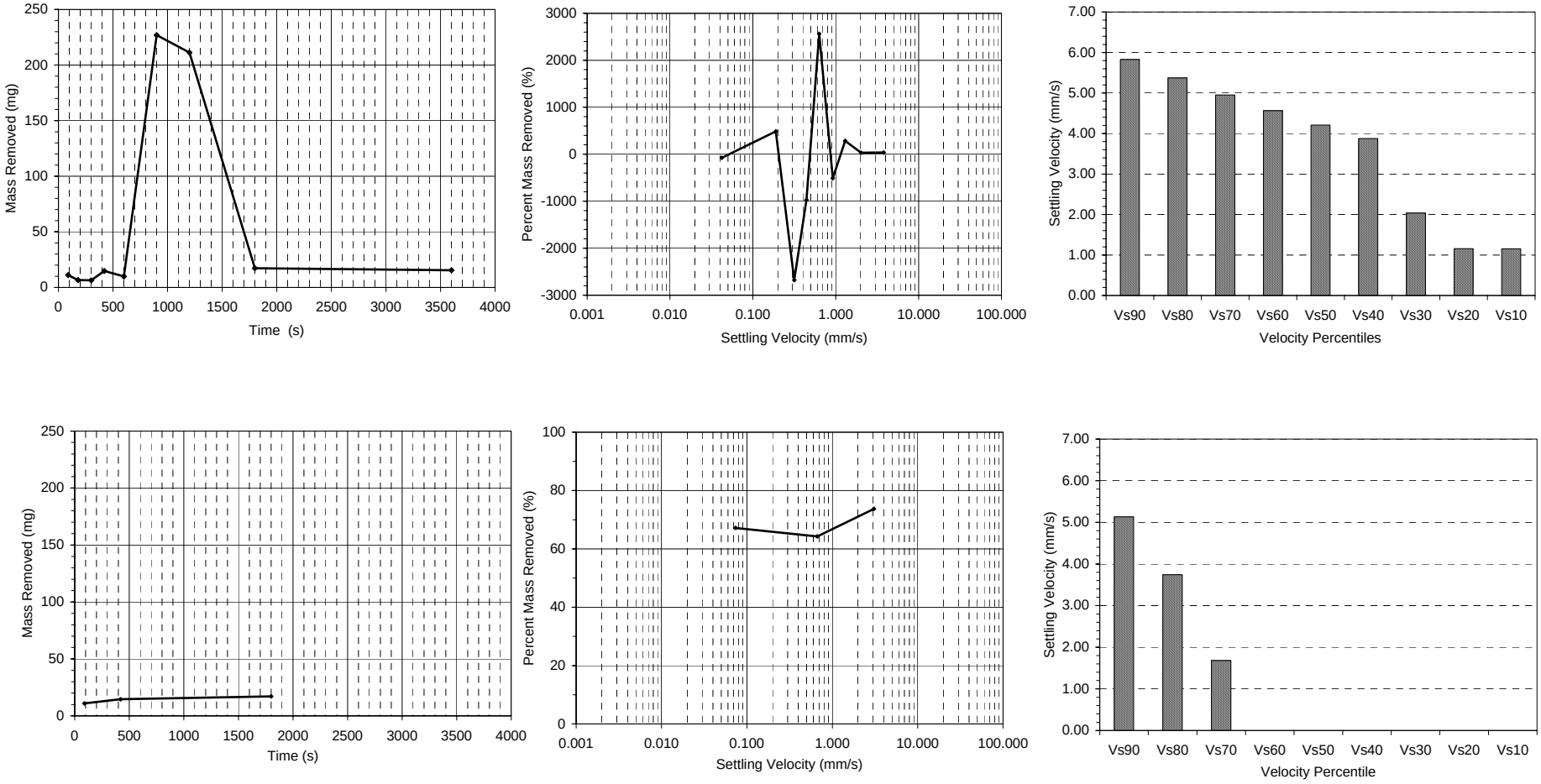


Figure F-10: Experiment 1, Percent Removal vs. Overflow Rate, CERGRENE Column, Suspended Solids, 2 Data Points Removed

Figure G-1 Victor Matrix Output for Experiment 1, Phase III, Suspended Solids (Top Row All Data , Bottom Row with Suppression)



Note: Background suspended solids concentration used instead of t_0 concentation for Analysis with Suppresion.

Figure G-2 Victor Matrix Output for Experiment 1, Phase III, Volatile Suspended Solids (Top Row All Data , Bottom Row with Suppression)

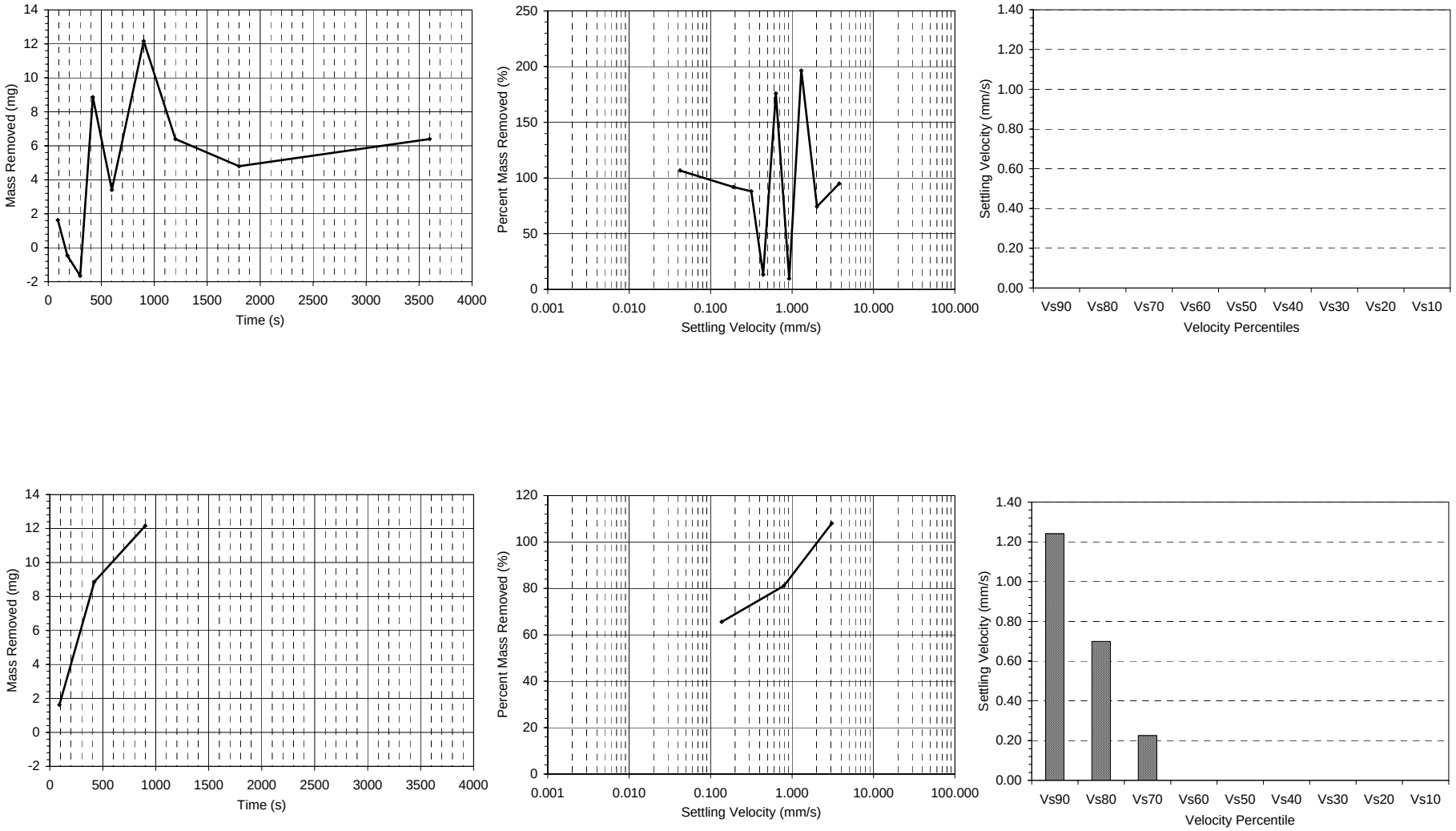


Figure G-3 Victor Matrix Output for Experiment 2, Phase III, Suspended Solids (Top Row All Data , Bottom Row with Suppression)

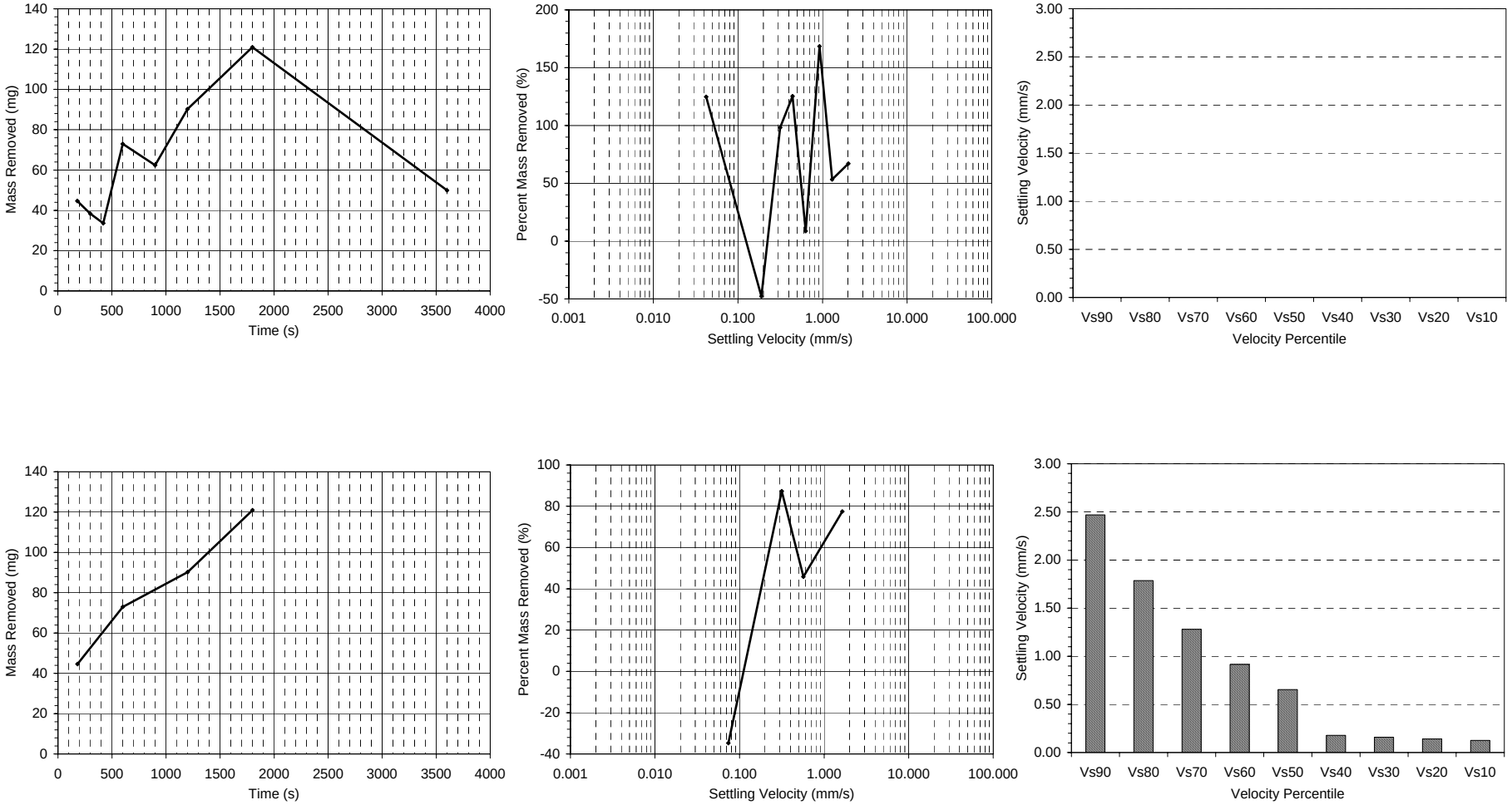


Figure G-4 Victor Matrix Output for Experiment 2, Phase III, Total Solids (Top Row All Data , Bottom Row with Suppression)

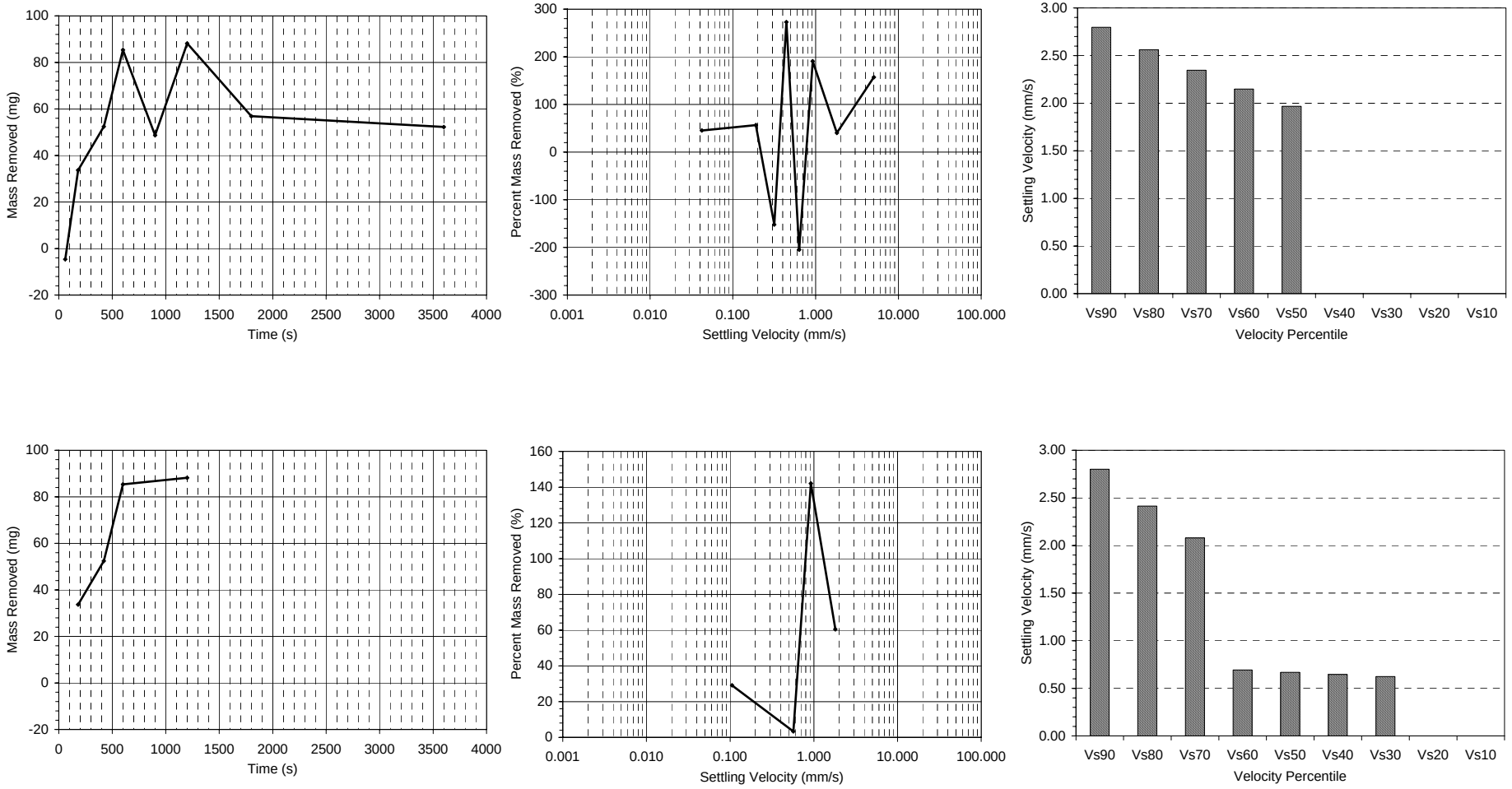
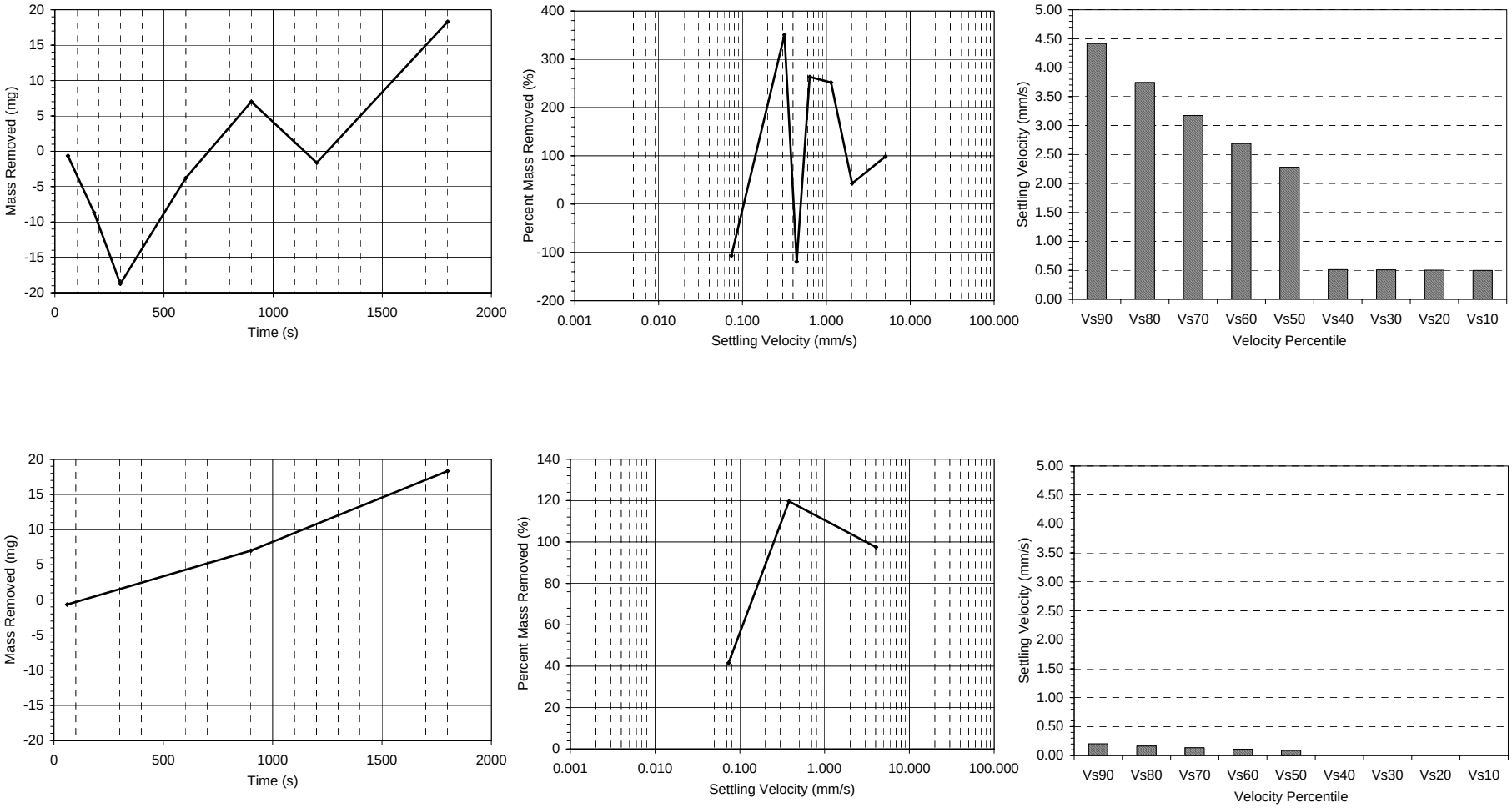


Figure G-5 Victor Matrix Output for Experiment 3, Phase III, Total Solids (Top Row All Data , Bottom Row with Suppression)



Experiment 1: 6/9/98 Long Column Initial Height=7'10"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.60	256.18
5	0.88	292.00
7	1.15	289.96
8	1.42	327.84
3	1.85	274.73
5	2.12	268.69
7	2.42	n/a
8	2.70	284.58
3	3.10	258.20
5	3.18	267.41
7	3.58	276.89
8	3.90	268.18
3	5.18	244.80
5	5.37	275.37
7	5.73	255.81
8	6.08	255.69
3	10.38	224.23
5	10.78	269.03
7	11.08	268.90
8	11.37	n/a
3	58.83	171.98
5	59.17	295.51
7	59.45	324.40
8	59.78	305.68

Blank Conc (mg/l)

3.03

Recycle Conc (mg/l)

1	267.14
2	267.97
3	265.20

Non-Settleable Solids (mg/l)

1	85.20
2	71.54

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	16.25	276.47
2	1.00	16.25	338.74
3	3.00	16.38	420.00
4	5.00	16.88	357.85
1	10.00	17.00	447.08
2	60.00	15.25	379.43
3	14.67	16.75	365.56

Experiment 2: 6/10/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.42	168.01
5	0.68	183.27
7	0.85	254.47
8	1.03	280.40
3	1.38	172.03
5	1.57	n/a
7	1.78	185.02
8	1.93	145.87
3	2.82	128.40
5	3.00	143.70
7	3.17	142.80
8	3.37	151.79
3	5.05	128.46
5	5.20	141.11
7	5.40	143.87
8	5.57	142.18
3	10.20	88.59
5	10.40	133.33
7	10.63	141.60
8	10.83	141.98
3	60.20	104.56
5	60.43	117.18
7	60.65	136.22
8	60.85	148.08

Blank Conc (mg/l)

0.44

Recycle Conc (mg/l)

1	335.90
2	258.37
3	n/a

Non-Settleable Solids (mg/l)

1	38.15
2	25.73

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	16.75	299.07
2	1.00	18.5	193.94
3	3.00	15.75	349.95
4	3.00	14.75	262.27
1	10.00	16.5	426.87
2	60.00	16.5	367.27
3	5.00	16.25	324.39

Experiment 3: 6/10/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.25	175.27
5	0.50	186.29
7	0.70	264.17
8	0.90	374.35
3	1.32	141.53
5	1.57	156.28
7	1.80	177.05
8	2.00	182.95
3	3.02	132.33
5	3.17	185.16
7	3.37	153.97
8	3.57	154.58
3	5.25	123.36
5	5.47	141.31
7	5.67	142.28
8	5.92	146.01
3	10.45	119.85
5	10.75	132.05
7	11.00	136.51
8	11.25	136.47
3	59.95	85.94
5	60.15	129.37
7	60.33	154.73
8	60.57	152.67

Blank Conc (mg/l)

n/a

Recycle Conc (mg/l)

1	288.89
2	220.08
3	286.38

Non-Settleable Solids (mg/l)

1	n/a
2	33.11

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	15.25	351.10
2	1.00	17	238.82
3	3.00	16	412.69
4	5.00	16.25	255.59
1	10.00	16.5	536.23
2	60.00	16.75	249.68
3	3.00	16.88	342.37

Experiment 4: 6/11/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.38	107.39
5	0.52	57.41
7	0.75	218.10
8	0.97	346.80
3	1.35	29.23
5	1.53	47.64
7	1.72	n/a
8	1.88	91.20
3	2.58	15.23
5	2.83	20.00
7	2.98	16.27
8	3.45	22.14
3	4.88	n/a
5	5.02	8.24
7	5.18	9.41
8	5.35	8.94
3	9.97	7.20
5	10.17	7.02
7	10.35	5.87
8	10.55	8.05

Blank Conc (mg/l)

1.06

Recycle Conc (mg/l)

1	156.50
2	256.76
3	207.08

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	15.5	315.31
2	1.00	15.75	116.13
3	3.00	15.5	213.62
4	5.00	15.5	116.02
1	10.00	16.38	463.14
2	1.00		124.84

Experiment 5: 6/11/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.27	193.77
5	0.47	263.57
7	0.70	312.81
8	0.88	292.69
3	1.08	242.91
5	1.27	262.73
7	1.42	248.18
8	1.58	277.07
3	2.85	228.00
5	2.98	248.35
7	3.15	256.61
8	3.32	261.16
3	4.95	209.16
5	5.13	226.82
7	5.30	248.35
8	5.48	#DIV/0!
3	11.22	170.82
5	11.40	221.97
7	11.57	240.63
8	11.77	247.06
3	59.95	140.08
5	60.17	221.11
7	60.35	255.56
8	60.63	266.14

Blank Conc (mg/l)

3.94

Recycle Conc (mg/l)

1	305.28
2	286.85
3	269.55

Non-Settleable Solids (mg/l)

1	56.74
2	43.35

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		339.48
2	1.00		291.85
3	3.00		384.09
4	5.00	16.25	312.08
1	10.00	14.5	442.47
2	60.00	16	387.99
3	0.00	16.25	267.18

Experiment 6: 6/12/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.20	254.96
5	0.42	243.51
7	0.58	319.48
8	0.72	338.27
3	0.93	254.03
5	1.13	260.25
7	1.32	272.65
8	1.52	242.03
3	2.90	231.75
5	3.07	233.72
7	3.22	255.19
8	3.38	267.18
3	5.00	212.08
5	5.17	235.12
7	5.33	246.69
8	5.48	254.55
3	9.90	179.92
5	10.07	215.29
7	10.25	246.30
8	10.42	257.14
3	59.95	119.69
5	60.08	212.70
7	60.25	255.34
8	60.47	244.62

Blank Conc (mg/l)

0.71

Recycle Conc (mg/l)

1	283.33
2	290.71
3	n/a

Non-Settleable Solids (mg/l)

1	34.62
2	49.26

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	16.25	322.97
2	1.00	15.75	290.85
3	3.00	15.25	369.12
4	5.00	15.75	339.92
1	10.00	16.5	464.36
2	60.00	16.5	411.72
3	60.00	16	454.04

Experiment 7: 6/12/98 Long Column Initial Height=8'

Long column data

Port	Time (min)	Conc (mg/l)
3	0.25	188.76
5	0.45	241.44
7	0.63	n/a
8	0.83	357.87
3	1.35	145.77
5	1.50	155.06
7	1.63	196.83
8	3.25	157.56
3	2.73	135.02
5	2.87	147.46
7	3.02	157.53
8	1.82	184.07
3	4.83	123.17
5	4.98	136.89
7	5.13	149.80
8	5.28	137.08
3	9.95	114.02
5	10.10	129.96
7	10.30	139.26
8	10.37	150.20
3	60.48	86.94
5	60.75	129.59
7	60.93	155.98
8	61.12	159.07

Blank Conc (mg/l)

	1.07
	1.08

Recycle Conc (mg/l)

1	298.74
2	327.46
3	257.99

Non-Settleable Solids (mg/l)

1	27.31
2	26.78

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	15.25	347.42
2	1.00	15.75	216.54
3	3.00	15.50	359.04
4	5.00	16.25	259.15
1	10.00	16.25	467.11
2	60.00	16.5	256.56
3	10.00	15.75	327.98

Experiment 8: 6/14/98 Long Column Initial Height=7'11.6"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.22	60.22
5	0.35	153.90
7	0.50	388.99
8	0.62	n/a
3	1.07	n/a
5	1.22	78.54
7	1.35	130.36
8	1.52	120.44
3	2.87	9.96
5	3.00	25.61
7	3.15	23.18
8	3.32	37.04
3	5.00	6.74
5	5.15	7.17
7	5.30	10.61
8	5.47	16.05
3	9.80	4.58
5	9.95	5.91
7	10.10	7.09
8	10.23	3.76

Blank Conc (mg/l)

3.38

Recycle Conc (mg/l)

1	290.98
2	238.26
3	310.80

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	15.25	291.05
2	1.00	16.125	160.11
3	3.00	15.5	197.34
4	5.00	16	143.87
1	10.00	15.5	445.89
2	5.00	16.25	152.55

Experiment 9: 6/15/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.20	157.87
5	0.35	189.24
7	0.50	329.32
8	0.70	345.31
3	1.15	126.80
5	1.27	155.65
7	1.38	145.53
8	1.53	201.98
3	2.80	93.42
5	2.93	128.95
7	3.07	137.36
8	3.22	144.62
3	4.80	94.09
5	4.95	114.45
7	5.08	128.90
8	5.27	116.97
3	9.72	82.61
5	9.90	105.62
7	10.05	118.50
8	10.22	118.22
3	59.92	63.71
5	60.10	111.11
7	60.28	142.05
8	60.47	136.36

Blank Conc (mg/l)

	0.77
	1.79

Recycle Conc (mg/l)

1	257.66
2	235.42
3	282.44

Non-Settleable Solids (mg/l)

1	24.62
2	21.84

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
2	0.00	16.25	206.04
4	1.00	17	265.51
1	3.00		485.70
3	5.00	16.25	308.30
2	10.00	16	255.21
4	60.00	16.75	279.57
1	3.00	16	447.19

Experiment 10: 6/15/98 Long Column Initial Height=7'11"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.25	260.34
5	0.42	302.07
7	0.58	327.98
8	0.77	347.62
3	1.10	257.92
5	1.30	285.56
7	1.47	276.47
8	1.63	291.76
3	2.83	229.20
5	2.97	260.59
7	3.12	276.15
8	3.27	272.16
3	n/a	n/a
5	4.88	246.72
7	5.05	256.32
8	5.23	264.57
3	9.87	187.68
5	10.07	236.80
7	10.15	258.40
8	10.32	257.33
3	59.80	131.82
5	60.00	212.00
7	60.18	286.82
8	60.33	n/a

Blank Conc (mg/l)

0.80

Recycle Conc (mg/l)

1	287.92
2	298.82
3	267.19

Non-Settleable Solids (mg/l)

1	48.05
2	46.56

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00	17.00	284.23
1	1.00	14.5	329.89
1	3.00	16.50	391.54
1	5.00		422.62
1	10.00	16.75	454.89
1	1.00	16.5	328.06
1	60.00	16.25	487.68

Experiment 11: 6/16/98 Long Column Initial Height=7'11.5"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.25	177.26
5	0.42	n/a
7	0.58	305.33
8	0.73	356.09
3	1.20	144.72
5	1.33	169.35
7	1.47	168.08
8	1.63	205.14
3	2.77	133.05
5	2.88	142.26
7	3.03	156.30
8	3.18	160.23
3	4.75	112.60
5	4.92	130.68
7	5.07	137.36
8	5.22	139.53
3	9.72	103.77
5	9.87	116.72
7	10.05	131.13
8	10.22	134.69
3	59.45	79.10
5	59.62	118.08
7	59.77	138.31
8	59.95	144.65

Blank Conc (mg/l)

-0.38

Recycle Conc (mg/l)

1	237.24
2	239.32
3	276.47

Non-Settleable Solids (mg/l)

1	30.42
2	28.99

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		290.21
1	1.00	17	413.54
1	3.00	16.75	381.56
1	5.00	16.5	429.53
1	10.00	15.5	487.29
1	0.00	17	290.94
1	60.00	16.38	469.90

Experiment 12: 6/16/98 Long Column Initial Height=7'11.6"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.23	62.64
5	0.37	152.96
7	0.50	291.61
8	0.65	354.75
3	0.95	26.29
5	1.08	68.06
7	1.23	113.62
8	1.37	138.08
3	2.65	15.98
5	2.80	10.11
7	2.97	35.88
8	3.13	48.69
3	5.30	10.40
5	5.43	9.09
7	5.57	11.67
8	5.70	13.85
3	9.78	8.08
5	9.92	6.44
7	10.05	5.15
8	10.22	11.35

Blank Conc (mg/l)

3.57

Recycle Conc (mg/l)

1	302.26
2	274.27
3	299.62

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		269.22
1	1.00	16.5	453.78
1	3.00	16.75	533.85
1	5.00	17	529.42
1	10.00	16.75	490.94
1	10.00	17	392.67

Experiment 13: 6/17/98 Long Column Initial Height=7'11.5"

Long column data

Port	Time (min)	Conc (mg/l)
3	0.48	50.00
5	0.62	123.08
7	0.75	166.28
8	0.90	253.72
3	1.27	24.24
5	1.40	54.51
7	1.53	98.80
8	1.67	110.98
3	2.85	8.63
5	3.00	3.40
7	3.20	n/a
8	3.37	43.56
3	4.90	5.90
5	5.05	7.63
7	5.18	9.62
8	5.37	10.64
3	10.13	3.18
5	10.30	5.56
7	10.42	4.12
8	10.57	8.40

Blank Conc (mg/l)

3.96

Recycle Conc (mg/l)

1	254.29
2	304.02
3	n/a

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		310.00
1	1.00	16.00	478.76
1	3.00	16.50	518.55
1	5.00	17.00	455.03
1	5.00	16.50	516.27
1	10.00	16.75	553.19

Experiment 14: 6/17/98 Long Column Initial Height=8'

Long column data

Port	Time (min)	Conc (mg/l)
3	0.23	270.33
5	0.38	283.14
7	0.52	331.52
8	0.72	333.86
3	1.23	264.20
5	1.40	282.87
7	1.53	n/a
8	1.68	299.23
3	2.82	258.61
5	3.03	268.60
7	3.18	293.49
8	3.33	292.28
3	4.87	236.96
5	5.02	264.37
7	5.15	278.60
8	5.28	284.56
3	10.22	217.99
5	10.38	253.01
7	10.57	282.73
8	10.75	294.80
3	59.47	138.24
5	59.67	227.84
7	59.83	273.91
8	59.97	291.97

Blank Conc (mg/l)

0.78

Recycle Conc (mg/l)

1	285.28
2	299.56
3	n/a

Non-Settleable Solids (mg/l)

1	46.69
2	56.81

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		262.09
1	1.00	16.50	384.19
1	3.00	16.50	458.46
1	5.00	17.25	509.18
1	3.00	16.50	408.54
1	10.00	17.00	469.89
1	60.00		541.58

Experiment 15: 6/17/98 Long Column Initial Height=8'

Long column data

Port	Time (min)	Conc (mg/l)
3	0.20	55.47
5	0.38	167.86
7	0.52	345.45
8	0.68	386.69
3	1.15	31.18
5	1.35	44.85
7	1.48	103.45
8	1.63	86.17
3	2.80	16.41
5	2.93	21.88
7	3.07	38.19
8	3.20	46.85
3	4.78	12.06
5	4.92	12.32
7	5.05	8.05
8	5.20	19.49
3	9.87	10.73
5	10.03	7.98
7	10.17	5.19
8	10.35	12.20

Blank Conc (mg/l)

0.40

Recycle Conc (mg/l)

1	235.81
2	275.83
3	282.84

CERGRENE data

Column	Time (min)	Height(in)	Conc. (mg/l)
1	0.00		269.33
1	1.00	16.50	492.50
1	3.00	17.00	470.94
1	5.00	16.00	493.68
1	1.00		482.38
1	12.00	16.75	517.29

Experiment 1: 3/17/2000

Long column data

Port	Time (min)	SS mg/L	VSS mg/L
3	0.67	Void	Void
5	0.83	52.12	28.48
7	0.92	46.21	36.36
8	1.17	89.13	41.30
3	1.53	55.97	46.54
5	1.82	Void	Void
7	1.88	45.35	27.91
8	2.12	47.09	30.69
3	3.02	54.55	22.73
5	3.28	43.40	25.79
7	3.57	48.95	29.47
8	3.67	44.00	24.50
3	5.65	Void	Void
5	5.90	43.87	27.10
7	6.02	Void	Void
8	6.17	55.00	29.00
3	9.38	53.13	30.47
5	9.58	47.53	27.78
7	9.80	47.79	22.79
8	10.03	48.03	30.92
3	14.85	Void	Void
5	15.00	50.28	28.81
7	15.13	53.50	34.00
8	15.28	60.00	31.00
3	31.08	43.02	20.93
5	31.18	46.67	27.33
7	31.32	47.14	27.86
8	31.45	45.20	25.99
3	59.22	32.77	18.08
5	59.38	35.83	18.33
7	59.57	50.00	23.00
8	59.73	38.85	22.29

Long Column Initial Height=7'11"

Field Blank

SS mg/L	VSS mg/L
Void	Void

Background

	SS mg/L	VSS mg/L
Start	46.00	26.00
Start	49.66	30.87
Start	60.00	32.00
End	Void	Void
End	55.86	22.07

CERGRENE data*

Time (min)	SS mg/L	VSS mg/L
0	*68.25*	33.33
1.5	64.41	35.03
3	**53.33**	**30.37**
3	**66.17**	**35.34**
5	**59.56**	**31.62**
7	68.24	42.57
10	**63.12**	**36.88**
15	**289.33**	46.00
20	**273.00**	**40.00**
30	70.83	**38.33**
60	**68.97**	**40.00**

* Values supressed in VICTOR are bolded;
backround value used in VICTOR is italicized.

Experiment 2: 3/28/2000

Long column data		SS	VSS	TS
Port	Time (min)	mg/L	mg/L	mg/L
3	0.02	165.00		518.13
5	0.06	171.00		521.94
7	0.08	180.00	109.00	525.71
8	0.11	151.00		546.56
3	0.66	172.00		502.27
5	0.82	168.00		457.24
7	0.92	161.00		495.8
8	1.10	156.00		489.44
3	2.80	155.00		537.66
5	2.97	155.00		535.06
7	3.18	131.00		517.93
8	3.37	151.00		522.92
3	4.78	145.00		598.12
5	4.95	153.00		493.17
7	5.13	157.00		500
8	5.28	148.00		500.6
3	9.53	127.00		526.32
5	9.70	126.00	-46.00	482.16
7	9.92	140.00		491.76
8	10.08	139.00		484.44
3	14.98	91.00		496.47
5	15.15	119.00		472.64
7	15.37	126.00		474.83
8	15.57	124.00		492.63
3	29.38	119.00		438.01
5	29.60	121.00		477.44
7	29.85	120.00		453.05
8	30.02	111.00		***9652.29***
2	55.15	127.00		474.68
3	60.48	103.00	83.00	430.23
5	60.65	95.00		434.08
7	60.83	165.00	110.00	481.46
8	61.15	97.00		484.12

Long Column Initial Height=7'10.7"

Field Blank

SS	VSS	TS
mg/L	mg/L	mg/L
95		542.8571

Background

	SS	VSS	TS
	mg/L	mg/L	mg/L
Start	200.00		606.62
Start	157.00		518.03
End	161.00		496.57
End	156.00		482.81

Extreme not used in graphs

CERGRENE data*	SS	VSS	TS
Time (min)	mg/L	mg/L	mg/L
0	167	112	554
1	**535**		**550**
3	213		601
3	214		578
5	**207**		**867**
7	**202**		609
10	243		643
15	**232**		**605**
20	261		646
30	293		**614**
60	**219**	155	**609**

* Values supressed in VICTOR are bolded.

Experiment 3: 6/9/2000

CERGRENE data*	TS	
Time (min)	mg/L	
0	241.09	
1	240.41	
3	**232.18**	X
3	**231.93**	X
5	**221.57**	X
10	**237.15**	X
15	248.38	
20	**239.40**	X
30	260.16	

* VICTOR Supressed in bold

Field Blank	
	TS
	mg/L
	244.21

Background	
	TS
	mg/L
Start	275.77
Start	303.93
Start	301.10

Long column - no samples collected for experiment 3.

COULTER& LS Particle Size Analyzer

27 Jan 1999

File name: tomsand.$01
Sample ID: sand from

Group ID: tomsand

Run number: 1

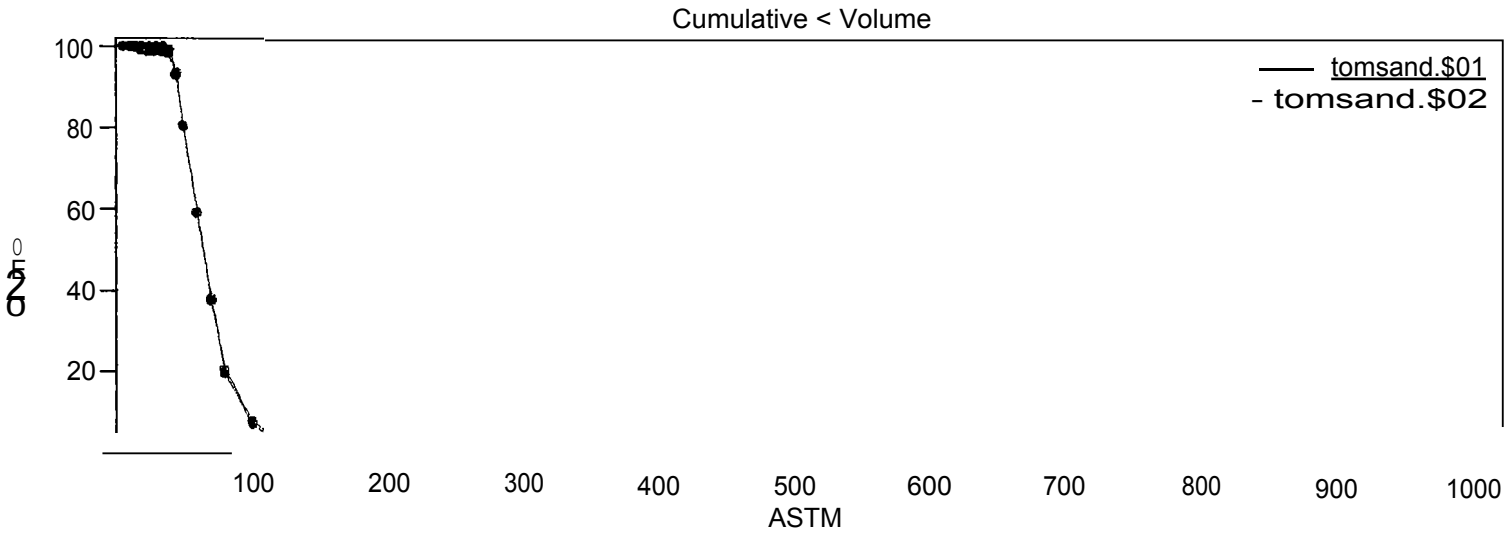
Optical model: Fraunhofer PIDS included
LS 230 Small Volume Module

File name: tomsand.$02
Sample ID: sand from

Group ID: tomsand

Run number: 2

Optical model: Fraunhofer PIDS included
LS 230 Small Volume Module



Size }gym	ASTM	tomsand.$01 Cum. < Volume	tomsand.$02 Cum. < Volume e
0	999	0	0
38	400	0	0
45	325	0	0
53	270	0	0
63	230	0	0
75	200	0.072	0.051
90	170	0.30	0.15
106	140	0.70	0.35
125	120	2.28	1.68
150	100	7.86	7.01
180	80	20.4	19.5
212	70	38.0	37.4
250	60	59.2	59.0
300	50	80.4	80.6
355	45	93.0	93.6
425	40	98.2	99.3
500	35	98.7	100.0
600	30	98.7	100
710	25	98.8	100
850	20	99.1	100

COULTER® LS Particle Size Analyzer

27 Jan 1999

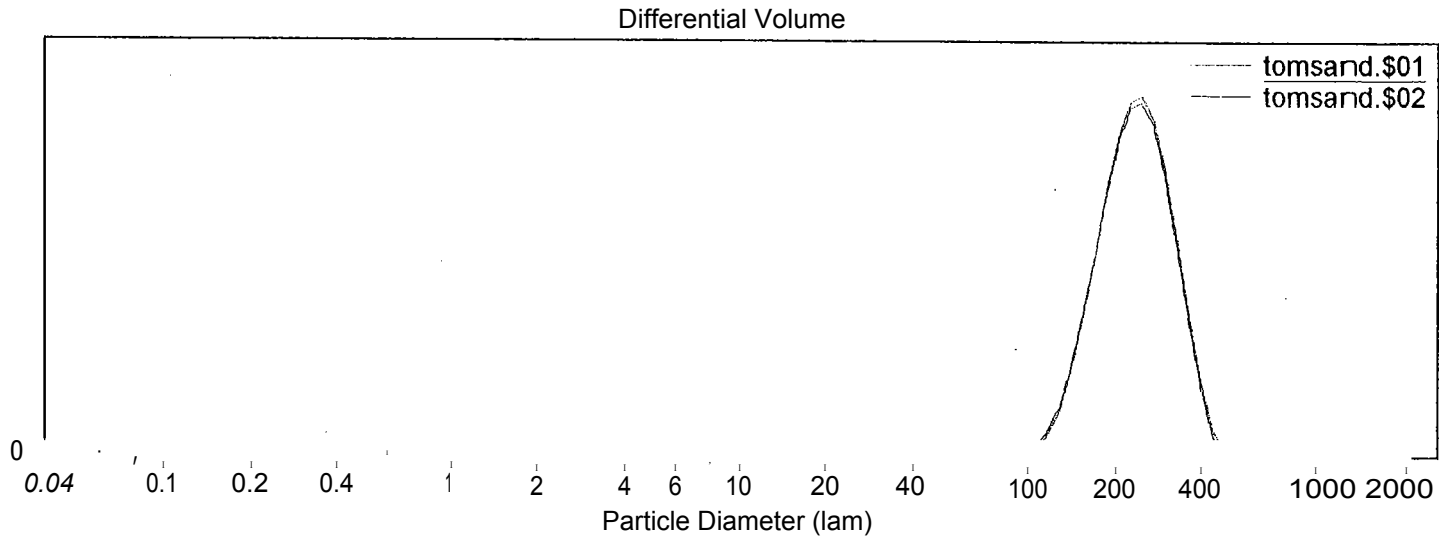
Size Jim	ASTM	tomsand.$01 Cum. < Volume	tomsand.$02 Cum. < Volume
1,000	18	99.5	100
1,180	16	99.8	100
1,400	14	100.0	100
1,700	12	100.0	100
2,000	10	100	100
		100	100

COULTER® LS Particle Size Analyzer

27 Jan 1999

File name: tomsand.$01
Sample ID: sand from
Group ID: tomsand
Run number: 1
Optical model: Fraunhofer PIDS included
LS 230 Small Volume Module

File name: tomsand.$02
Sample ID: sand from
Group ID: tomsand
Run number: 2
Optical model: Fraunhofer PIDS included
LS 230 Small Volume Module



Volume Statistics (Arithmetic) tomsand. $01

Calculations from 0.040 pm to 2,000 lam

Volume	100.0%		
Mean:	247.51 am	S.D.:	108.71 am
Median:	232.81 am	C.V.:	43.9%
D(3,2):	221.0 lam		
Mode:	245.2 lam		

<	10	25	50	75	90
Size lam	156.2	188.8	232.8	284.4	336.1

COULTER® LS Particle Size Analyzer

27 Jan 1999

Volume Statistics (Arithmetic) tomsand.$02

Calculations from 0.040 pm to 2,000 pm

Volume	100.0%		
Mean:	240.6 pm	S.D.:	67.12 pm
Median:	233.7 pm	C.V.:	27.9%
D(3,2):	222.0 tam		
Mode:	245.2 pm		

% <	10	25	50	75	90
Size pm	158.8	190.4	233.7	284.3	**334.0**

COULTER® LS Particle Size Analyzer

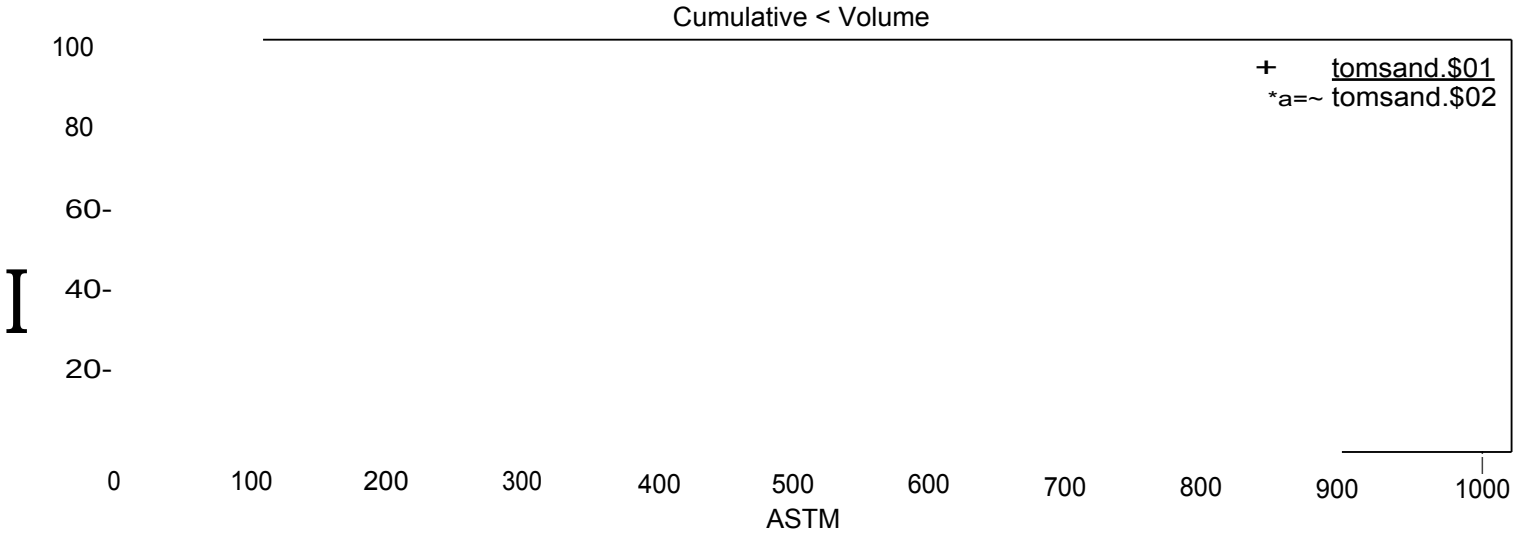
27 Jan 1999

Volume Statistics (Arithmetic) tomsand.$02

Calculations from 0.040 pm to 2,000 pm

Volume	100.0%		
Mean:	240.6 pm	S.D.:	67.12 pm
Median:	233.7 pm	C.V.:	27.9%
D(3,2):	222.0 pm		
Mode:	245.2 pm		

<	10	25	50	75	90
Size pm	158.8	190.4	233.7	284.3	334.0



Size }gym	ASTM	tomsand.$01 Cum. < Volume	tomsand.$02 Cum. < Volume
0	999	0	0
38	400	0	0
45	325	0	0
53	270	0	0
63	230	0	0
75	200	0.072	0.051
90	170	0.30	0.15
106	140	0.70	0.35
125	120	2.28	1.68
150	100	7.86	7.01
180	80	20.4	19.5
212	70	38.0	37.4
250	60	59.2	59.0
300	50	80.4	80.6
355	45	93.0	93.6
425	40	98.2	99.3
500	35	98.7	100.0
600	30	98.7	100
710	25	98.8	100
850	20	99.1	100

COULTER® LS Particle Size Analyzer

27 Jan 1999

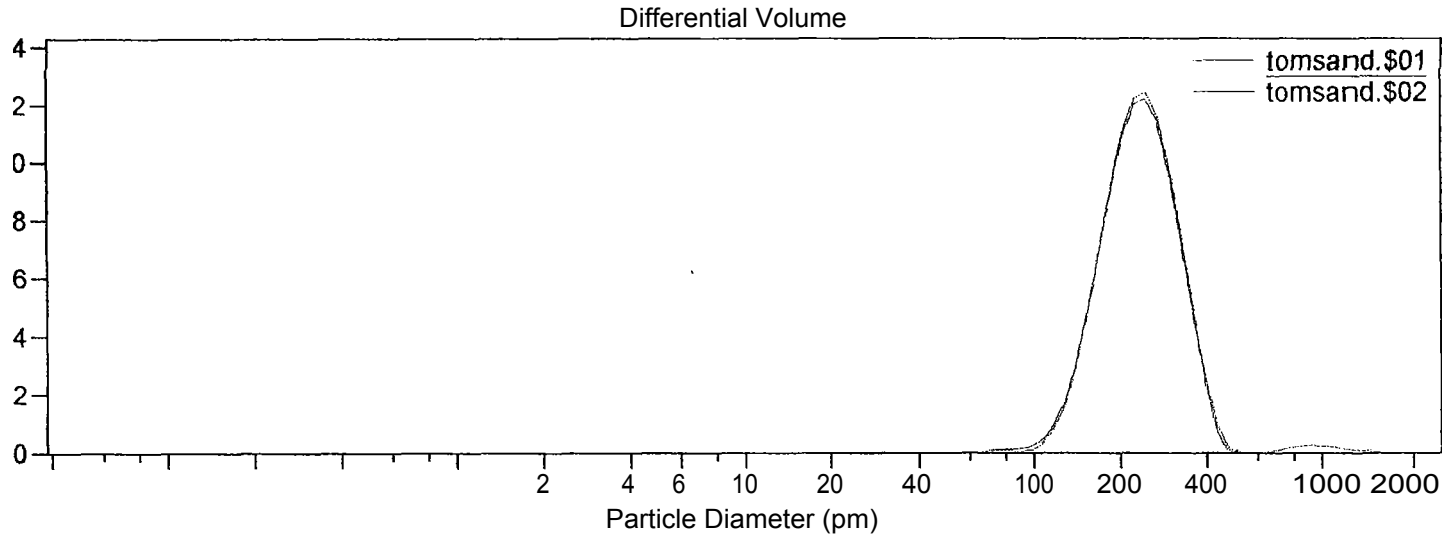
Size pm	ASTM	tomsand.$01 Cum. < Volume	tomsand.$02 Cum. < Volume
1,000	18	99.5	100
1,180	16	99.8	100
1,400	14	100.0	100
1,700	12	100.0	100
2,000	10	100	100
		100	100

COULTER® LS Particle Size Analyzer

27 Jan 1999

File name:	tomsand.$01	Group ID:	tomsand
Sample ID:	sand from		
		Run number:	1
Optical model:	Fraunhofer PIDS included		
LS 230	Small Volume Module		
Start time:	15:08 27 Jan 1999	Run length:	60 Seconds
Obscuration:	9%		
PIDS Obscur:	34%		
Fluid:	Water		
Software:	2.11	Firmware:	2.02 2.02

File name:	tomsand.$02	Group ID:	tomsand
Sample ID:	sand from		
		Run number:	2
Optical model:	Fraunhofer PIDS included		
LS 230	Small Volume Module		
Start time:	15:11 27 Jan 1999	Run length:	60 Seconds
Obscuration:	9%		
PIDS Obscur:	29%		
Fluid:	Water		
Software:	2.11	Firmware:	2.02 2.02



Volume Statistics (Arithmetic) tomsand.$01

Calculations from 0.040 pm to 2,000 pm

Volume	100.0%		
Mean:	247.5 pm	S. D.:	108.7 pm
Median:	232.8 pm	C.V.:	43.9%
D(3,2):	221.0 pm		
Mode:	245.2 pm		

<	10	25	50	75	90
Size pm	156.2	188.8	232.8	284.4	336.1

Appendix K. CERGRENE Matrix Analysis (Victor)

Each CERGRENE column has a top section and a bottom section which can be isolated by the central ball valve. The settling height (h) is measured from the top of the water level to the start of the bottom section. The initial mass of particles is introduced by vacuum aspiration into each column. If the mixing basin is homogeneous, the initial mass of solids (Moi) should be the same for columns i to (Nf-1), Nf being the total number of sampling points.

$$Mo_i = Mo \quad \forall i = 1 \; to \; (Nf - 1)$$

By noting, MH, the mass of particles in the top section and MB, the mass of particles in the bottom section, the following relation can be written:

$$Mo_i = MBo_i + MHo_i \quad \forall i = 1 \; to \; (Nf - 1)$$

Also, assuming the mixing is homogeneous, the top and bottom section should be of same initial mass

$$MBo_i = MBo \quad and \quad MHo_i = MHo \quad \forall i = 1 \; to \; (Nf - 1)$$

The settling height is noted h, if the columns are identical this value should be constant:

$$h_i = h \quad \forall i = 1 \; to \; (Nf - 1)$$

At time $t = 0$, the initial mass, MBo_i, in the bottom part of the column is equal to the initial mass, MHo_i, in the top section of the column. At any given time, t= t_i and for any column *i*, the central ball valve can isolate the top and bottom sections of the column. The mass of solids found in the bottom section correspond to the initial mass in the bottom MBo_i and a fraction of settled solids M_i from the top section MHo_i that effectively settled between times $t = 0$ and $t = t_i$.

$$MB_i = MBo_i + M_i \quad \forall i = 1 \; to \; (Nf - 1)$$

The accumulated masses from one column to the next, in function of time is given by :

$$MB_i - MB_{i-1} = MBo_i + M_i - MBo_{i-1} - M_{i-1} \quad \forall i = 1 \; to \; (Nf - 1)$$

Assuming an homogeneous mixing:

$$MB_i - MB_{i-1} = M_i - M_{i-1} = P_i \quad \forall i = 1 \; to \; (Nf - 1)$$

with P_i being the mass of the settled particles from the top section between time $t = t_{i-1}$ and $t = t_i$.

Thus

$$MB_i = MBo + M_i = MBo + \sum_{k=1}^{i} P_k \quad \forall i = 1 \; to \; (Nf - 1)$$

The accumulated mass becomes:

$$M_i = \sum_{k=1}^{i} P_k \quad \forall i = 1 \; to \; (Nf - 1)$$

Chebbo et al. (1992) analyzed this curve in the following fashion :

$$M(t) = S(t) + t\frac{dM(t)}{dt}$$

where

$M(t)$	cumulated mass of settled particles between $t = 0$ et t
$S(t)$	settled particles at time t with a settling velocity greater than $\frac{h}{t}$
$t\frac{dM(t)}{dt}$	mass of settled particles at time t with a settling velocity less than $\frac{h}{t}$

Establishment of steady flow
Derived from "Fluid Mechanics with Engineering Applications", Daugherty et al. (1985), p 454, 455

		tube	column	
Diameter, D	in.	**0.75**	**2.5**	**Bold = given**
Diameter, D	m	0.01905	0.0635	
Length, L	m	**3**	**0.91**	

Velocity, Vo, assumed to be equal to average measured velocity

Calculation of Friction

kinematic viscosity, m^2/s			D	D	e in.	e mm
1.003E-06		m^2	in.	m	**0.000005**	**0.0015**
	Area tube	0.003167	2.5	0.0635	e/D in.	
	Area col.	0.000285	0.75	0.01905	0.00008	1.24E-06
	Ratio	11.11111				

Velocity	cm/s	m/s	D, M	Reynolds Number R	Friction - f	Average f
Vo JM pump - col	**11**	0.11	0.0635	6964.108	0.034592	0.03219
Vo EPA pump - col	**20**	0.2	0.0635	12662.01	0.029789	
Vo* JM pump - tube	122.2222	1.222222	0.01905	23213.69	0.025601	0.023824
Vo* EPA pump - tube	222.2222	2.222222	0.01905	42206.71	0.022047	

* calculated from continuity equation

	tube	column	
friction, f	0.023824	0.03219	(f = 0.316/R^0.25 for 3000 < R < 100000)

Equation for losses, k
k = k'+fL/d
k' (not used)

Solve for V = 0.25Vo, 0.5Vo & 0.75Vo

L	k	L/1+K	Vo (m/s)	0.25Vo	0.50Vo	0.75Vo	0.95Vo
0.91	0.461313	0.622728	0.11	0.0275	0.055	0.0825	0.1045
			0.2	0.05	0.1	0.15	0.19
3	3.751752	0.631346	1	0.25	0.5	0.75	0.95
			2.222222	0.555556	1.111111	1.666667	2.111111

Time, t, to fraction of full velocity
t=L/[Vo(1+k)]*ln[(Vo+V)/(Vo-V)]

	L m	0.25Vo s	0.50Vo s	0.75Vo s	0.95Vo s
Column	0.91	2.891867	6.219422	11.01611	20.74002
		1.590527	3.420682	6.058862	11.40701
Tube	3	0.322508	0.693604	1.228543	2.281402
		0.145128	0.312122	0.552844	1.026631

Calcualtion of Wall Effects

from Dalrymple et al. "Physical and Settling Characteristics of Particulates in Storm and Sanitary Wastewaters" EPA-670/2-75-011.

For Column Vd = V*[1-(d/D)^2][1-1/2(d/D)^2]^0.5

		1	2	3
Settling veloc cm/sec	Vd			
Settling veloc cm/sec	V	0.86	0.76	0.48
diameter part cm*10^-4	d	100	80	60
diameter colu cm	D	6	6	6

	Vd for 1	Vd for 2	Vd for 3
	0.859997	0.759998	0.479999
% difference	0.000347	0.000222	0.000125

Threshhold 5% Effect

For Tubing Vd = V*[1-(d/D)^2][1-1/2(d/D)^2]^0.5

		1
Settling veloc cm/sec	Vd	
Settling veloc cm/sec	V	0.86
diameter part cm*10^-4	d	100
diameter colu cm	D	0.051

	Vd for 1
	0.818949
5 % Effect	4.773375