1989

Development of scale factors for clarifier design based on batch settling data

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DEVELOPMENT OF SCALE FACTORS FOR CLARIFIER DESIGN BASED ON BATCH SETTLING DATA

BY

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B.S., Geneva College, 1985

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Graduate Studies Program
of the College of Engineering
University of Central Florida
Orlando, Florida

Fall Term
1989

ABSTRACT

Traditionally, batch settling tests have been employed to determine the values of the settling parameters V_0 and K of the Vesilind equation which represents activated sludge settling velocity as a function of solids concentration. It remains unresolved how closely batch settling tests describe settling in full-scale clarifiers. An experimental procedure was developed to determine scale factors between batch settling and full-scale solids flux curves.

An experimental protocol was determined for full-scale clarifier operation, including specific criteria of necessary instrumentation and operational flexibility. Several graphical techniques were evaluated and a procedure was selected to determine a scale factor between batch and full-scale settling. The specified procedure requires determination of underflow velocity and concentration. The scale factor was approximately 0.84 as applied to the limiting flux, thus clarifiers designed from batch settling tests would be underdesigned. In addition, a methodology was developed to account for batch flux curve variability in the form of a safety factor. Finally, a design procedure was recommended to calculate clarifier area based

on the scale factor determined from the batch and full-scale experiments.

ACKNOWLEDGEMENTS

I would like to express my graditude to the professors and staff of the Environmental Engineering Department at the University of Central Florida for making my masters program an enjoyable and rewarding experience. I especially want to thank Dr. John Dietz for his guidance and patience throughout all phases of this research; my parents and family who have given me encouragement and the opportunity to complete my education; and finally, Dan Smith and Andy Woodcock for thier assistance with graphics and fieldwork.

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CHAPTER I

INTRODUCTION

Public concern about surface and groundwater quality has prompted many state and local governments to tighten effluent quality standards for municipal wastewater treatment. In response, municipal wastewater treatment plants must remove all regulated constituents to acceptable levels creating the need for highly efficient treatment systems. Future wastewater treatment plants can be designed to meet the stringent effluent standards, but many existing plants must be expanded or retrofitted to achieve the necessary results.

Since its introduction in 1914, the activated sludge process has become the most common method for treating municipal wastewater. The overall process objective is to stabilize the wastewater by converting organic material into an active biomass which can be separated from the liquid stream by gravity sedimentation. Several modifications of the process exist (i.e., step aeration, contact stabilization, Bardenpho process, etc.); however, the fundamental unit operations and flows are the same. The basic process is a loop consisting of an aeration tank followed by a secondary clarifier as shown in Figure 1.

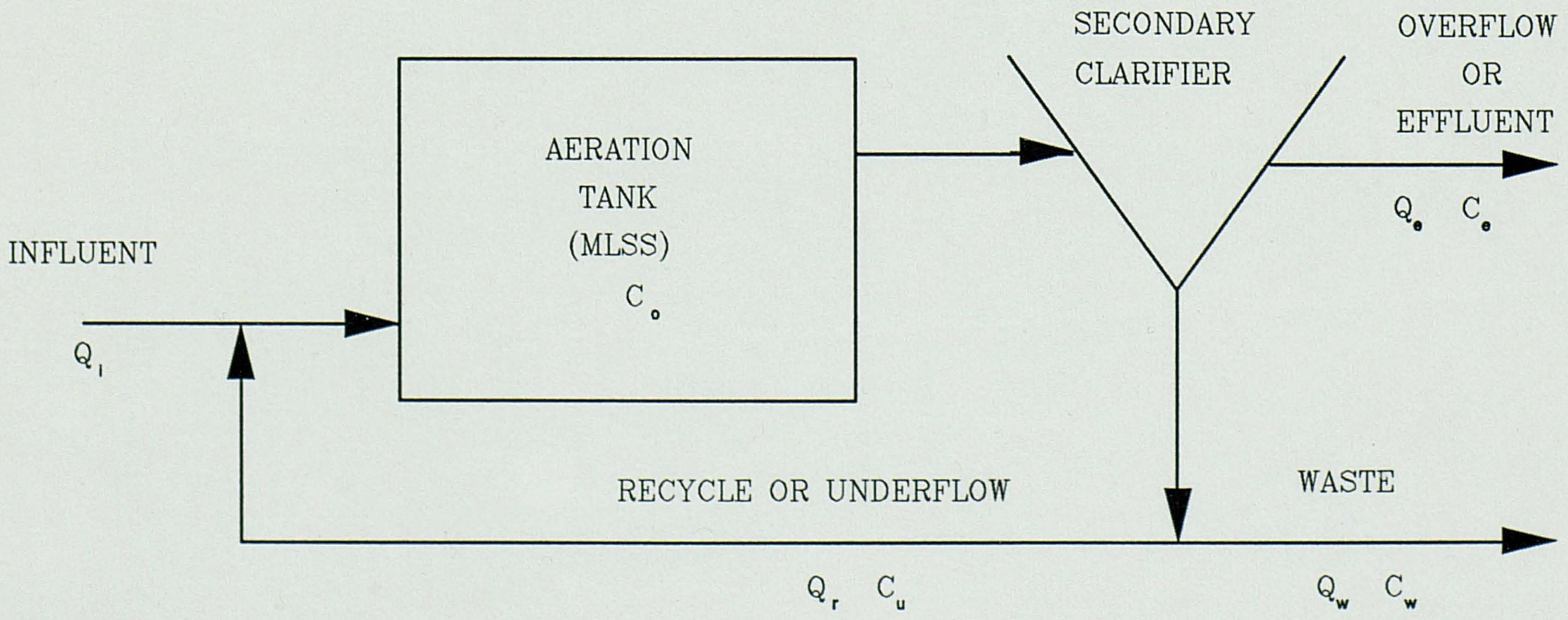

Figure 1. Activated Sludge Process

The two are joined by a recycle line which is necessary to maintain the microbial biomass population in the continuous system.

The influent stream often goes through pretreatment before entering the aeration tank. Common pretreatment operations include grinding and shredding by a comminutor to diminish large objects, screening to remove large objects and primary sedimentation to remove settleable material. Many wastewater treatment plants utilize one or more of these pretreatment methods to reduce suspended solids and create a more uniform influent stream composition.

In the aeration tank, organic material is converted to a microbial population in the presence of oxygen. The organics are utilized as a substrate by the biomass for cell maintenance and synthesis. Air is usually supplied as the oxygen source, although pure oxygen is used in some systems. Oxygen is required by the biomass for respiration and serves as the terminal electron acceptor for the process. Nutrients, such as nitrogen and phosphorus, are necessary for microbial processes and can become rate limiting if not present in sufficient quantities. Supplementation may be provided for nutrient deficient wastewaters. Commonly referred to as the mixed liquor, the contents of the aeration tank must be sufficiently mixed to ensure contact between the substrate, oxygen and biomass to promote the biochemical reactions.

The mixed liquor is transferred from the aeration tank to the secondary clarifier where it is exposed to a quiescent environment. The solid biomass flocculates and settles to the bottom of the clarifier leaving a clear supernatant layer at the surface. The clear layer overflows a weir and is known as the overflow or effluent. The solids thicken towards the clarifier bottom and are pumped back to the aeration tank in the recycle or underflow line.

The secondary clarifier performs two functions in respect to solids separation. First, it clarifies the overflow so that the amount of suspended solids in the effluent is minimized. Second, it thickens the underflow so that sufficient biomass is returned to the aeration tank to maintain the desired solids inventory. Failure of either of these functions can result in excessive suspended solids in the effluent and, consequently, poor effluent quality. The solids inventory in the activated sludge system is maintained by wasting biomass in proportion to the rate of biomass growth. The waste sludge is commonly taken from the recycle line, since the solids content is highest and volume of waste sludge is lowest at this point. The waste sludge is sent to the sludge management system for stabilization and disposal.

The aeration tank and clarifier function in tandem and successful operation of the system requires efficient performance from each. Secondary clarifier control techniques have been developed based on the theory of solids flux. Solids flux is the mass of solids that flow through the clarifier area in a unit of time (i.e., Kg/m^2-day). The control techniques, collectively known as the state point concept, require definition of a settling flux curve. The state point concept is a graphical representation of a mass balance around a clarifier, and although theoretically sound, has not been widely accepted by design engineers and plant operators because of the time and labor involved in developing the settling flux curve.

A settling flux curve is developed from multiple batch settling tests performed at varying suspended solids concentrations. In each batch test, the solids-liquid interface height is measured with respect to time, and a solids settling velocity is determined. Solids flux is the product of the settling velocity and the suspended solids concentration for each batch test. The settling flux curve is produced when the solids fluxes from all the batch settling tests are combined on one plot vs. their respective concentrations. To be representative of actual slurry settling characteristics, the settling flux curve must be updated regularly.

Another problem with the state point concept is that it remains uncertain how closely the batch settling flux curve represents settling performance in a full-scale clarifier. The focus of this research is to develop a procedure for determining scale factors between batch settling solids flux curves and continuous full-scale performance. Several procedures will be explored and evaluated to determine which one gives more utility to clarifier design and operation. In particular, a procedure for determining scale factors for clarifier design will be introduced for use in expanding and retrofitting wastewater treatment plants.

CHAPTER II

LITERATURE REVIEW

Gravitational Thickening - Historical Development

Theoretical work in solids flux began as early as 1916 with the work of Coe and Clevenger (1916). Solids flux is the mass of solids that flow through the clarifier surface area in a unit of time. According to the theory, any layer of suspended solids in a thickener has a specific solids flux. The limiting layer is determined using a series of batch settling tests performed over a range of slurry concentrations. The required thickener surface area is determined by providing enough area to assure that solids are loaded at a rate less than the solids flux of the limiting layer.

Kynch (1952) developed the mechanism of batch thickening for ideal suspensions. The basic assumption of Kynch's work was that the settling velocity of a particle in a layer was a function of concentration, only. Dick and Ewing (1967) confirmed Kynch's analysis for "ideal" suspensions but not for activated sludge. In addition, they supported the use of multiple batch settling tests at different slurry concentrations to determine the limiting flux.

Yoshioka et al. (1957) developed the modern settling flux curve. The settling flux curve, shown in Figure 2, is a plot of solids flux vs. concentration and is a representation of the limiting layer. A tangent to the batch flux curve extends in one direction to the limiting flux (G_L) and in the other to the underflow concentration (C_u) with a slope of -u, the negative of the underflow velocity.

Solids flux analysis was first used to analyze secondary clarifiers by Dick (1970). According to his analysis, solids must be applied at a rate that is not in excess of the settling rate. Keinath et al. (1977) demonstrated that the settling flux approach can be used to optimize treatment plant operation and evaluate the economics of activated sludge design. This "unified systems approach" gives plant operators a theoretically sound tool to initiate system changes in response to variations in influent, recycle and overflow rates and settling characteristics.

State Point Concept

Keinath refined the State Point Concept first introduced by McHarg (1974). A line drawn tangent to the settling flux curve through a desired underflow concentration (X-axis) intercepts the Y-axis at the

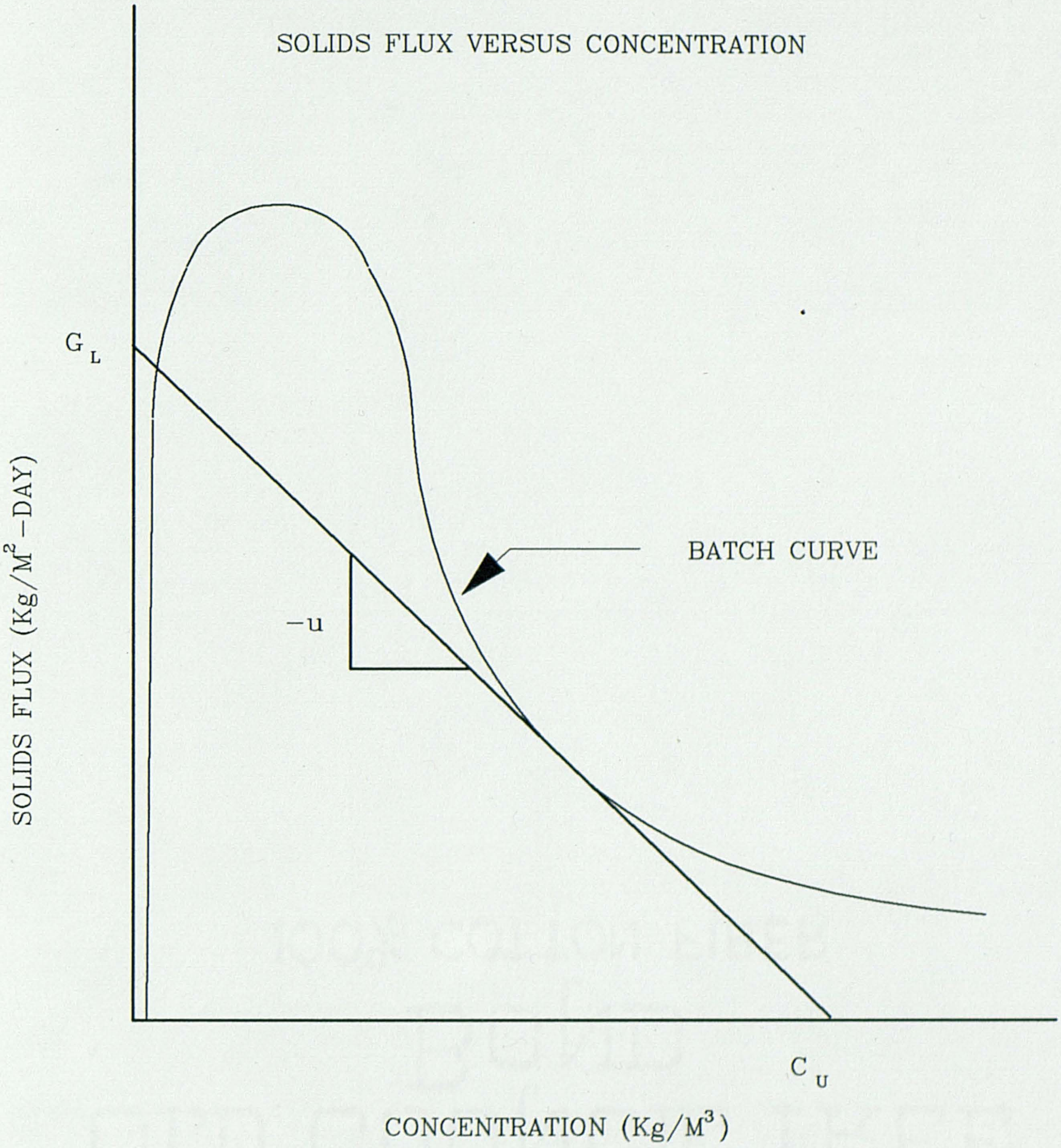

Figure 2. Settling Flux Curve

limiting flux (G_L) and has a slope equal to the clarifier underflow velocity (-u) as shown in Figure 3. The underflow velocity neglects the sludge wasting flow rate (Qw), since Qw is usually less than 3% of Q_i and can be omitted without significant error (Keinath et al. 1977). A vertical line (line C, Figure 3) drawn from the point of tangency intersects the X-axis at the clarifier blanket concentration (C_b). Another line drawn from the origin at a slope equal to the clarifier overflow velocity (v) intersects the previous line (line A) at the state point (S). By varying the slope(s) of either one or both of these lines, the state point can be moved (Figure 4). Satisfactory thickening performance can be expected as long as the state point (S) remains underneath the settling flux curve, and the underflow velocity line (-u) falls tangent to or below the curve (Figures 4 and 5). Drastic changes in sludge settling characteristics would make the flux curve obsolete and stands as the exception to the above discussion. A new flux curve would have to be generated in this case.

The settling flux plot will have a characteristic state point for each combination of recycle, overflow rate and mixed liquor concentration (Figure 4). To locate the state point, the underflow and overflow velocities (u and v, respectively) are determined by dividing the flow rates (Q_r

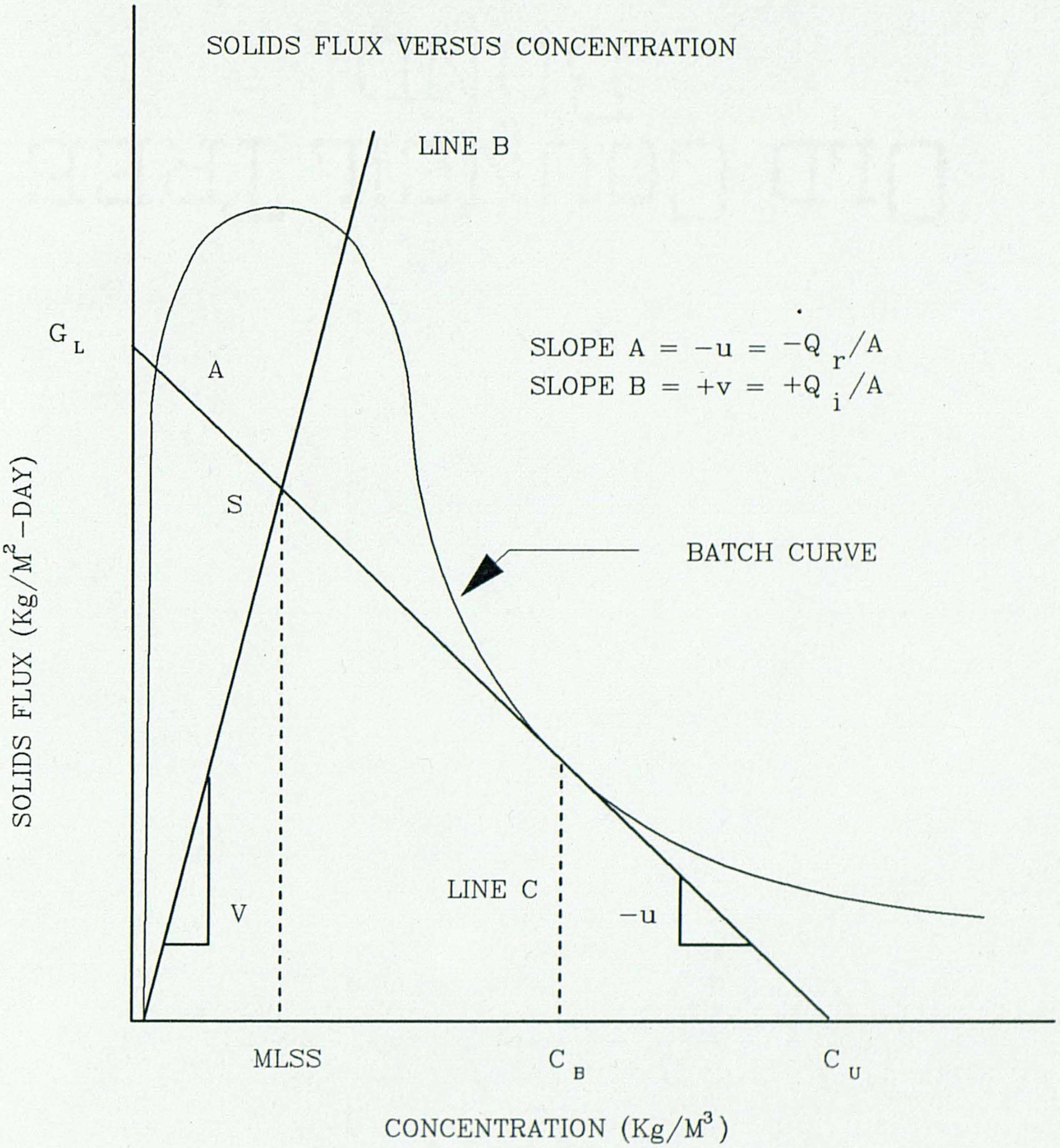

Figure 3. Settling Flux Curve with State Point (S)

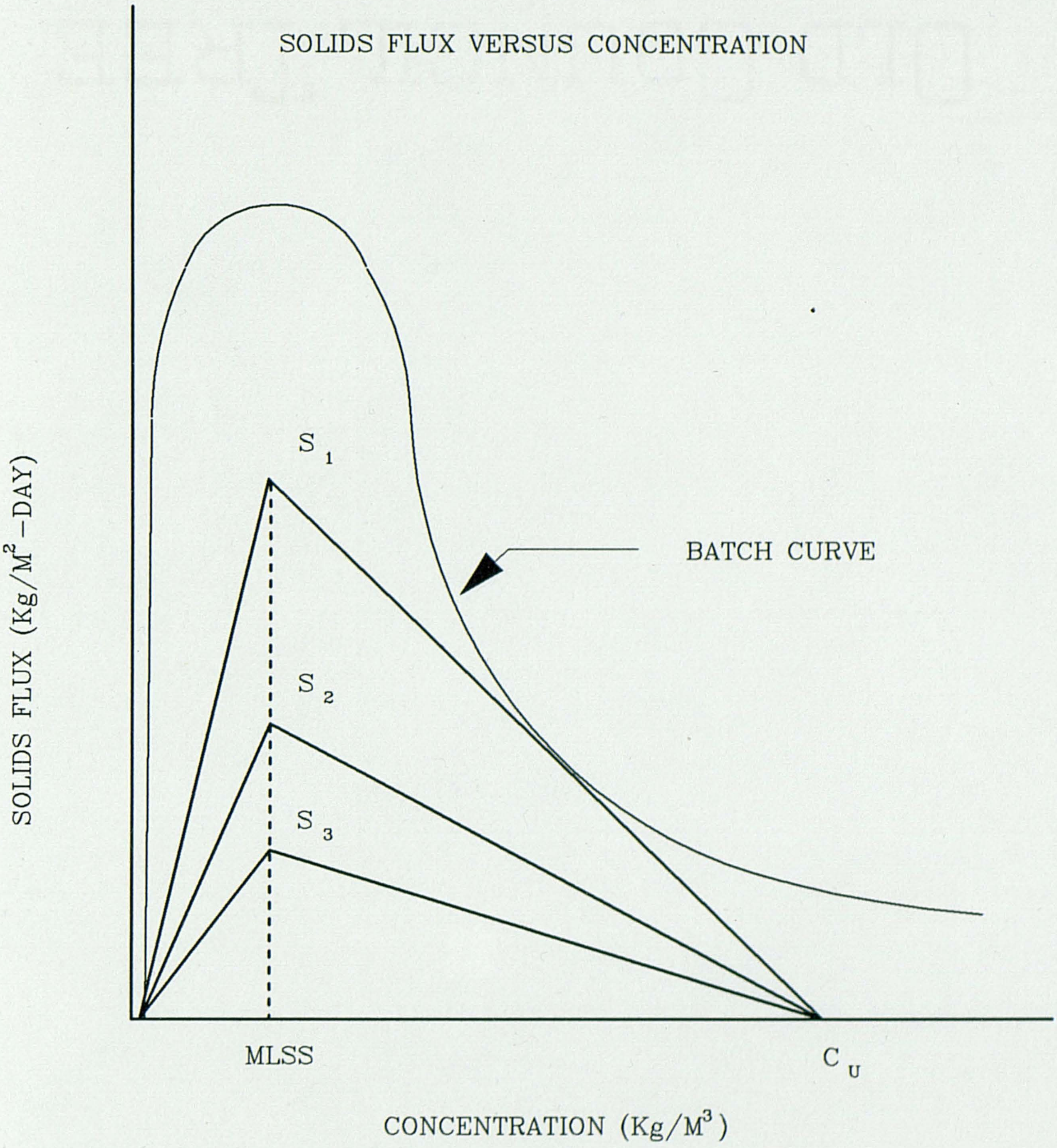

Figure 4. Solids Flux Curve with Varying Overflow and Underflow Velocities and Constant MLSS

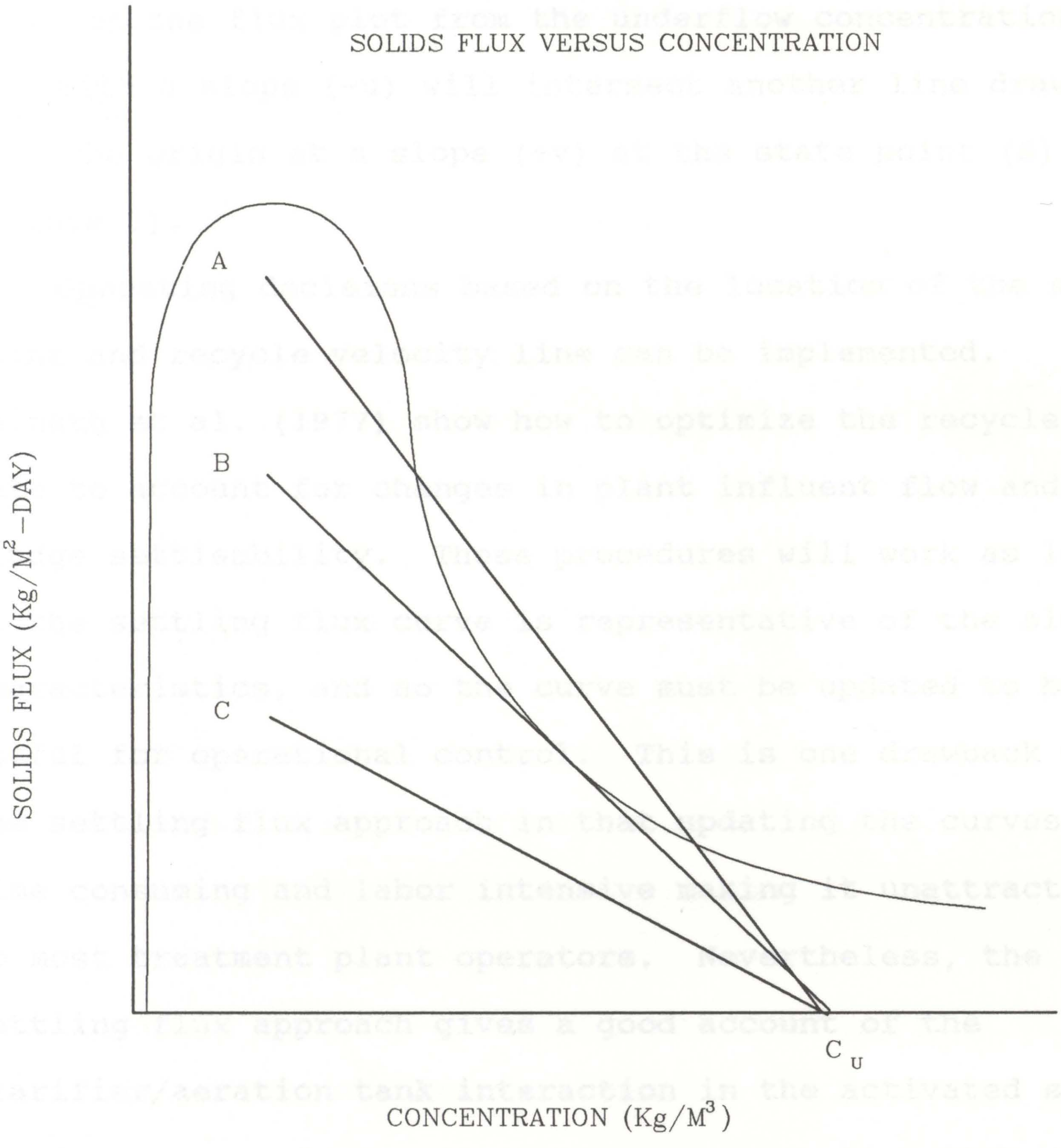

Figure 5. Solids Flux Curve at (A) Overloaded, (B) Limiting, and (C) Underloaded Conditions

and Q_i, respectively) by the surface area of the clarifier (A). When the system is operating at steady state, a line drawn on the flux plot from the underflow concentration (C_u) with a slope (-u) will intersect another line drawn from the origin at a slope (+v) at the state point (S) (Figure 3).

Operating decisions based on the location of the state point and recycle velocity line can be implemented. Keinath et al. (1977) show how to optimize the recycle flow rate to account for changes in plant influent flow and sludge settleability. These procedures will work as long as the settling flux curve is representative of the sludge characteristics, and so the curve must be updated to be useful for operational control. This is one drawback of the settling flux approach in that updating the curves is time consuming and labor intensive making it unattractive to most treatment plant operators. Nevertheless, the settling flux approach gives a good account of the clarifier/aeration tank interaction in the activated sludge process.

Riddell et al. (1983) developed a method for estimating the capacity of an activated sludge plant based on the solids handling capacity of the clarifier. Based on a material balance for suspended solids, an equation was derived which expresses the thick blanket concentration

(C_B) as a function of mixed liquor concentration (MLSS) and recycle ratio (R):

$$C_u = \frac{(1+R)\,MLSS}{2R} + \left[\left(\frac{1+R}{R}\right)^2 \frac{MLSS^2}{4} - \frac{(1+R)\,MLSS}{R\ K}\right]^{0.5} \tag{1}$$

where

C_B = thick blanket concentration (Kg/m^3)

MLSS = mixed liquor concentration (Kg/m^3)

R = recycle ratio (unitless)

Furthermore, an equation for limiting flux was given in terms of thick blanket concentration and the Vesilind parameters (V_0 and K):

$$G_L = V_0\ K\ C_B^{\ 2}\ \exp(-KC_B) \tag{2}$$

where

G_L = limiting flux (Kg/m^2-day); and

C_B = thick blanket concentration (Kg/m^3); and

V_0 = settling parameter (m/day); and

K = settling parameter (m^3/Kg).

When MLSS, R, V_0 and K are known, the limiting flux (G_L) can be solved for by substituting equation (1) into (2).

Clarifier Concentration Profiles

Keinath et al. (1976) describes solids concentration profiles in terms of three distinct zones or blankets. Figure 6 shows the blanket variation between clarifiers which are (A) underloaded, (B) critically loaded and (C) overloaded. In most cases, underloaded clarifiers have two

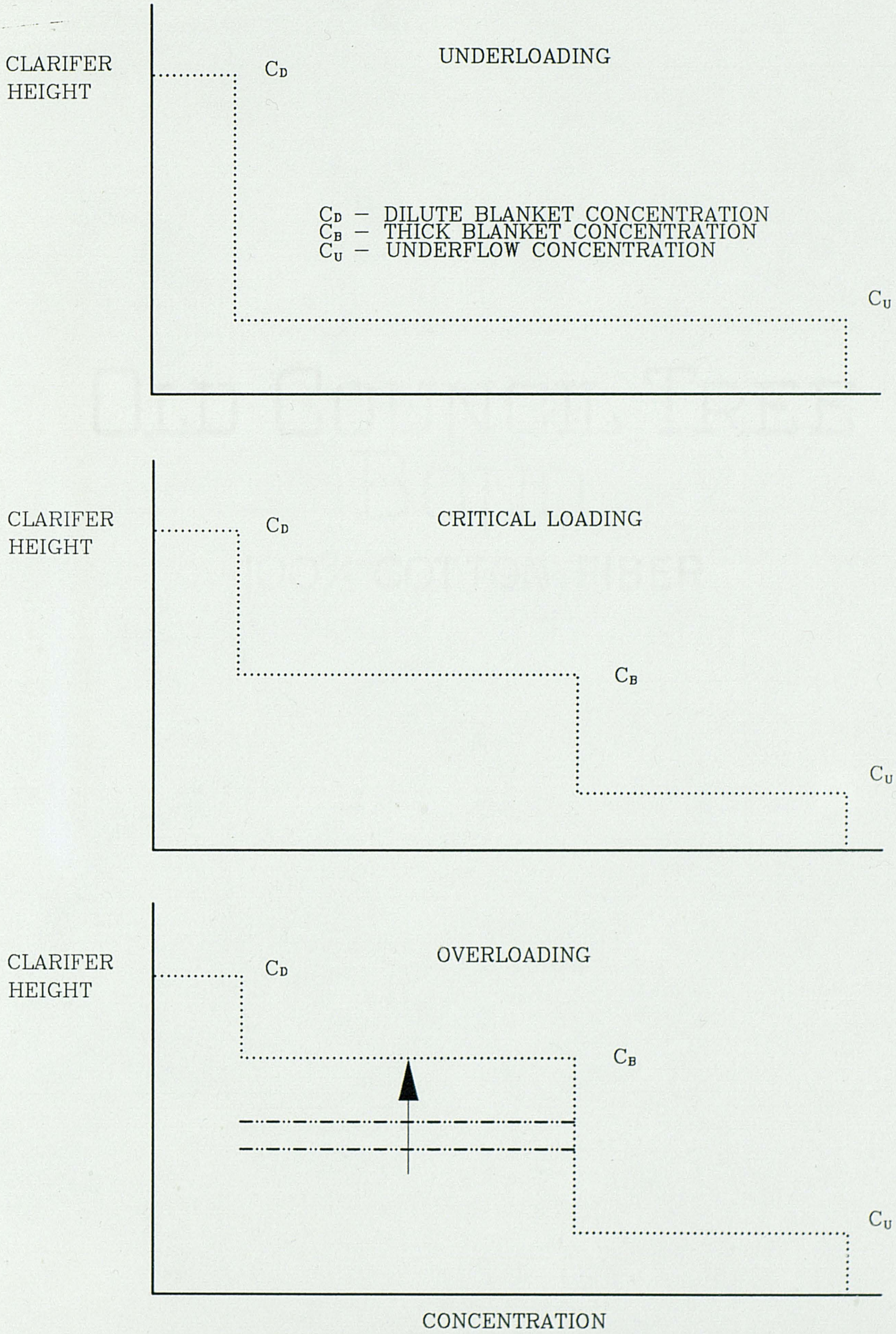

Figure 6. Clarifier Profile

stable blankets, a dilute blanket (C_d) and an underflow blanket (C_u). Critically and overloaded clarifiers have a third blanket, C_b, which is the thick blanket. In a critically loaded clarifier, the solids loading equals the limiting flux and the thick blanket maintains a constant depth. When the applied solids exceed the limiting flux, the thick blanket propagates and an overloaded condition exists. Prevailing overloaded conditions can result in the thick blanket scouring or overflowing the weir.

Flux Curve Definition

An empirical relationship developed by Vesilind (1968) relates solids flux to sludge concentration:

$$V_s = V_0 \; C \; \exp(-KC) \tag{3}$$

where

Vs = solids flux (kg/m^2-day); and

Vo = settling parameter determined by non-linear least squares (m/day); and

C = batch slurry concentration (kg/m^3); and

K = settling parameter determined by non-linear least squares (m^3/kg).

Dick and Young (1972) proposed another relationship relating concentration to solids flux,

$$Vs = N \; C^{-M} \tag{4}$$

where Vs is solids flux (Kg/m^2-day), C is concentration (Kg/m^3) and N and M are settling parameters (m/day and unitless, respectively). A statistical analysis by Johnstone et al. (1979) shows that the Vesilind model gives a better fit. These developments are the framework for the settling flux approach to solids inventory control proposed by Keinath et al. (1977).

Recently, Whalberg and Keinath (1988) investigated the creation of the settling flux curves from the sludge volume index (SVI). This work is crucial to the evolution of the settling flux approach to operational control, since it provides treatment plant operators with a simple procedure to update the settling flux curve. If needed, this equation can be modified to fit specific plant settling characteristics. The general empirical model given is:

$$N_{A,S} = (15.3 - .0615SVI)(X_i \exp[-.426 + 3.84*10^{-3}(SVI) - 5.43*10^{-5}(SVI)^2]X_i) \quad (5)$$

where

$N_{A,S}$ = settling flux (kg/m^2-hr)

SVI = sludge volume index (ml/g)

X_i = solids concentration (g/l)

The sludge volume index (SVI) for this equation is defined as the volume of settled mixed liquor divided by the slurry concentration after 30 minutes in a slowly stirred 1-liter graduated cylinder. The SVI technique found to give the best statistical results for purposes of state point control is the slowly stirred SVI in a 1 liter graduated cylinder as described in Standard Methods (American Public Health Association 1985).

The variability of the settling flux approach was recently studied by Morris et al. (1989). After studying long-term averages, short-term, diurnal and extreme upset events at three activated sludge wastewater treatment plants over a 14-month period, it was concluded that solids settling variations were significant enough to recommend updating the flux curve every 2-4 days under normal operating conditions. A daily update is recommended during extreme events. These findings give utility to a safety factor to account for batch curve variability. No correlation between SVI and sludge settling variability could be made which contradicts the findings of Whalberg and Keinath (1988) and emphasizes the need for more research. The parameters used by Morris et al. to express the variability are described next.

The Vesilind parameters, Vo and K, defined previously, were used to show variation in the nature of the settling characteristics. The limiting flux (G_L) is used because it is sensitive changes in flux curve shape and operating constraints. The limiting flux (G_L) is the maximum solids loading that can be applied to the clarifier without accumulating solids in the blanket. Another descriptive parameter, delta G was introduced. As shown in Figure 7, delta G is the change in maximum solids flux observed between flux curves. Its purpose is to show variability in an easily grasped measure. It should be noted that it does not represent variability in settling characteristics at concentrations in the useful region of the flux curve. The useful region of the flux curve is where underflow velocity lines become tangent with the curve (normally in the slurry concentration range 3 - 13 Kg/m^3). The conclusions of this study show that it is prudent to consider flux curve variablility when using the state point concept for clarifier design and control.

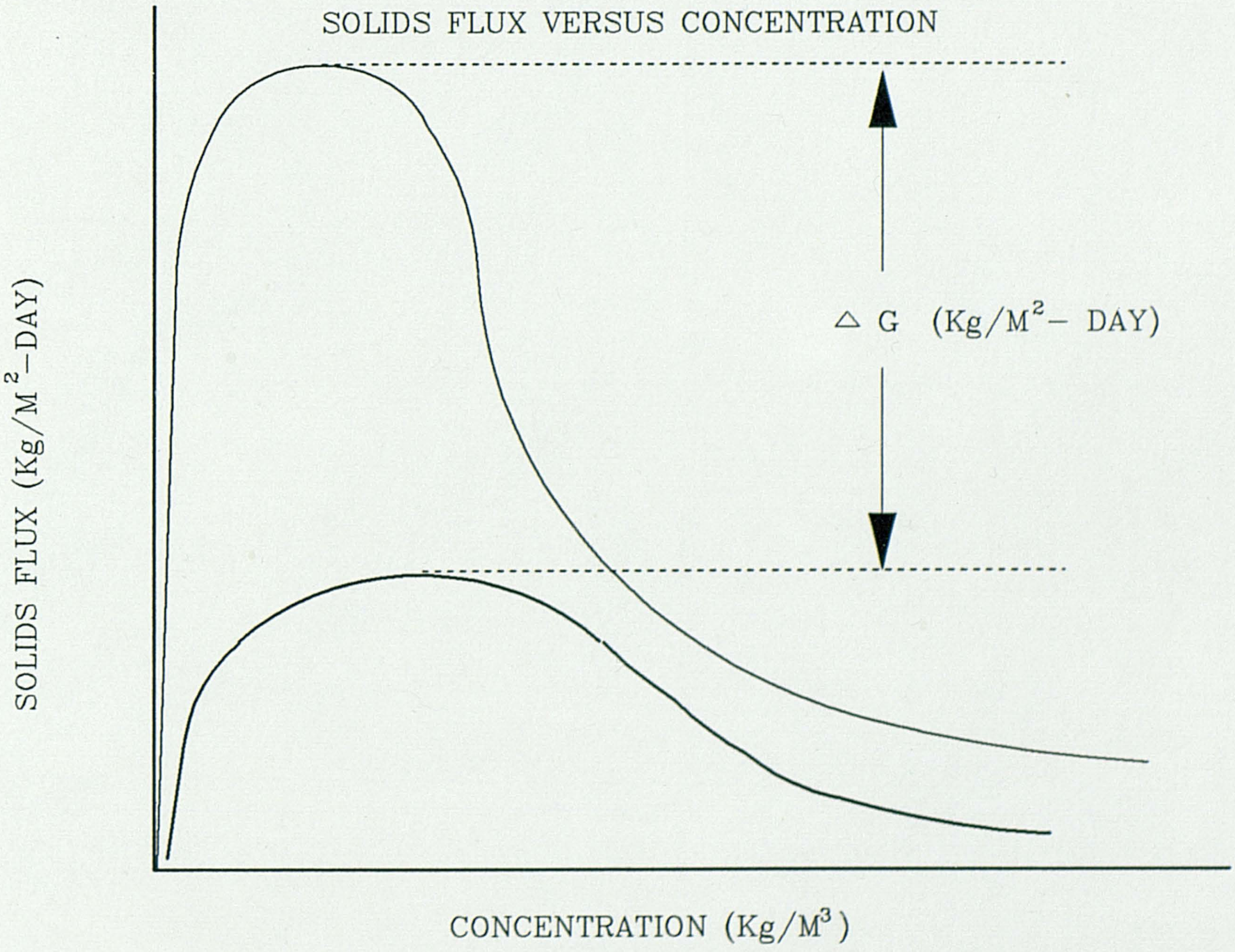

Figure 7. Morris (1989) Delta G Value

The need for full scale research on activated sludge secondary clarifiers is recognized by Tekippe and Bender (1987). This review concludes that pilot-scale research does not adequately represent full-scale conditions and suggests that future experimentation be done on full-scale clarifiers.

White (1976) studied the relationship between applied and predicted solids loading to activated sludge secondary clarifiers. He used the following equation to predict solids loadings in treatment plants corresponding with the critical underflow rate at the time of blanket propagation:

$$F = 8.85(100/SSV)^{.77}[Q_r/A]^{.68} \qquad (6)$$

where

F = mass flux (Kg/m^2-hr); and

SSV = stirred specific volume (SSVI 3.5); and

Q_r = return sludge flow rate (m^3/hr); and

A = clarifier surface area (m^2).

The stirred specific volume 3.5 (SSVI 3.5) is defined as the settled volume of mixed liquor with concentration equal to 3.5 kg/m3 after 30 minutes in a 1-liter graduated cylinder with stirring at one rpm. It is often approximated by linearly interpolating between two SSVs done at slurry concentrations higher and lower than 3.5 kg/m3. For treatment plants operating with recycle rates higher than critical (as determined from flux curve), the following equation was employed:

$$F = MLSS[V_{MLSS} + (Q_u/A)] \tag{7}$$

where

V_{MLSS} = interface settling velocity of the mixed liquor (m/hr); and

MLSS = mixed liquor concentration (kg/m3).

A total of ten full-scale facilities were tested, five for each case above; and of these, eight became overloaded at solids loadings 20% less than predicted by the corresponding equations. The equations over-estimated the solids handling capacity of the clarifiers supporting the use of scale-up factors in clarifier design. Very poor settling characteristics were observed in the other two facilities, and clarifier overloading occurred at solids loadings 30% higher than the predicted values.

The literature shows a need for full-scale research on clarifiers. Full-scale research must be performed in order to address the discrepancy between solids handling capacities predicted by batch settling tests and those observed in continuous full-scale clarifiers. In addition, it is necessary to frequently update batch flux curves due to variability.

CHAPTER III

OBJECTIVES

The overall objective of this research was to develop an experimental procedure for determining scale factors for settling flux curve definition from a small scale batch apparatus to continuous operating clarifiers. A scale factor is a number which when multiplied by the batch limiting flux yields the observed full-scale limiting flux. Emphasis was placed on development of techniques and identification of required data for determining scale factors rather than on actual scale factor determination for operating systems. To facilitate flow control and data collection, two pilot scale continuous clarifiers were used. The objectives included:

1. Develop an experimental procedure for full-scale flux curve determination.
2. Define the necessary instrumentation and operational capabilities of the full-scale system.
3. Develop techniques for specification of a scale factor between batch and full-scale flux curves.
4. Develop a methodology to account for batch curve variability in clarifier design.

The results were combined to produce a unified procedure for determining scale factors. In addition, a design procedure was developed to calculate clarifier area based on the scale factor determined from the batch and full-scale experiments. A complementary procedure is proposed to address uncertainty in design associated with variability of settling characteristics.

CHAPTER IV

EXPERIMENTAL PROCEDURE

Facilities

The University of Central Florida (U.C.F.) Wastewater Treatment Plant was chosen as the location for conducting the experiments. The U.C.F. facility is an extended aeration activated sludge plant which produces a nitrified effluent. During the period of this study, the mixed liquor concentration ranged from 2.9 to 3.5 kg/m^3 and no obvious upset conditions were encountered.

The experiments were conducted over a 5-week period from mid June to late July 1989, and each set of experiments took 4 days to complete. On the first day of each set, the batch settling tests were completed. The second day included suspended solids analysis, plotting batch data, generation of batch flux curves and selection of flows for the continuous clarifier experiment. The continuous experiments were done on day 3, and the suspended solids were analyzed on day 4.

Batch Settling Test Apparatus

The batch settling test apparatus was similar to the one used by Whalberg (1987). Five separate 9.52 cm clear plexiglass settling columns were enclosed inside a larger clear plexiglass tube 29.21 cm in diameter as shown in Figure 8. In this arrangement, water was continually forced by tap pressure into the large tube. The water formed a blanket around the 5 inner columns to maintain a constant temperature. The settling columns were filled from the bottom via a small pump to ensure equal distribution of sludge within each column. Each column was stirred by a round steel rake which was turned by a 1 rpm motor located on the apparatus lid. The motors and rakes were removable allowing for easy cleanup.

Batch Settling Data Collection

The batch settling apparatus was placed on the concrete walkway next to the aeration tank. In this location, the mixed liquor was pumped directly into the settling columns using a submersible pump. The return sludge was not as accessible and was obtained by dipping a 1-liter sampling bucket into the return sludge line. The return sludge at the U.C.F. facility ranges between 3.0 and 5.0 kg/m^3, so it was concentrated by gravity thickening for 15 minutes in several 5 gallon buckets in order to obtain the higher concentrations (6.0 - 12.0 kg/m^3) necessary to obtain data points throughout the useful region of the flux curve. Unchlorinated clarifier effluent was used as the dilution water and was obtained from the clarifier overflow channel. Two separate settling sessions were completed each day to cover all the dilutions and replicates. At least one replicate concentration was completed during each day of batch settling.

The settling columns were filled to a height of 1800 mm with various dilutions of mixed liquor and return sludge as shown in Table 1. Upon being filled, the columns were mixed vigorously for one minute each using a diffusing stone, polyurethane tubing and an air compressor. The mixing was undertaken sequentially starting with the most concentrated dilution and working to the least concentrated. Since all of the motors operated simultaneously, the stirring rakes were not started until all the mixing was completed. Starting with the least concentrated mixture, time zero was defined by the formation of a flocculent interface, and the height of this interface was measured and recorded according to the time intervals shown in Table 1.

Similarly, the interface heights of the other columns were measured and recorded allowing a fixed allotment of time to elapse between each reading. For example, to allow 1 minute to elapse between each reading of column 1, 12

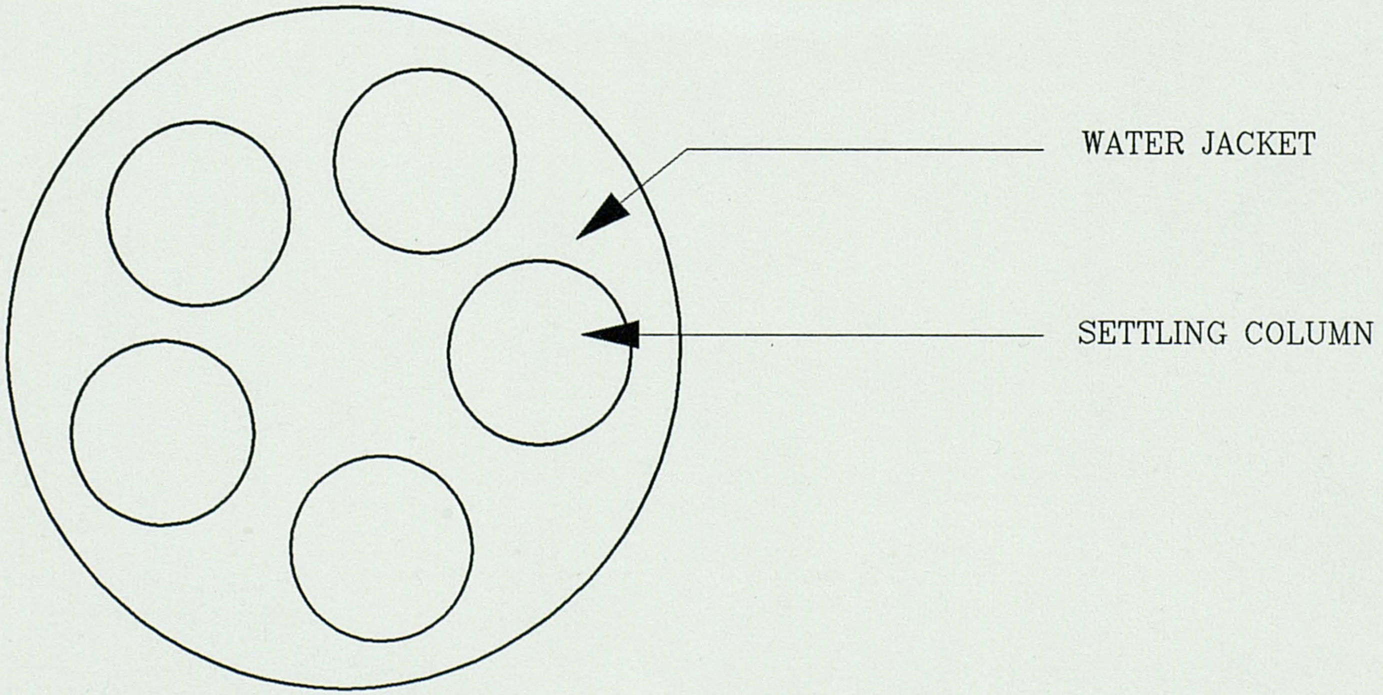

Figure 8. Batch Settling Apparatus Plan View

TABLE 1

BATCH SETTLING TEST GUIDELINES

Settling Session 1 (AM) 90 minutes

Column #	Mixed Liquor (cm)	Return Sludge (cm)	Clarifier Effluent (cm)	Observation Interval (sec)	Duration (min)	Approx. Conc. (kg/m^3)
1	90	0	90	60	90	1600
2	135	0	45	60	90	2400
3	180	0	0	60	90	3200
4	0	90	90	60	90	4000
5	135	45	0	60	90	4400

Settling Session 2 (PM) 150 minutes

Column #	Mixed Liquor (cm)	Return Sludge (cm)	Clarifier Effluent (cm)	Observation Interval (sec)	Duration (min)	Approx. Conc. (kg/m^3)
1	135	45	0	120	150	4400
2	135	45	0	120	150	4400
3	90	90	0	120	150	5600
4	45	135	0	120	150	6800
5	0	180	0	120	150	8000

seconds separated the readings of the five columns. The first settling session of each day was continued for 30 - 90 minutes and the second for 90 - 150 minutes depending on how quickly the sludge settled.

After the settling measurements were completed, each column was drained into a 5 gallon bucket, stirred vigorously and sampled for suspended solids analysis. This technique allows a direct measurement of concentration for each slurry. The samples were immediately refrigerated at approximately 4 degrees celsius and analyzed for suspended solids within 24 hours.

Suspended solids analysis was performed by vacuum filtering through pre-washed and pre-weighed Whatman 934-AH 1.0 micron glass fiber filters. The filters were placed in an oven and dried for 1 hour at 102 degrees C. After an hour, the samples were placed in a desiccator for at least 1 hour to allow them to cool to room temperature. The dry samples were then weighed to determine the total suspended solids (TSS). The procedure followed Standard Methods 209c & 209d (American Public Health Association 1985).

Several versions of the sludge volume index (SVI) test were done on the same day as the batch settling to further characterize the settling characteristics of the sludge. The basic SVI test was done by filling a 1-liter graduated cylinder with mixed liquor, allowing the solids to settle for 30 minutes and recording the volume of the settled sludge. The settled sludge was mixed thoroughly back into solution and sampled for suspended solids. The sludge volume index was calculated using equation (8) below and has units of ml/g,

$$SVI = Vss/M \tag{8}$$

where Vss is milliliters of settled sludge per liter and M is grams of solids per liter. Another test, the stirred sludge volume index (SSVI) was done similarly to the basic SVI, except slow stirring (1 rpm) was provided during settling (<u>Standard Methods</u> American Public Health Association 1985). The stirring was accomplished by a round steel rake turned by a 1 rpm motor.

The third version of the test, the diluted sludge volume index (DSVI) was done as follows (Koopman and Cadee 1983):

1. A 2-liter graduated cylinder was filled with mixed liquor and mixed vigorously.
2. One liter of this slurry was poured into a 1-liter graduated cylinder and set aside.
3. The remaining slurry was diluted with unchlorinated clarifier effluent to the 2-liter line and thoroughly mixed.
4. Again, one liter of the diluted slurry was poured into a 1-liter graduated cylinder and set aside.

5. Two more dilutions were made as in steps 2-4 above.
6. The four 1-liter slurries were mixed for 1 minute each and allowed to settle for 30 minutes.
7. After 30 minutes, the volumes of the settled sludge were measured and the one which was closest to and less than 200 ml was recorded, mixed and sampled for suspended solids.
8. The DSVI was then calculated from equation (8) above using the diluted volume and concentration.

The SVI tests serve as a general indication of sludge settleability.

Batch Settling Data Analysis

A plot of interface height vs. time was made for each column and a linear section was identified visually as shown in Figure 9. The settling velocity was calculated as the slope of the linear segment using linear least squares regression. The product of the column's settling velocity and concentration defines the solids flux for that particular concentration,

$$G_s = V_s C_i \tag{9}$$

where

G_s = solids flux (Kg/m^2-day); and

V_s = settling velocity (m/day); and

C_i = slurry concentration (Kg/m^3).

A settling flux plot was developed by plotting solids flux

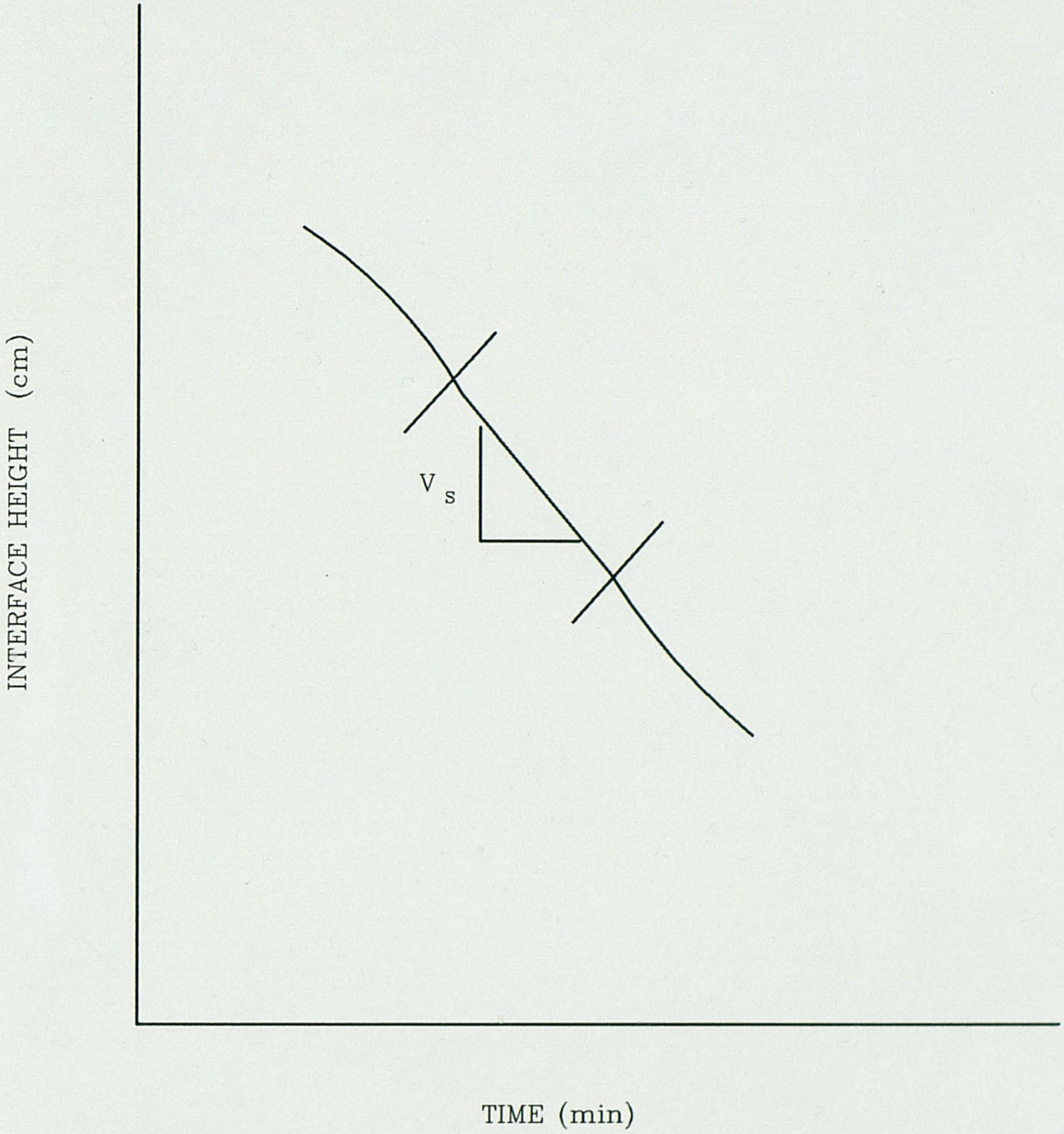

Figure 9. Interface Height Versus Time

(G_s) vs. concentration (C_i) for each column as illustrated in Figure 10.

To generate the flux curve, the Vesilind equation ($V_s = V_0\ C\ \exp(-KC)$) was utilized. As previously discussed, the Vesilind equation is a two parameter model where V_0 and K are the parameters to be estimated. Estimation of V_0 and K was done using nonlinear least squares regression (Statistical Analysis System 1982).

Experimental Continuous Clarifier System

Two acrylic plexiglass columns 20.3 cm in diameter and 3.0 meters tall were used as clarifiers. Each was equipped with a center feed well 6.35 cm in diameter which extended 1 meter below the effluent surface. The effluent overflowed a 90 degree V-notch weir. To prevent accumulation of solids along the lower inside walls in each clarifier, a 1 rpm stirring rake was used. The clarifiers were equipped with sampling ports located at the following heights above the clarifier bottom.

Sample port #	Height above bottom (cm)
7	170.2
6	132.1
5	91.4
4	71.1
3	50.8
2	30.5

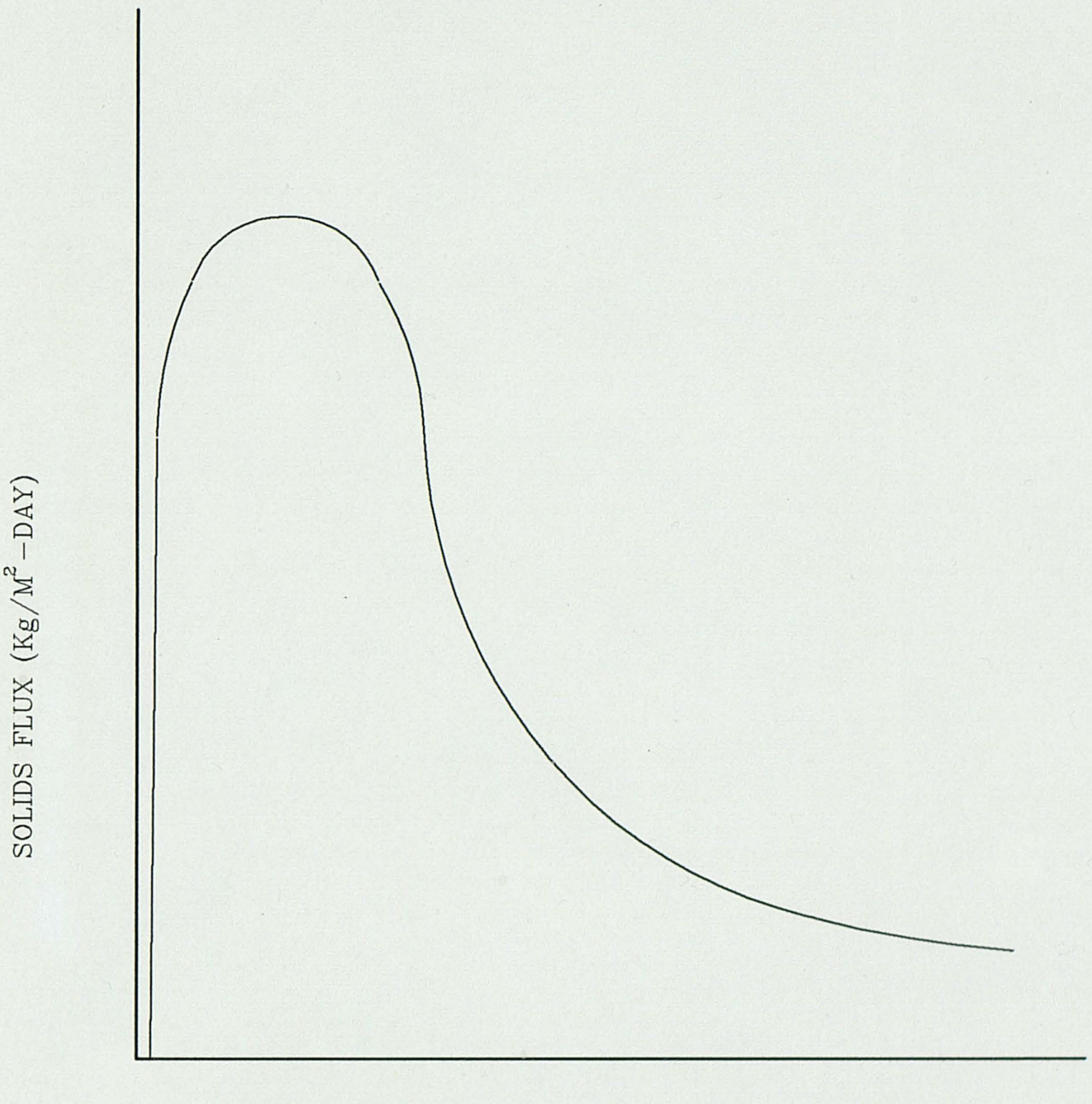

Figure 10. Solids Flux Versus Concentration

1 (underflow) 10.2

Variable speed Masterflex positive displacement pumps were used to establish the feed and underflow rates. A motor speed controller attached to each pump provided the necessary flow control. Two 55-gallon plastic cylindrical reservoirs were used as aeration tanks, one for each clarifier. The equipment was set up as shown in Figure 11. An air compressor and PVC diffuser accompanied each aeration cylinder to provide dissolved oxygen in excess of 2 mg/L to the mixed liquor.

The mixed liquor was pumped from the U.C.F. Wastewater Treatment Plant aeration tank to the plastic reservoirs using a screw-type pump. Screening was provided on the suction side of the pump to remove objects which could cause feed and underflow line blockage. The screening worked well as only one blockage of a feed line was encountered.

Continuous Clarifier Data Collection

The following procedure was used to collect the data for the full scale experiments:

1. The aeration tanks were filled by pumping the MLSS from the U.C.F. Wastewater Treatment Plant through garden hose.
2. The reservoir aerators were turned on and remained on throughout the experiment.

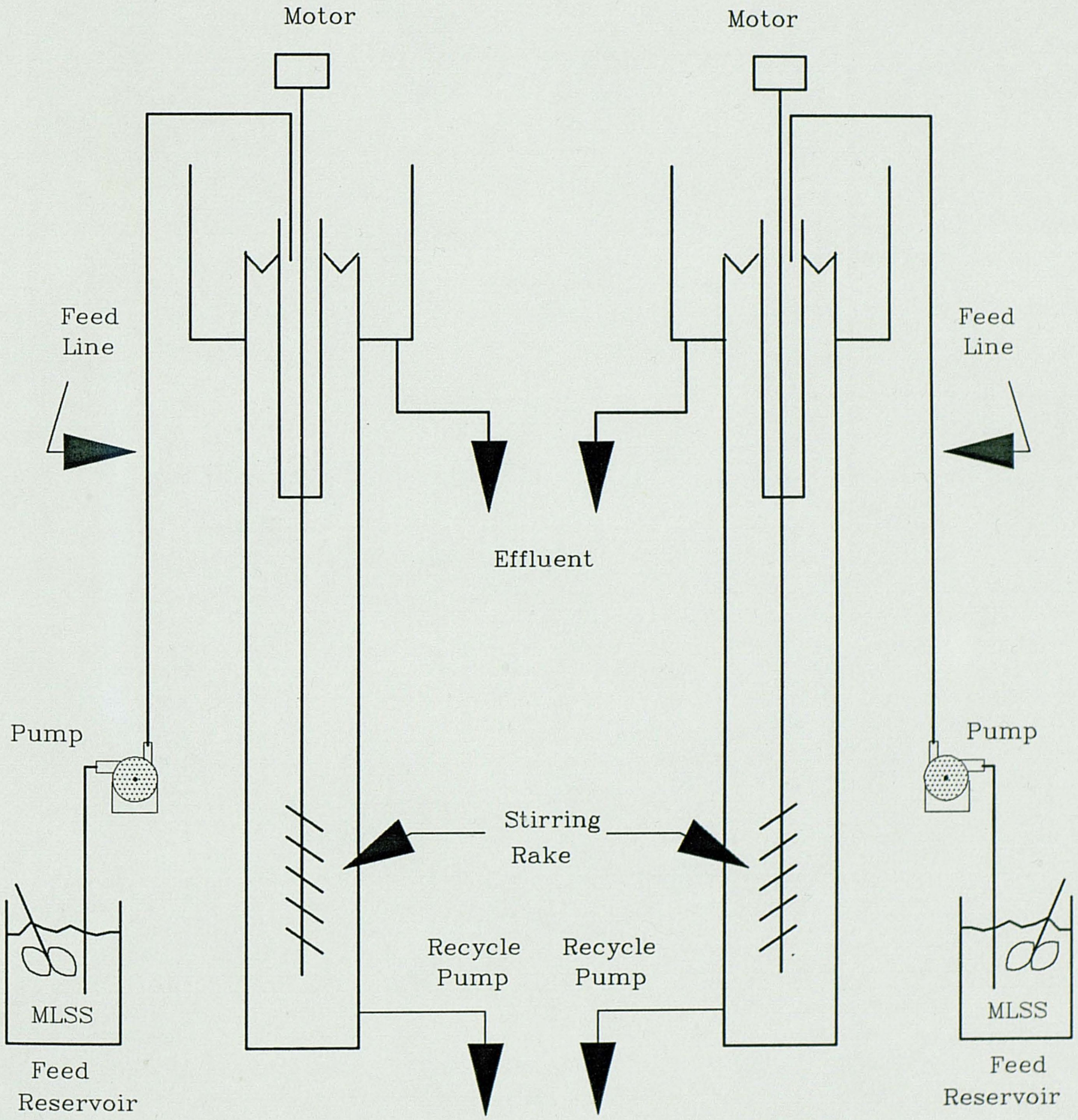

Figure 11. Side by Side Experimental Clarifiers

3. The settling columns were filled with mixed liquor.
4. The MLSS feed pumps were turned on, and the desired rates set (flows determined with a stopwatch and graduated cylinder).
5. The underflow pumps were turned on and the flows adjusted.
6. The stirring rakes were turned on.
7. Operation continued for 4 hours to allow the system to stabilize (Margio, 1985). During this time, flows were measured along with the following parameters listed in Table 2.
8. The clarifier concentration profile was established by sampling the underflow, thick and dilute blankets for suspended solids.
9. The recycle rates were decreased incrementally every hour until a blanket propagation occurred. Blanket propagation was determined visually through the clear clarifier by measuring the thick blanket height. Prior to each recycle rate change, the clarifier blankets were sampled to define changes in the profiles.
10. Flow rates continued to be measured every 15 minutes and the pH, temperature and D.O. values were measured every 60 minutes.

TABLE 2.

PARAMETERS AND FREQUENCY OF MEASUREMENTS FOR CONTINUOUS EXPERIMENTS

PARAMETER	FREQUENCY 15 min.	 30 min.	 60 min.
FEED FLOW RATE (ml/min)	X		
OVERFLOW RATE (ml/min)	X		
UNDERFLOW RATE (ml/min)	X		
FEED CONC. (sample)			X
FEED D.O. (mg/L)		X	
FEED TEMPERATURE (°C)		X	
FEED pH		X	
OVERFLOW pH		X	
UNDERFLOW pH		X	

Depending upon how quickly the blankets propagated, 2-4 data points were generated on each day of continuous experimention.

Continuous Clarifier Data Analysis Options

The specific purpose of the continuous experiments is to define the point of overload to correspond with blanket propagation. A scale factor is determined by comparing the condition associated with overload as determined by continuous tests with values determined via batch settling tests. Three options were considered for determining scale factors from the continuous data. These options were explored to determine which was most reliable in terms of measurable data and most useful for design and control.

Option 1: Use measured values C_u, C_b and u

This option used the underflow and thick blanket concentrations (C_u and C_b, respectively) and the underflow velocity (u) to determine a full scale point on the flux curve. The values of C_u and C_b were those determined in the continuous experiments which corresponded with blanket propagation.

1. A line was drawn from the underflow concentration (C_u) at a slope equal to the negative of the underflow velocity (-u). The line was labeled line A on Figure 12.

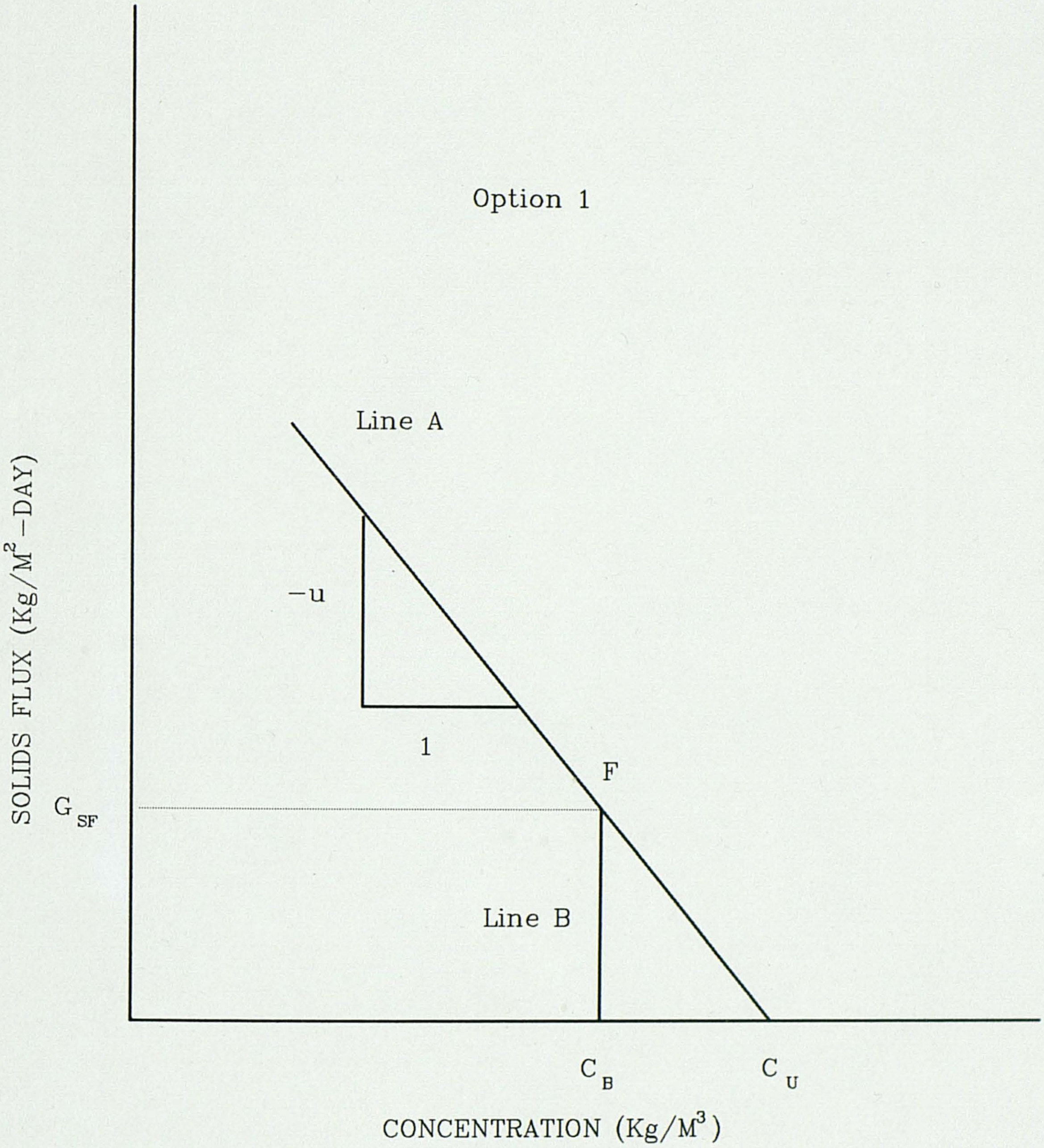

Figure 12. Full Scale Point Using C_B, C_u and u

2. A vertical line (line B) was drawn from the clarifier blanket concentration (C_b) up to the point of intersection with line A. This point was labeled F on Figure 12 and was the full scale point.
3. A ratio was set up comparing the full scale point's solids flux value (G_{sf}) to the solids flux predicted by the batch flux curve (G_{sb}) for the same blanket concentration. This ratio was the scale factor (SF),

$$SF = G_{sf}/G_{sb} \qquad (10)$$

where

SF = scale factor (unitless); and

G_{sf} = solids flux using continuous data (kg/m^2-day); and

G_{sb} = solids flux predicted by batch curve at the same blanket concentration (kg/m^2-day).

Option 2: Use measured values MLSS, C_b, u and v

This option used the mixed liquor and blanket concentrations (MLSS and C_B, respectively) along with the underflow and overflow velocities (u and v, respectively) to determine a full scale point on the flux plot. The procedure corresponds with Figure 13:

1. A line (line A) was drawn from the origin at a slope equal to the overflow velocity (v) until it reached another line (line B) drawn vertically up from the

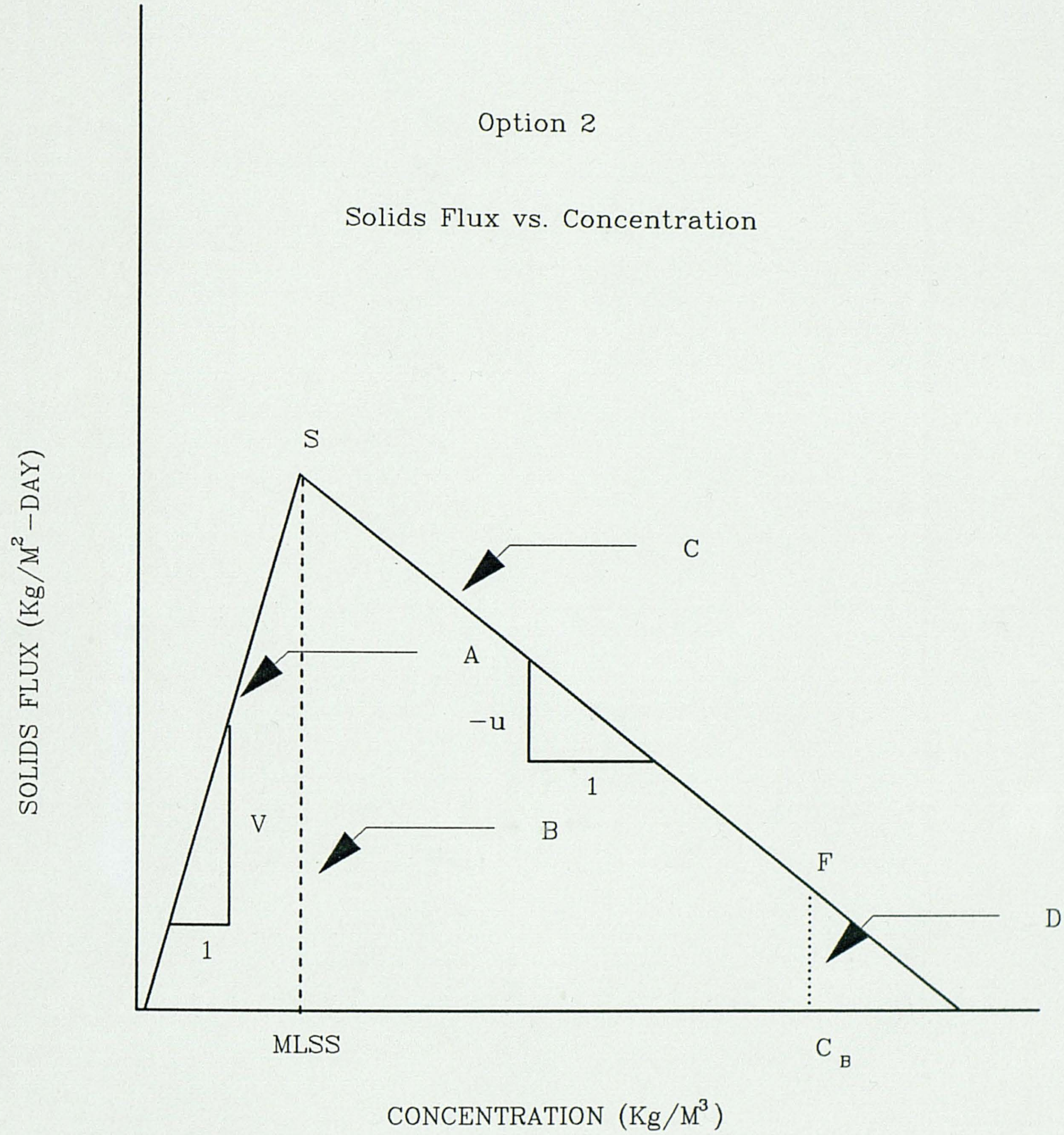

Figure 13. Full Scale Point Using MLSS, C_B, u and v

mixed liquor concentration (MLSS). The point (S) was the state point.

2. A line (line C) was drawn with a slope equal to the negative of the underflow velocity (-u) from the state point (S) to the x-axis.
3. A vertical line (line D) was drawn up from the blanket concentration (C_b) until it intersected line C. The point of intersection of lines C and D was the full scale point F.
4. The scale factor was determined by the ratio of the full scale point's solids flux to the predicted batch solids flux as was done in option 1 equation (10).

Option 3: Use measured values C_u & u

The third option used the measured values for underflow concentration and velocity (C_u and u, respectively) to locate the limiting flux (G_l). A line was drawn with a slope equal to the negative of the underflow velocity (-u) from the underflow concentration (C_{uf}) to the y-axis as shown on Figure 14. The point of intersection with the y-axis was the limiting flux (G_{lf}). To determine the scale factor, the underflow velocity line was moved parallel until it reached a point of tangency with the batch flux curve as shown on Figure 14. Another limiting flux (G_{lb}) was determined at the new y intercept. The scale factor

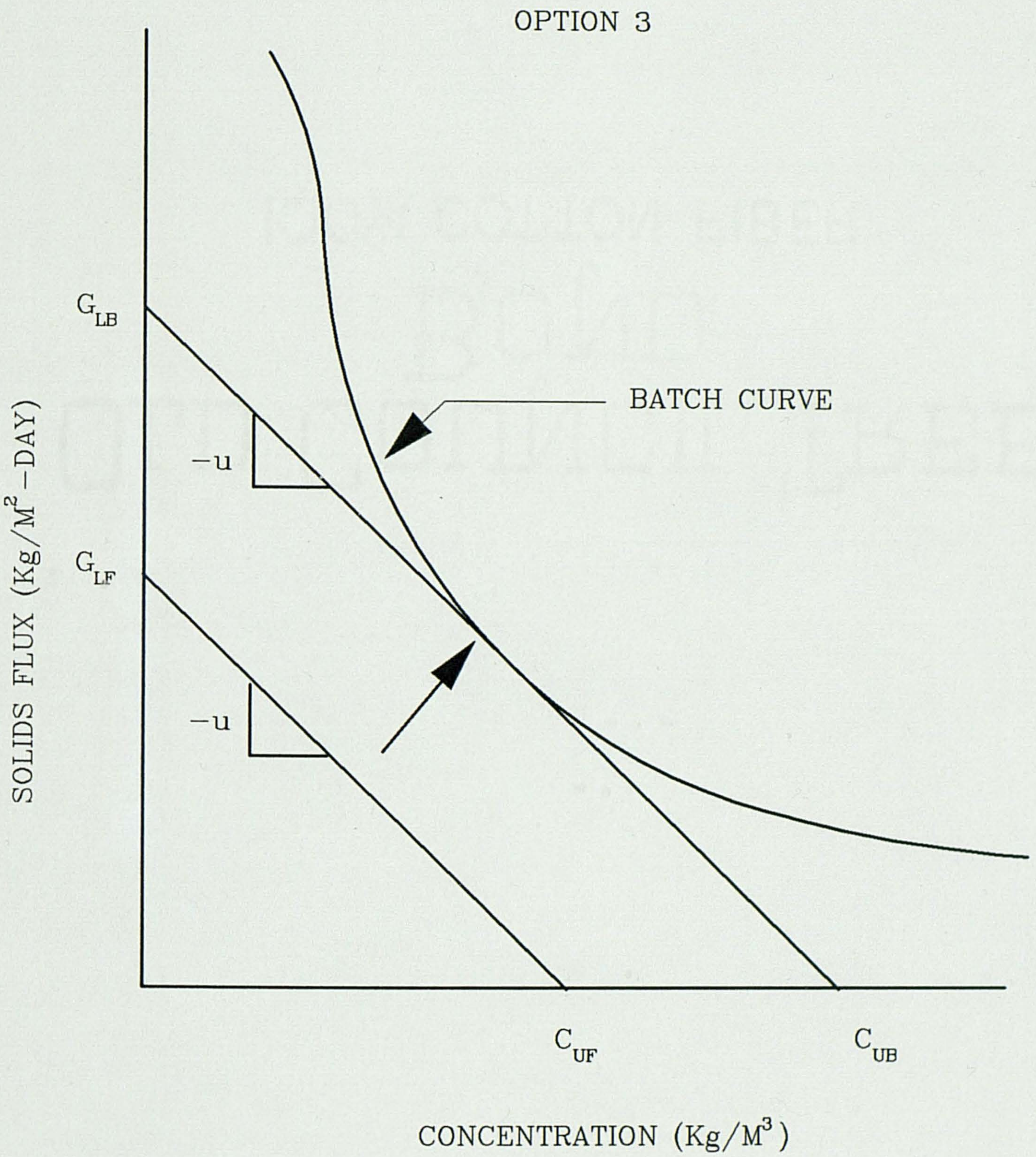

Figure 14. Scale Factors Based on Limiting Flux

was the ratio of the limiting fluxes as shown below:

$$SF = G_{\ell f}/G_{\ell b} \tag{11}$$

where

SF = scale factor (unitless); and

$G_{\ell f}$ = limiting flux using continuous data (kg/m^2-day);

and

$G_{\ell b}$ = limiting flux after moving underflow velocity line parallel to a point of tangency with the batch flux curve (kg/m^2-day).

CHAPTER V

RESULTS AND DISCUSSION

Experimental Results

Batch Settling Flux Curves

The results of the non-linear least squares determination of the Vesilind parameters, V_0 and K (Flux = V_0 C exp(-KC) are listed in Table 3. Raw settling data and SVI results are included in Appendix A (Table 13 and 19, respectively). The five individual batch settling flux curves are given in Figures 15-19. The curves were generated using settling data with slurry concentrations ranging from 3.0 to 13.5 Kg/m^3. Data falling outside of this range was omitted from the analysis because it may have biased the parameter estimates which were determined for the useful region of the curve as previously defined.

Continuous Clarifier Experiments

The flow rates and concentrations which caused the thick blankets to propagate are listed with the raw data in Appendix A (Tables 14, 15 and 18). Blanket propagation was determined visually during the continuous experiments and later verified by the clarifier concentration profiles

TABLE 3

VESILIND PARAMETERS FOR FIVE FLUX CURVES

Date	Number of Points	V_o (m/day)	K (m^3/kg)
6/18	8	295	0.509
6/27	6	1365	0.779
7/ 5	10	514	0.559
7/12	7	584	0.529
7/19	7	307	0.424

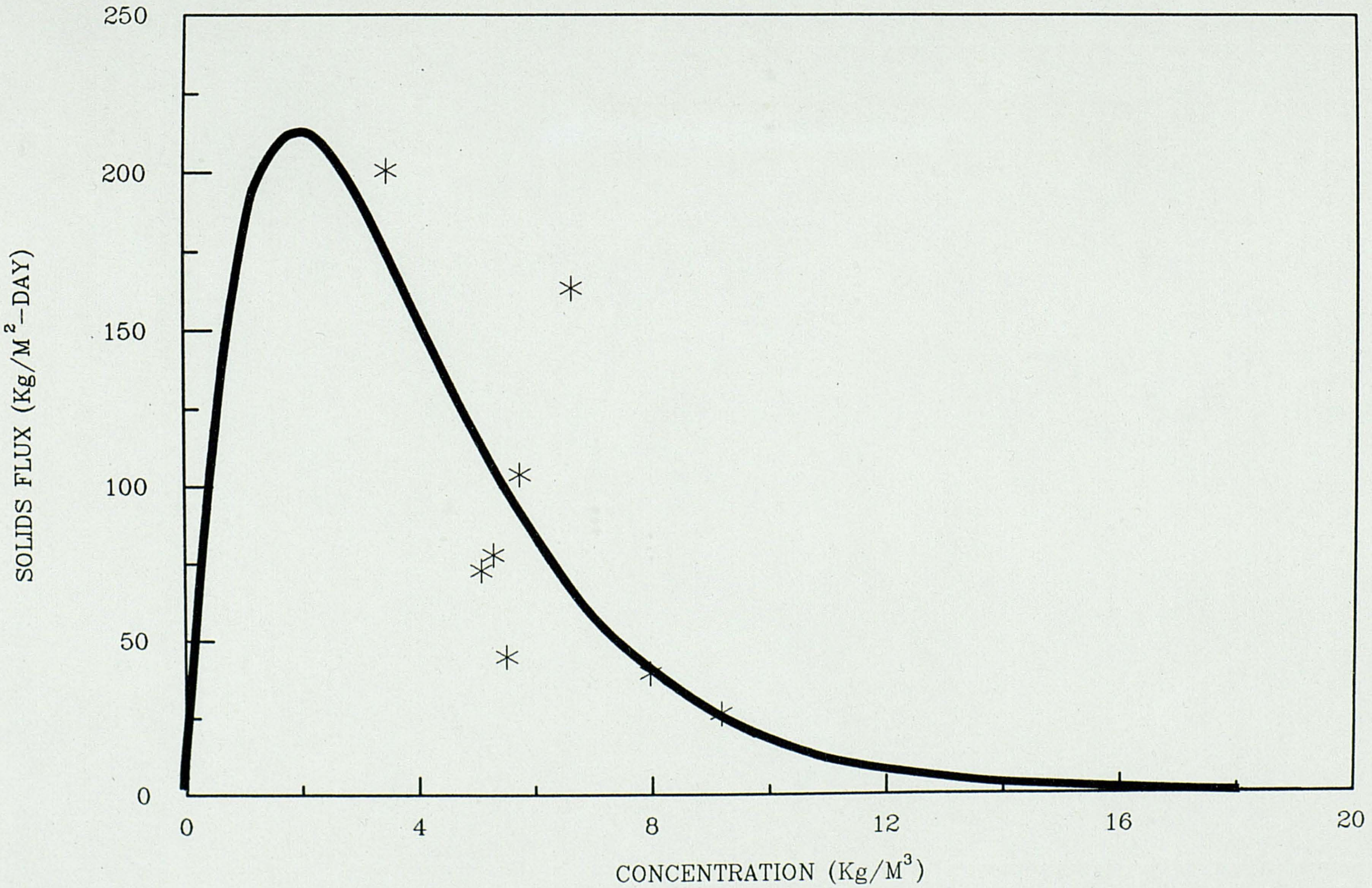

Figure 15. Solids Flux Versus Concentration on June 27, 1989

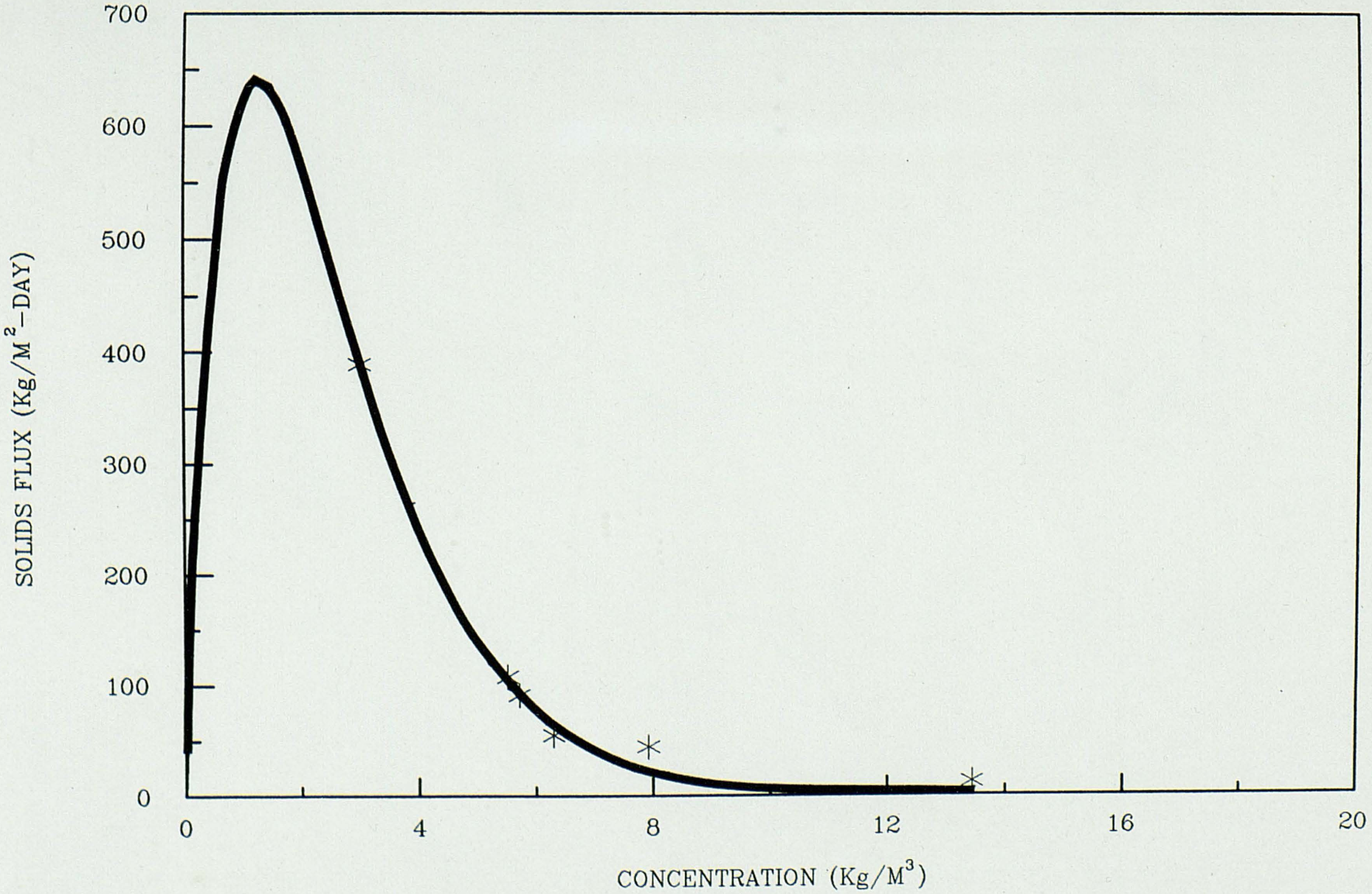

Figure 16. Solids Flux Versus Concentration on June 27, 1989

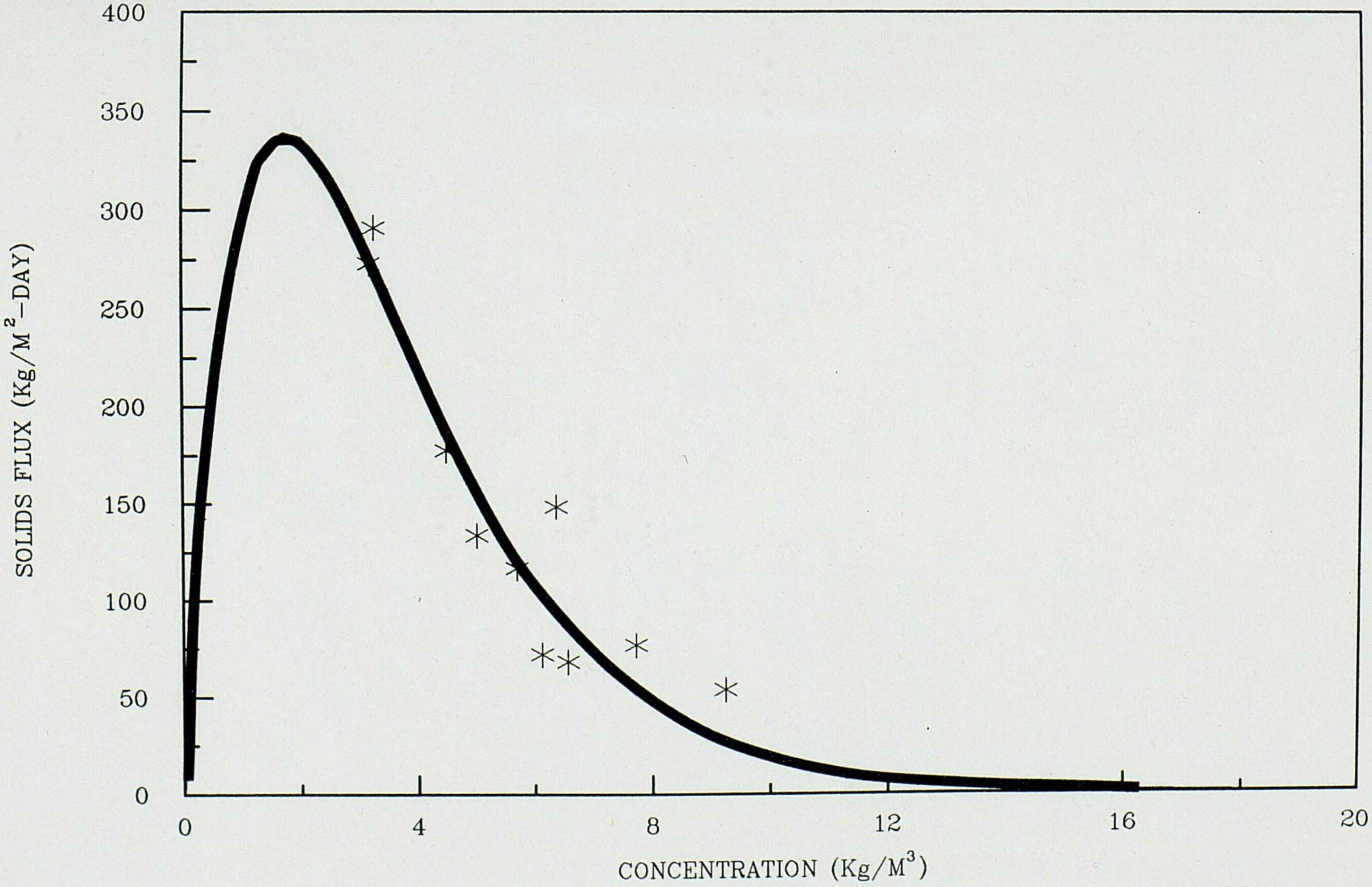

Figure 17. Solids Flux Versus Concentration on July 5, 1989

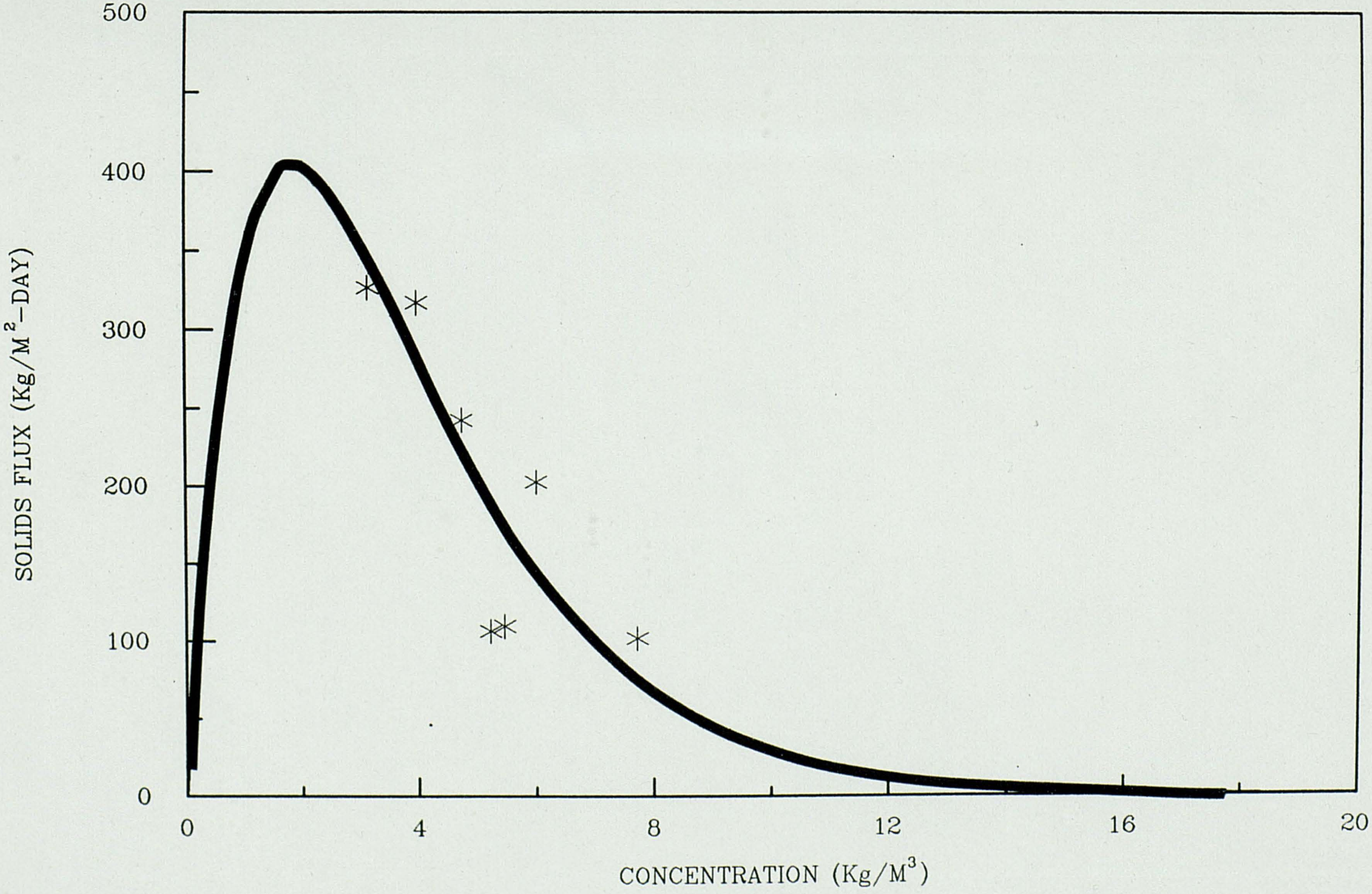

Figure 18. Solids Flux Versus Concentration on July 12, 1989

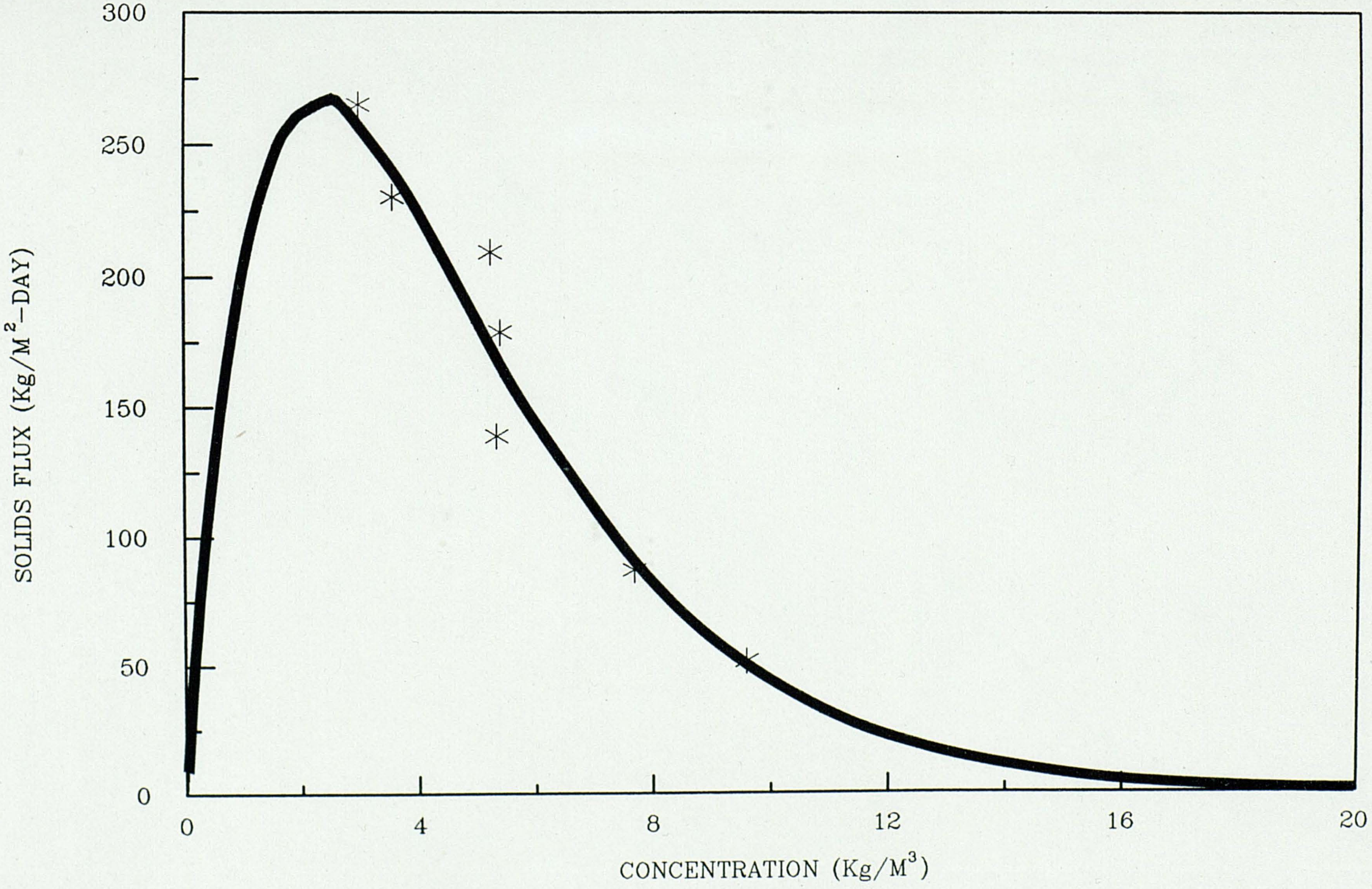

Figure 19. Solids Flux Versus Concentration on July 19, 1989

shown in Figures 20-29. Raw suspended solids data for definition of clarifier profiles are included in Appendix A (Tables 16 and 17). The flows and concentrations associated with the blanket propagation were subsequently used to determine scale factors. No results were obtained from the continuous experiments performed on June 6, 1989. On this day, blanket propagation was not observed in clarifier A, and a blanket sampling anomaly was experienced in clarifier B as evidenced in Figures 22 and 23, respectively.

Referring to Figure 22, under normal circumstances, the underflow concentration (sample port #1) is the highest concentration in the clarifier profile. However, the samples obtained from port #2, clarifier B on June 29 contain much higher concentrations than the underflow. Because of this irregularity, a thick blanket concentration was not clearly defined, and consequently, the data was omitted from further use.

Statistical Analysis

In order to properly interpret the data and determine the significance of the results, a statistical analysis was used. The analysis of variance (ANOVA) technique of comparing two or more sample variances is the basis of the statistical analysis. Replicate samples and experiments provide an estimate of the experimental error. A

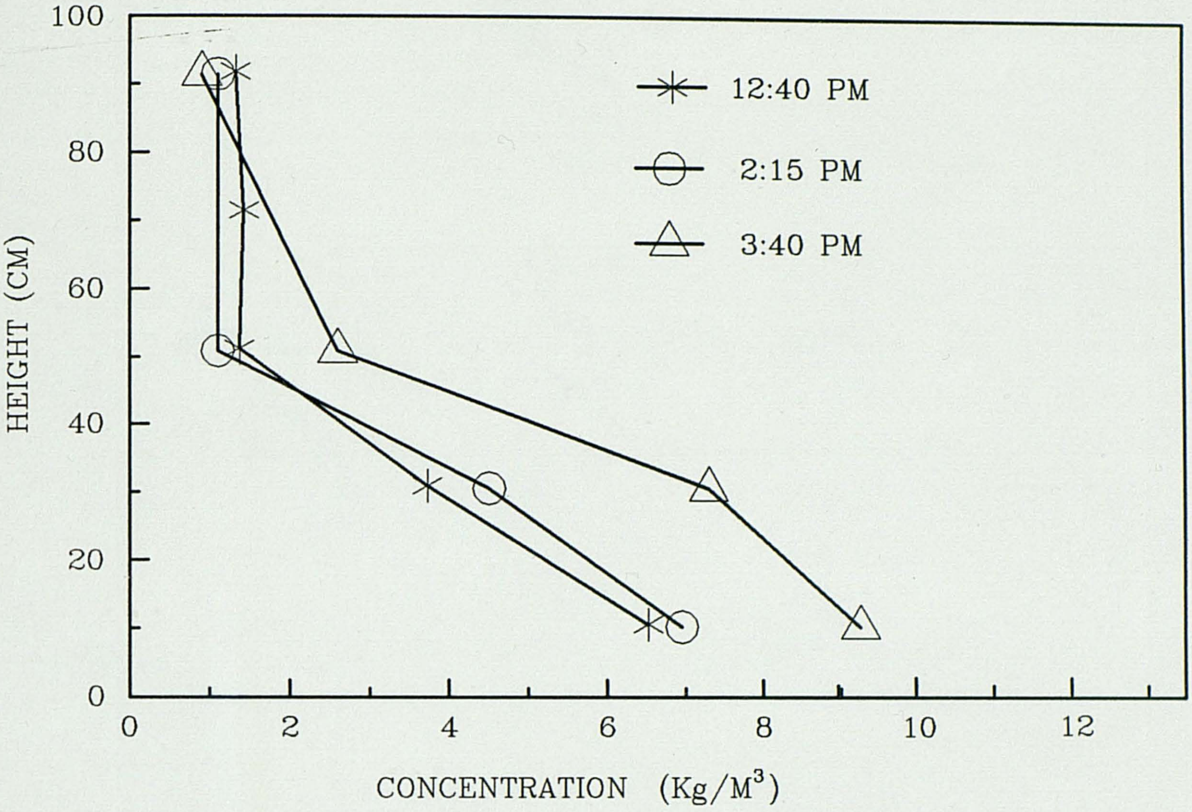

Figure 20. Clarifier A Profile for June 21, 1989

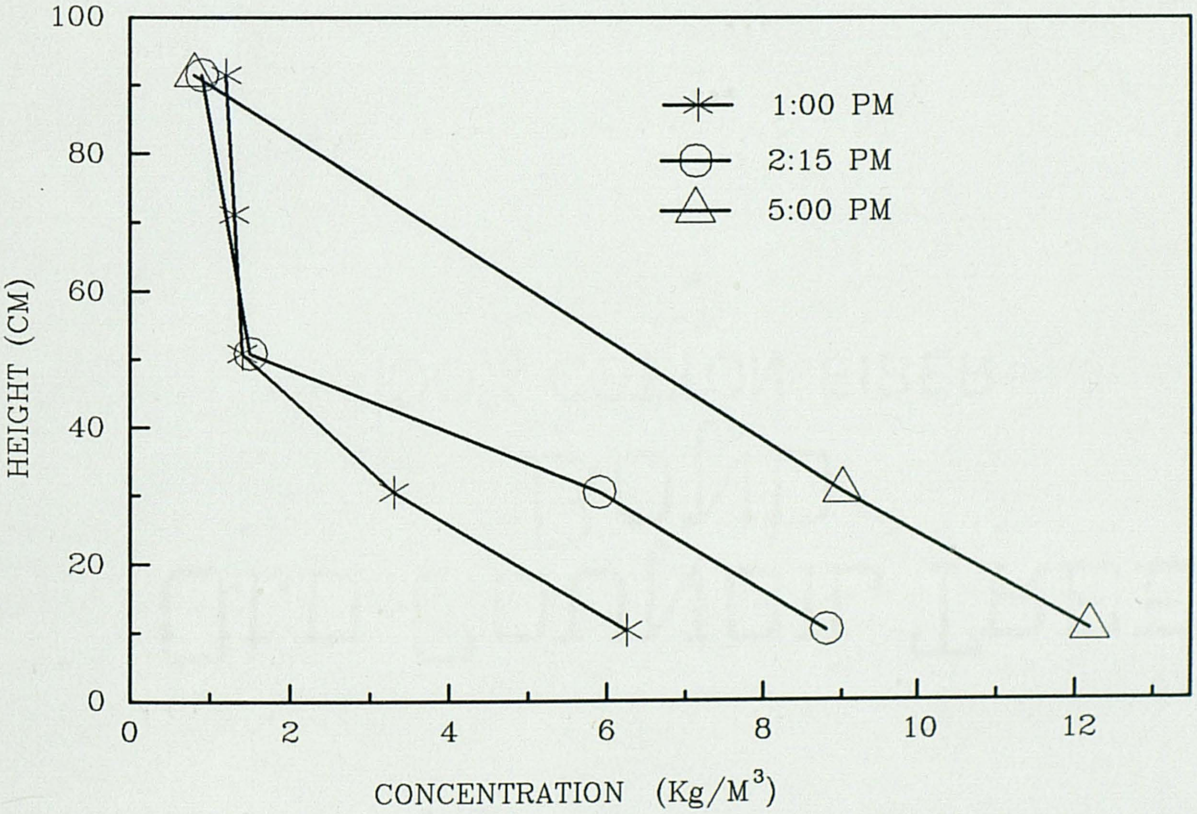

Figure 21. Clarifier B Profile for June 21, 1989

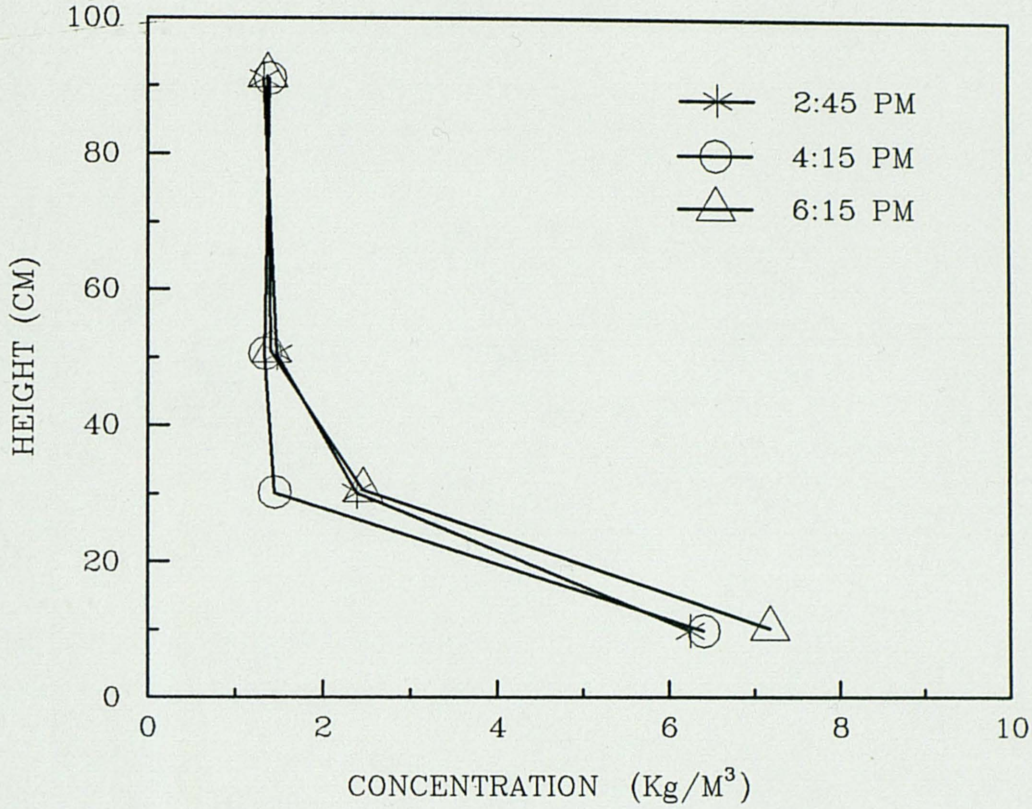

Figure 22. Clarifier A Profile for June 29, 1989

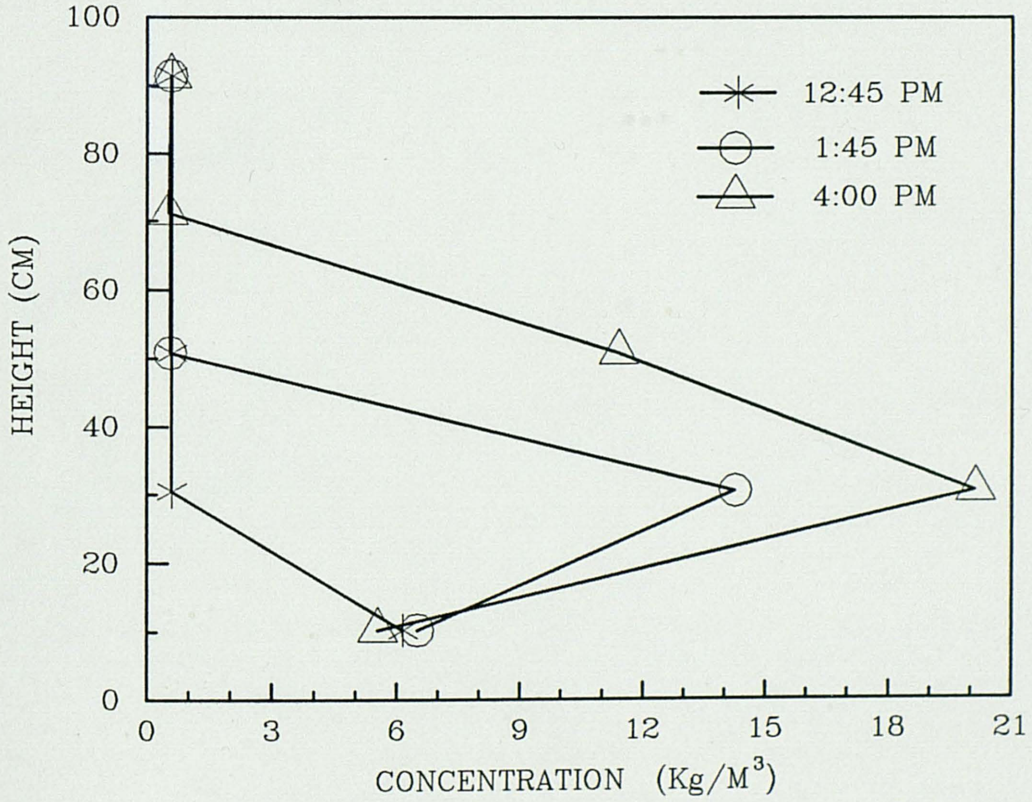

Figure 23. Clarifier B Profile for June 29, 1989

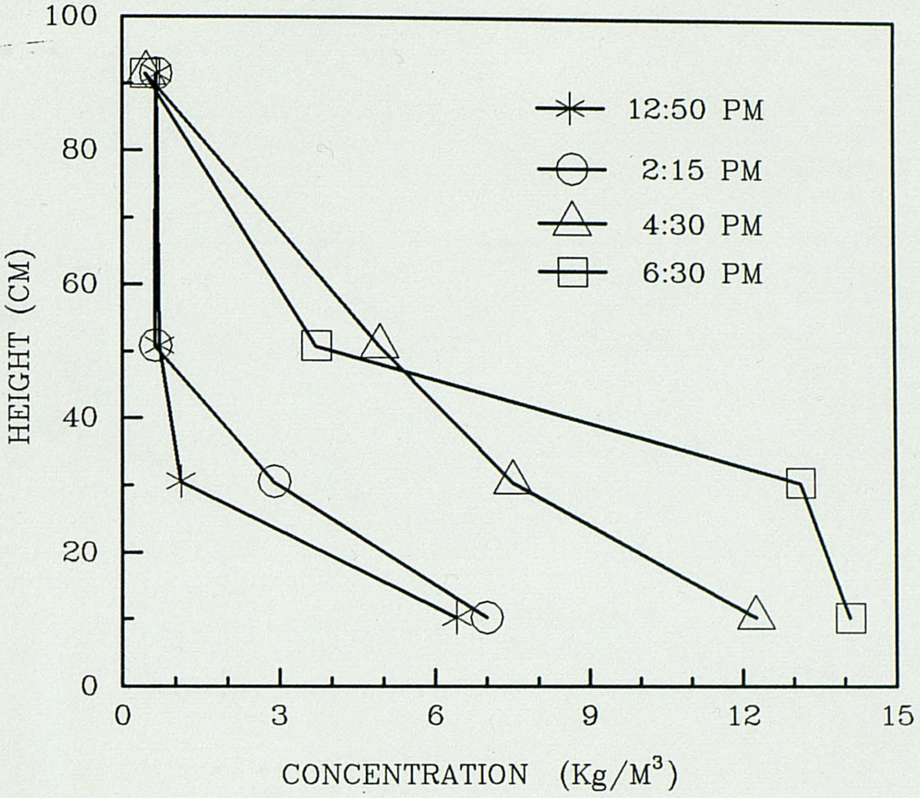

Figure 24. Clarifier A Profile for July 7, 1989

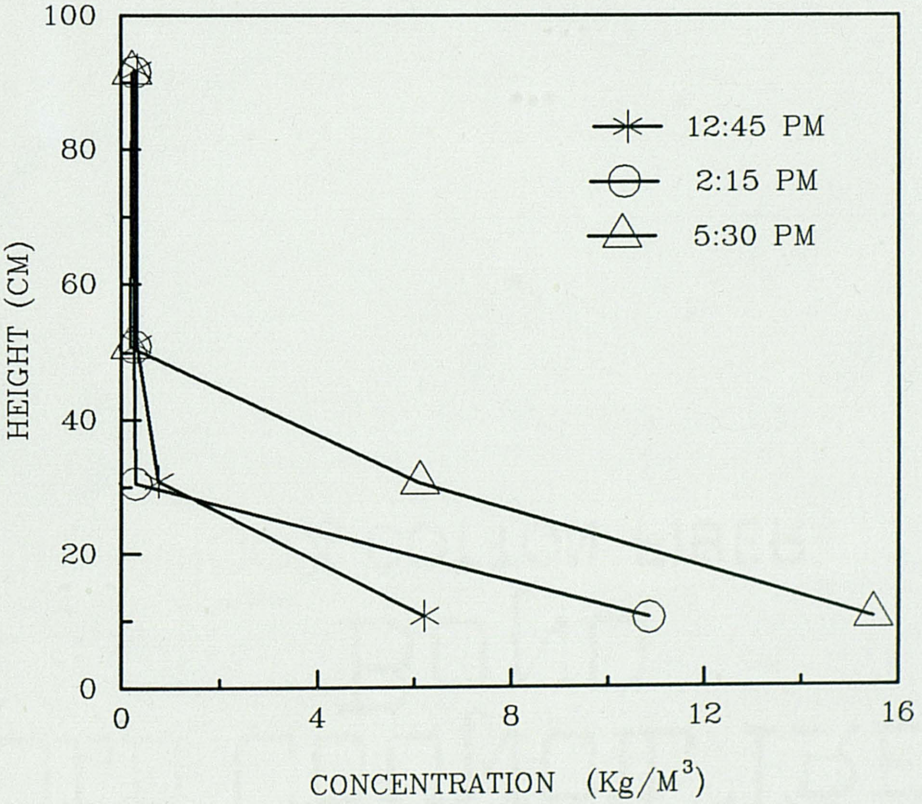

Figure 25. Clarifier B Profile for June 7, 1989

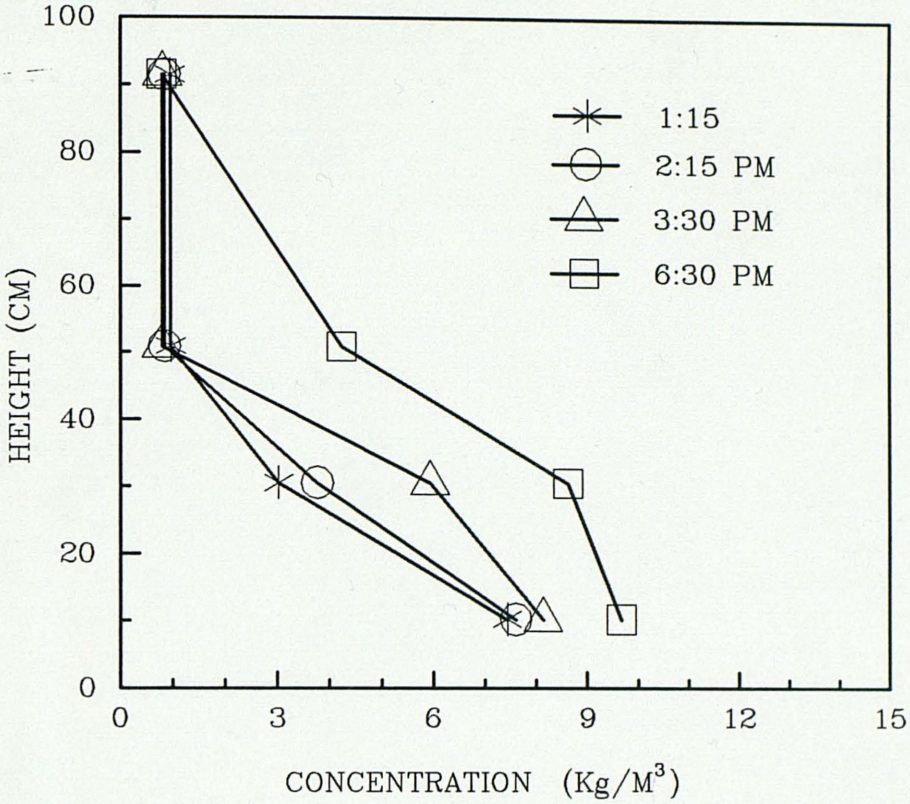

Figure 26. Clarifier A Profile for July 14, 1989

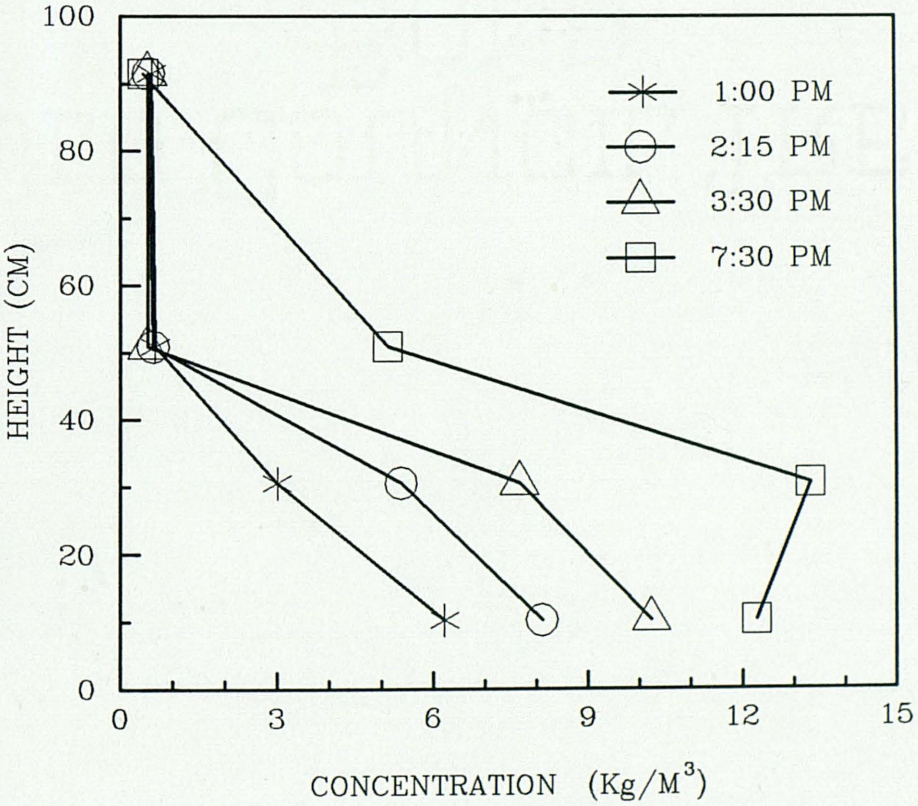

Figure 27. Clarifier B Profile for June 14, 1989

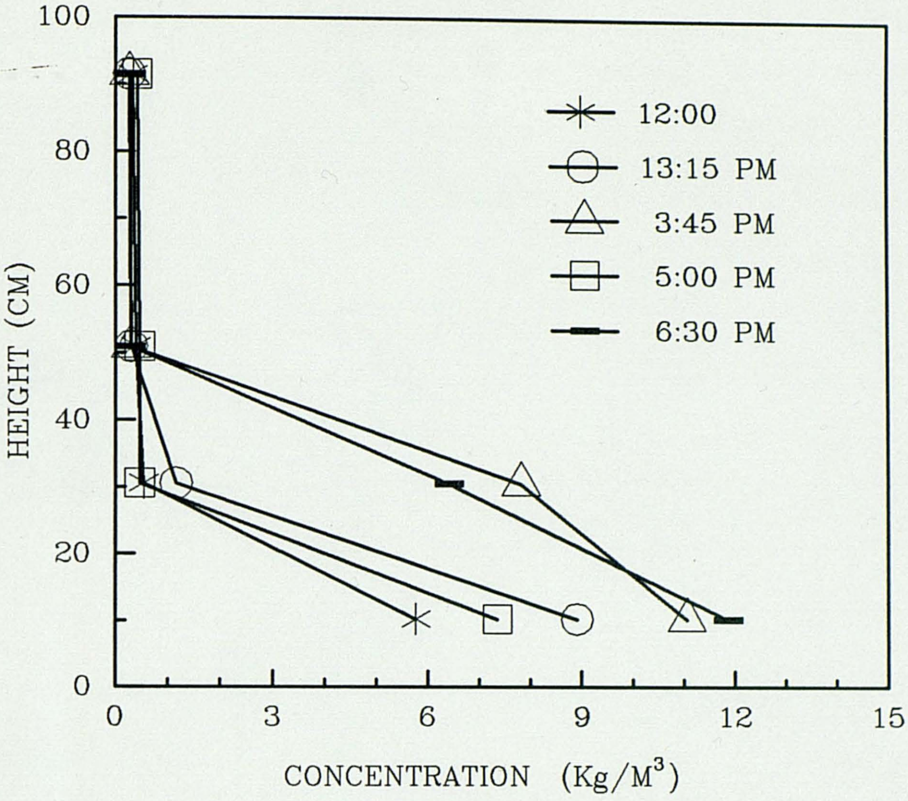

Figure 28. Clarifier A Profile for July 21, 1989

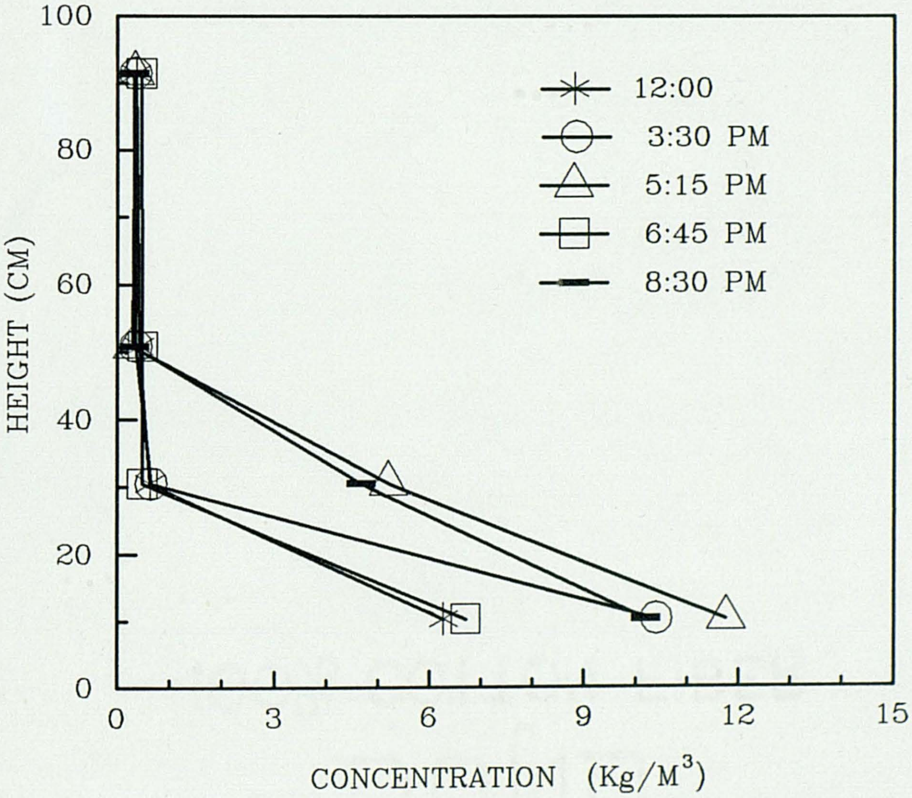

Figure 29. Clarifier B Profile for June 21, 1989

description of the statistical methods employed follows and is adopted from McClave and Dietrich (1985).

The Linear Model

Experimental data which consists of one independent variable, x, and one dependent variable, y, can be modeled by a two parameter linear model as,

$$y = A_0 + A_1x \qquad (12)$$

where A_0 and A_1 are parameter estimates. Predicted values for these parameters can be made by a linear least squares fit to the data.

Linear least squares is a method used to fit a curve to a data set by minimizing the sum of the squares of the deviations of the observed and predicted values of y. The equation for the sum of squares of deviations or sum of squares of errors (SSE), as it is commonly referred, is,

$$SSE = \Sigma\ (y_i - y_p)^2 \qquad (13)$$

where y_i is the observed value, and y_p is the predicted value. The least squares fit is the one with the smallest sum of squares of errors.

Analysis of Variance

When a comparison of two sources of variation is required, an analysis of variance (ANOVA) can be performed to determine whether the population means and/or variances are the same, provided the following assumptions apply:

1. The population probability distributions are normal.

2. The within-sample variances are equal.
3. All samples are independently and randomly selected.

An ANOVA utilizes two types of variances; those associated with the populations are called treatment variances, and that associated with the experimental replicates is called the within-sample variance. The variation of a population about the sample mean is proportional to the total sum of squares of errors (TSS), or,

$$TSS = \Sigma\ (y_i - y_{ave})^2 \tag{14}$$

where y_{ave} is the sample mean. An estimate of the sample variance, S^2, is obtained by dividing TSS by the number of degrees of freedom (n-1), where n is the number of observations.

The analysis of variance technique partitions the TSS and attributes the respective parts first to an independent variable and the remainder to random error. The random error portion is the SSE estimated from the replicate experiments and samples. The SSE is a pooled measure of the variance within the data sets.

The part of TSS associated with the independent variable is the treatment sum of squares (SST). Stated mathematically,

$$TSS = SST + SSE. \tag{15}$$

Thus, SST is the difference between TSS and SSE. When the terms in equation (15) are divided by the associated degrees of freedom, TSS, SST and SSE become the sample variance (σ^2), mean square for treatment (MST) and mean square for error (MSE), respectively.

To compare the variability between treatment means (SST) to the within-sample variability (SSE), the F-statistic is employed. The F-statistic is:

$$F = MST/MSE \tag{16}$$

A null hypothesis (H_o) is made which states that the sample means are equal:

$$H_o\text{: } u_1 = u_2 = \ldots u_k$$

The alternative hypothesis (H_a) states that at least two of the means differ:

$$H_a\text{: } u_1 \neq u_k$$

Large values of the F-statistic indicate large differences in sample means and support the alternative hypothesis; therefore, the rejection region for a given risk, α, is:

$$F \geq F_\alpha$$

The degrees of freedom for the F-statistic are the treatment (population) degrees of freedom and the error degrees of freedom associated with MST and MSE, respectively.

Experimental Models

Replicate Batch Settling Data

The batch settling experiments were set up so that at least one replicate concentration was done each day. The replicates provide an estimation of variance within each set of settling data. A pooled variance of the batch data sets determines the MSE as shown in Table 4. The MSE is used in further analysis as an estimate of variance within all the batch settling experiments.

Batch Flux Curve Model Selection

The five individual batch flux curves are shown on Figures 15-19. Three models are developed to estimate the Vesilind settling parameters, V_o and K.

Model 1. In the first model, V_o and K are estimated from a single data set which includes all the data. This is a 2-parameter model.

$$\text{Flux} = 550(C)\exp^{(-0.566(C))}$$

Model 2. The second model is a 5-parameter model where V_o is estimated for each of the 5 data sets, while K is held constant.

$$\text{Flux} = 385(C)\exp^{(-0.566(C))}$$

$$\text{Flux} = 605(C)\exp^{(-0.566(C))}$$

$$\text{Flux} = 529(C)\exp^{(-0.566(C))}$$

$$\text{Flux} = 682(C)\exp^{(-0.566(C))}$$

$$\text{Flux} = 539(C)\exp^{(-0.566(C))}$$

Model 3. The third model is a 10-parameter model in which all 5 data sets are used individually to estimate values for both V_o and K.

$$\text{Flux} = 295(C)\exp^{(-0.509(C))}$$

TABLE 4

BATCH SETTLING REPLICATE ANALYSIS

Date	CONC. (kg/m^3)	FLUX (kg/m^2-day)	MEAN FLUX (kg/m^2-day)	RESIDUAL SUM OF SQUARES	DEGREES OF FREEDOM
6/18	5.13	71.8			
	5.34	43.5			
	5.56	76.8	64.0	646.3	2
6/27	5.56	103.4			
	5.76	86.7	94.7	150.0	1
7/ 5	3.18	273.1			
	3.26	291.2	282.2	162.8	1
7/12	5.35	106.1			
	5.59	109.2	108.0	5.2	1
7/19	5.31	139.0			
	5.37	179.0	159	800	1
				Σ 1764.3	Σ 6

$$\text{MSE} = \frac{1764.3}{6}$$

$$\text{MSE} = 294.0$$

$$\text{Flux} = 1365(C)\exp^{(-0.779(C))}$$

$$\text{Flux} = 514(C)\exp^{(-0.559(C))}$$

$$\text{Flux} = 584(C)\exp^{(-0.529(C))}$$

$$\text{Flux} = 307(C)\exp^{(-0.424(C))}$$

The parameter estimates and residual sum of squares for each model were determined using a non-linear least squares parameter estimation procedure (Statistical Analysis System 1982) and are shown in Table 5.

An analysis of variance is performed for model selection. The ANOVA compares two models at a time. Each test is set up as shown on Table 6. The hypothesis sum of squares (HSS) is the difference in the total residual sum of squares between models a and b. The hypothesis degrees of freedom (HDF) is the difference in the number of degrees of freedom between the models. HMS is the hypothesis mean square. The calculated F-statistic (F_{calc}) is the ratio of HMS to MSE, where MSE is derived from the replicates. The null hypothesis is rejected when F_{calc} is greater than or equal to the tabulated value of the F-statistic.

Model selection consists of sequential comparisons of lower and higher parameter models. The comparisons continue until no significant improvement in the model is achieved. In this case, the 2-parameter model is first compared to the 5-parameter model as shown in Table 7. The comparison shows that the 5-parameter model gives a

TABLE 5

MODELS WITH PARAMETERS, RSS AND DF

Model	Number of Parameters	V_o (m/day)	K (kg/m^3)	RESIDUAL SUM OF SQUARES	DEGREES OF FREEDOM
1	2	550	0.556	65460.03	2
			$RSS_1 = 65460.03$	$DF_1 = 2$	
2	5	385	0.566	15880.52	1
		605	0.566	10593.91	1
		529	0.566	6650.76	1
		682	0.566	17576.65	1
		539	0.566	9175.53	1
			$RSS_2 = 59877.37$	$DF_2 = 5$	
3	10	295	0.509	15622.08	2
		1365	0.779	499.71	2
		514	0.559	6634.32	2
		584	0.529	17149.24	2
		307	0.424	2482.59	2
			$RSS_3 = 42387.93$	$DF_3 = 10$	

TABLE 6

ANALYSIS OF VARIANCE

H : The Difference in Parameter Estimates Equals Zero

H : The Difference is Significant

$HSS = RSS_A - RSS_B$
$HDF = HDF_A - HDF_B$
$HMS = HSS / HDF$
$F_{calc} = HMS / MSE$
Rejection Region: $F_{calc} \geq F_{\propto}$

TABLE 7

MODEL COMPARISONS USING ANOVA

Compare Model 1 to 2

2 – Parameter RSS_1 = 65460.03 DF = 2

5 – Parameter RSS_2 = 59877.37 DF = 5

HSS = 65460.03 – 59877.37

HSS = 5582.67

HDF = 5 – 2

HDF = 3

HMS = HSS / HDF

HMS = 5582.67 / 3

HMS = 1860.89

MSE = 294.0 (Table C)

F_{calc} = HMS / MSE

F_{calc} = 1860.9 / 294.0

F_{calc} = 6.33

$F_{0.5,3,6}$ = 4.76

$6.33 > 4.76$ ($F_{calc} > F_{tab}$)

Therefore, the 5 – parameter model is superior to the 2 – parameter model.

---

significantly better description of the data. The 5-parameter model is next compared to the 10-parameter model (Table 8). The 10-parameter model significantly improves the model fit. The 10-parameter model is selected, since it gives the best description of the settling data.

Scale Factor Development

A scale factor is a ratio of continuous to batch solids limiting flux values. There are three techniques, discussed in the previous chapter, considered for interpreting the continuous data in order to determine scale factors. The continuous solids flux values are those associated with blanket propagation for a particular experiment. Three techniques can be used to determine continuous limiting flux values.

Technique number 1 uses measured values of u, C_u and C_b from the continuous experiments to determine a full scale point (F) and scales the solids flux value of point F (G_{Sf}) to the flux value at the point where the batch curve intersects C_b, (G_{Sb}), as shown in Figure 30. The ratio of continuous to batch solids flux values is the scale factor,

$$SF = G_{Sf}/G_{Sb}. \tag{17}$$

Technique number 2, shown in Figure 31, uses measured values for v, u, MLSS and C_b to determine the continuous point F, and then employs the same procedure as number 1 to determine the scale factors. The first two techniques

TABLE 8

MODEL COMPARISONS USING ANOVA

Compare Model 2 to 3

5 − Parameter $RSS_2 = 59877.37$ $DF_2 = 10$

10 − Parameter $RSS_3 = 42387.93$ $DF_3 = 10$

HSS = 17489.43

HDF = 5

HMS = 3497.9

MSE = 294.0

$F_{calc} = 11.90$

$F_{0.5,5,6} = 4.39$

$11.9 > 4.39$

Therefore, the 10 − parameter model is superior to the 5 − parameter model.

TABLE 9

MODEL COMPARISONS USING ANOVA

Compare Model 1 to 3

2 − Parameter $RSS_1 = 65460.0$ $DF_1 = 10$

10 − Parameter $RSS_3 = 42387.93$ $DF_3 = 10$

HSS = 23072.1

HDF = 8

HMS = 2884.0

MSE = 294.0

$F_{calc} = 9.81$

$F_{0.5,8,6} = 4.15$

$9.81 > 4.15$

Therefore, the 10 − parameter model is superior to the 2 − parameter model

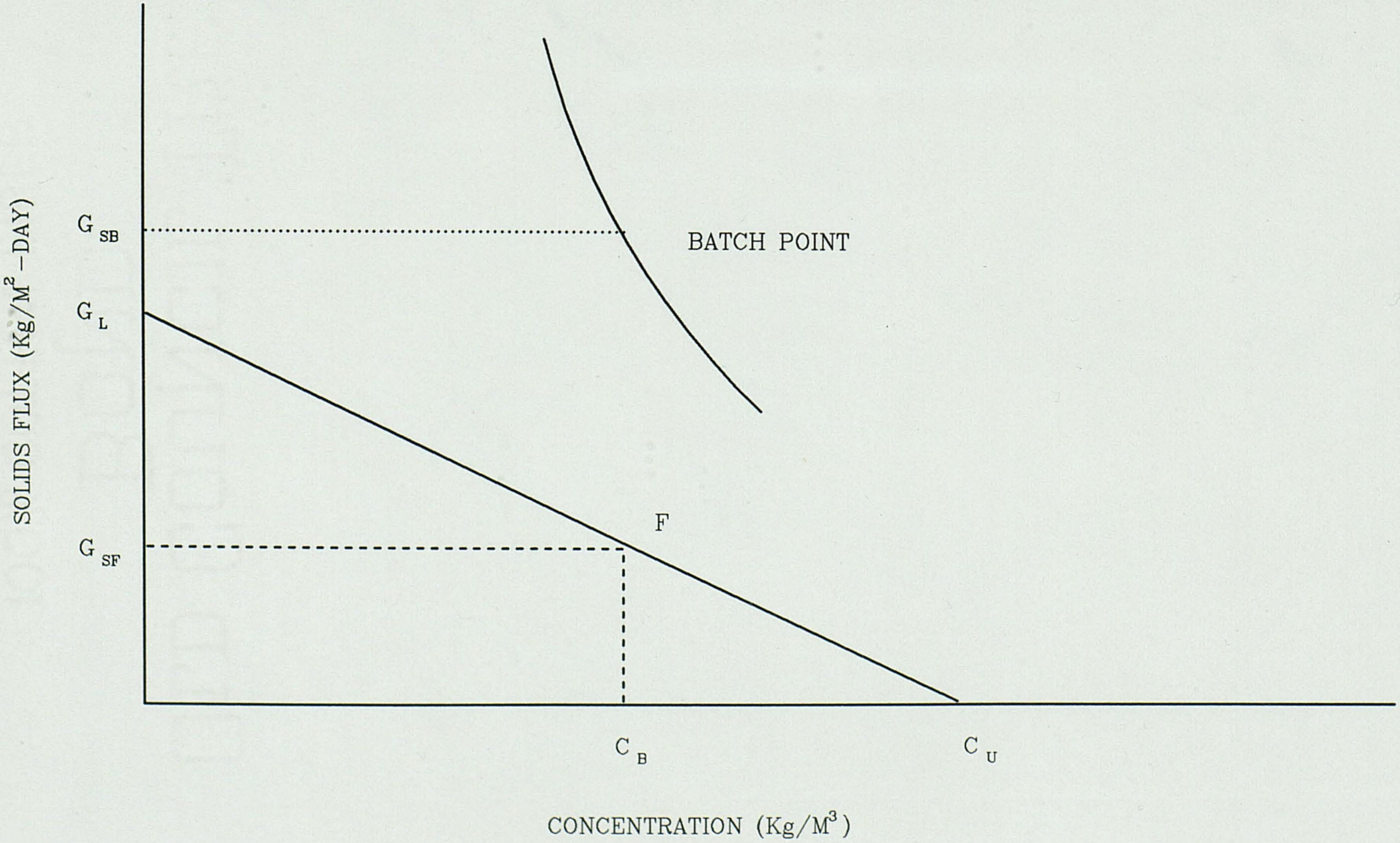

Figure 30. Technique 1

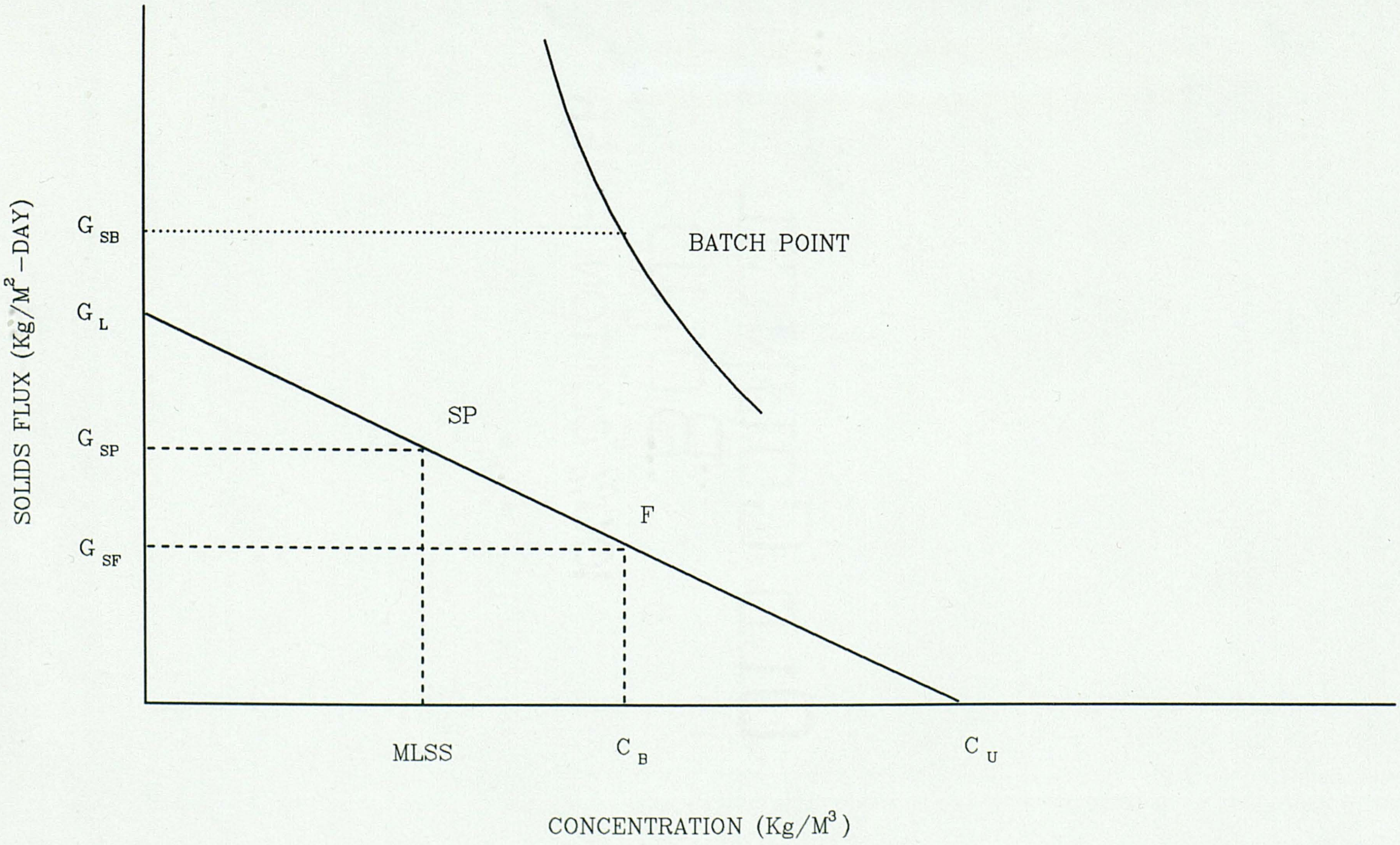

Figure 31. Technique 2

depend upon an accurate measurement of thick blanket concentration to determine scale factors.

The third technique determines the scale factor from a ratio of continuous to batch limiting flux values. From measured values of u and C_u, the maximum allowable loading (G_{Lf}) is determined as shown in Figure 32. The underflow velocity line (line U) is moved parallel until it becomes tangent with the batch curve. The limiting flux (G_{Lb}) associated with the batch curve is calculated and the scale factor determined from,

$$SF = G_{Lf}/G_{Lb}. \tag{18}$$

Technique Selection

Technique number 3 was selected for the following reasons:

1. Only two measurements are required for the continuous experiments, C_u and u. Techniques 1 and 2, on the other hand, both require an accurate measurement of blanket concentration which was difficult to sample.
2. At many full scale facilities, C_u and u are easily, and usually, routinely measured. Other parameters, such as C_b, may be more difficult to measure, since they are not typical operating parameters.
3. The scale factor (G_{Lf}/G_{Lb}) is the inverse of the ratio of clarifier design surface areas (A_b/A_f):

$$G_{Lf}/G_{Lb} = A_b/A_f \tag{19}$$

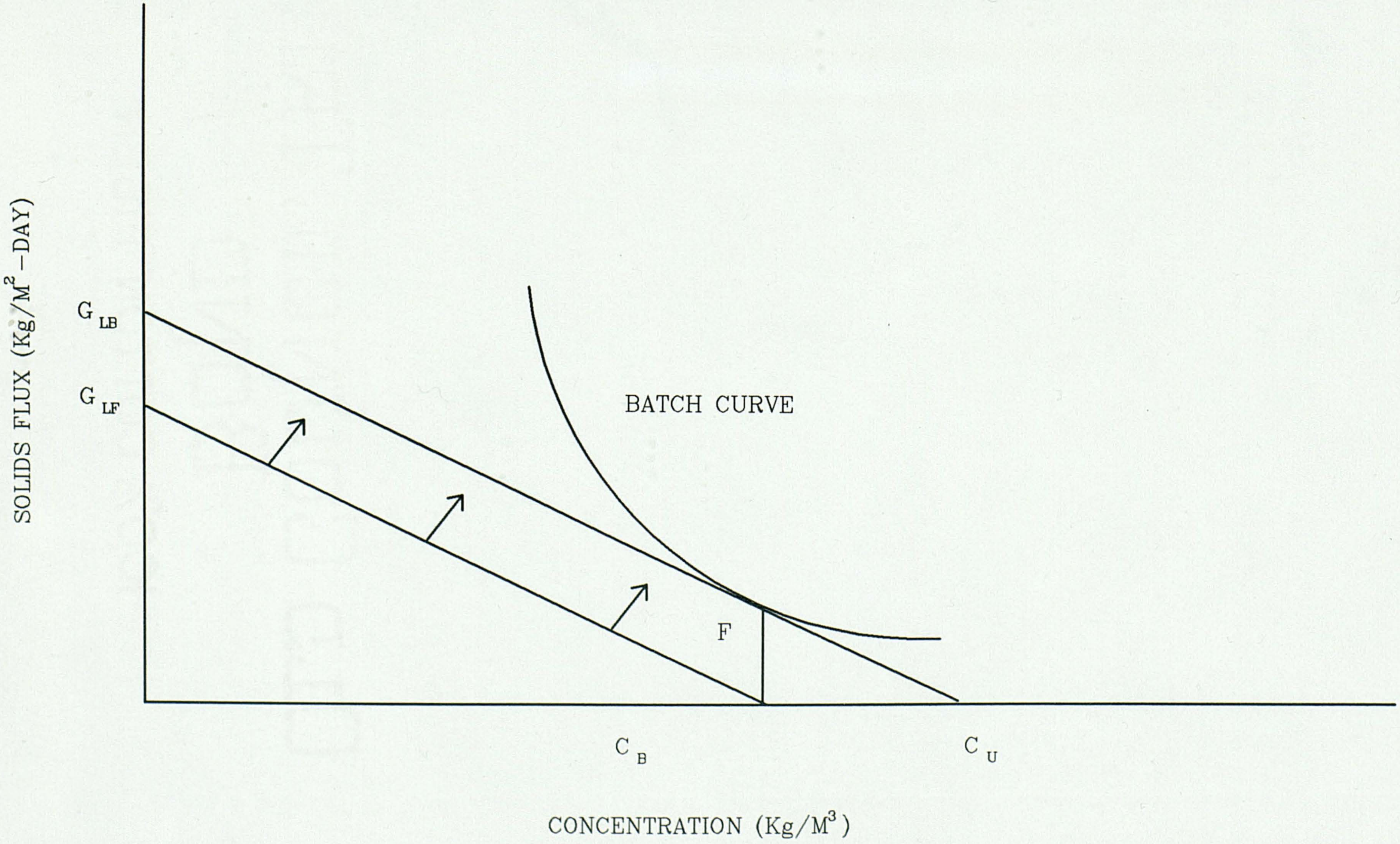

Figure 32. Technique 3

Appendix B contains a justification of the scale factor defined by equation (18).

Selecting a Scale Factor

Scale factors are shown in Table 10 for each continuous experiment. An analysis of variance between scale factor and blanket concentration is detailed in Table 11 and indicates that scale factor is not dependent on blanket concentration, and thus the mean scale factor value (0.84) can be selected for clarifier design. The mean square error (MSE) was determined using replicates from the continuous experiments performed on July 21, 1989.

Batch Flux Curve Variability - Safety Factor

Although working from a small data base (5 batch flux curves), a safety factor can be incorporated into the analysis to account for flux curve variability. Because the 10-parameter model gives the best fit to the data, all 5 batch flux curves are used to develop the safety factor and are shown in Figure 33. A general procedure for safety factor development follows and includes two approaches.

For each concentration in the batch data range, 3.0 to 13.0 Kg/m^3 in increments of 1.0 Kg/m^3, five solids flux values were calculated, one for each daily batch settling curve. The flux values were then ranked in order of increasing concentration and given a Weibull probability

TABLE 10

SCALE FACTORS

Date	CLARIFER	RECYCLE (m/day)	CONTINOUS G_L (kg/m^2–day)	BATCH G_L (kg/m^2–day)	SCALE FACTOR	C_B (kg/m^3)
6/21	A	14.2	131	153	.86	8.2
	B	18.2	160	185	.86	7.5
7/ 7	A	13.3	163	150	1.09	9.0
	B	2.4	38	36	1.06	12.8
7/14	A	15.5	150	184	.82	9.5
	B	7.1	83	97	.86	11.4
7/21	AC	5.77	64	91	.70	12.9
	AE	5.99	71	94	.76	12.8
	BC	6.22	73	97	.75	12.7
	BE	6.22	63	97	.65	12.7

TABLE 11

ANOVA TO DETERMINE SF DEPENDENCE ON C_B

10 PARAMETER MODEL

Average SF = .841

SST = .1827

1 PARAMETER MODEL

$SF = B_1 C_B + B_o$
$B_1 = -.0266$
$B_o = 1.13$

RSS = .155

ANOVA

HMS = (SST − RSS) / 1
HMS = .02773
MSE = .02374
$F_{calc} = 1.17$
$F_{.05,1,3} = 10.13$

$1.17 < 10.13$

∴ SF is independent of C_B

TABLE 12

DEVELOPMENT OF EXCEEDENCE PROBABILITY FOR 3.0 (Kg/m^3)

Solids Flux	Date	Rank (m)	Weibull Pr.	Exceedence Pr.
192	6/18/89	1	.167	.833
258	7/19/89	2	.333	.667
288	7/ 5/89	3	.500	.500
358	7/12/89	4	.667	.333
396	6/27/89	5	.833	.167

Mean Flux = 299 (kg/m^2-day)

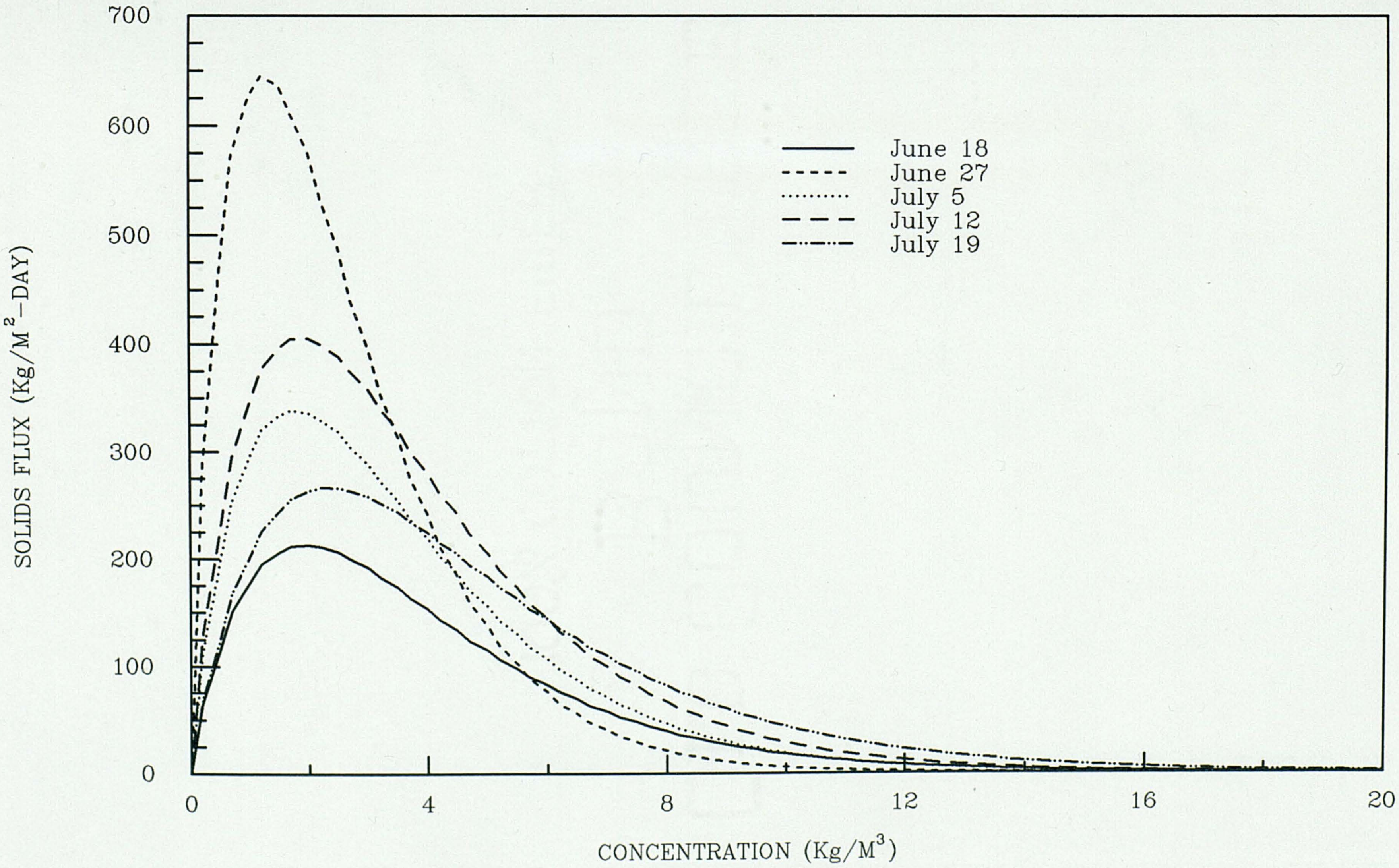

Figure 33. Settling Flux Curves

(Benson 1962) according to,

$$\text{Weibull probability} = m/n+1 \qquad (20)$$

where m is the rank (1-5) and n is the number of flux values (5). The mean flux values and exceedence probabilities were also calculated. The exceedence probability is defined by,

$$\text{Exc. Pr.} = (1\text{-Weibull Pr.}) \qquad (21)$$

For example, the five flux values, mean, rank, Weibull Pr. and Exceedence Pr. for 3.0 Kg/m^3 are shown in Table 12. Similar tables were generated for concentrations 4.0, 5.0...13.0 Kg/m^3.

The flux values were plotted vs. the Weibull probabilities on normal-probability paper. Linear least squares was then used to fit a line to the points so that a flux value could be determined for any given probability. The probability range was limited by the data to values between 0.167 and 0.833.

To effectively use the plot, the exceedence probabilities were substituted for the Weibull probabilities using equation (21). In this manner, flux values were determined for each concentration at the 0.80 exceedence probability level, and a flux curve was generated from the points. The 80% exceedence probability level was chosen because it is gives a conservative design safety factor and falls within the data range. The flux curve was labeled the 80% exceedence curve and is shown with the 50% curve in Figure 34. Other exceedence curves could be generated using the same procedure. An exceedence probability curve can be chosen based upon the level of risk deemed acceptable for clarifier design.

A mean flux curve was generated using the mean flux values for each concentration. Limiting flux values were determined for both the mean and 80% exceedence curve. The ratio of mean to exceedence limiting flux values was the safety factor. Two approaches were considered for determining the design limiting flux values.

In the first approach, the underflow concentration was held constant for both the exceedence and mean limiting flux calculations, while the underflow velocity was allowed to vary. The procedure corresponds to Figure 35 and is listed in Appendix C. The second approach fixed the underflow velocity and thus allowed the underflow concentration to vary. The procedure corresponds to Figure 36 and is listed in Appendix C.

The selection of an approach depends on the needs of the design engineer. Approach number 1 should be used when a particular underflow concentration is absolutely required. Approach number 2 may be used when the recycle ratio or a particular recycle rate is specified and when periodic reduction in underflow concentration could be tolerated.

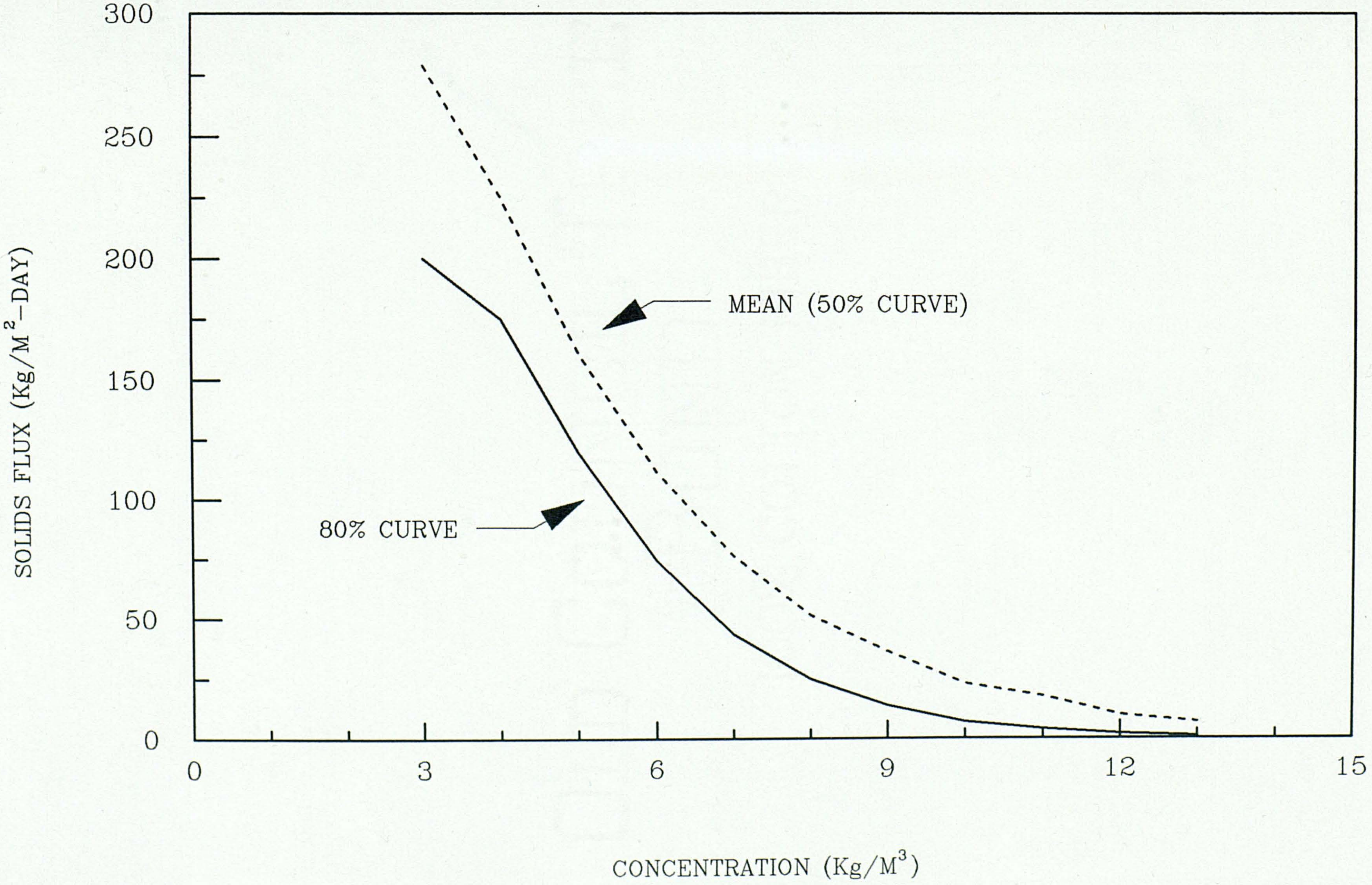

Figure 34. 80% and 50% Exceedence Curves

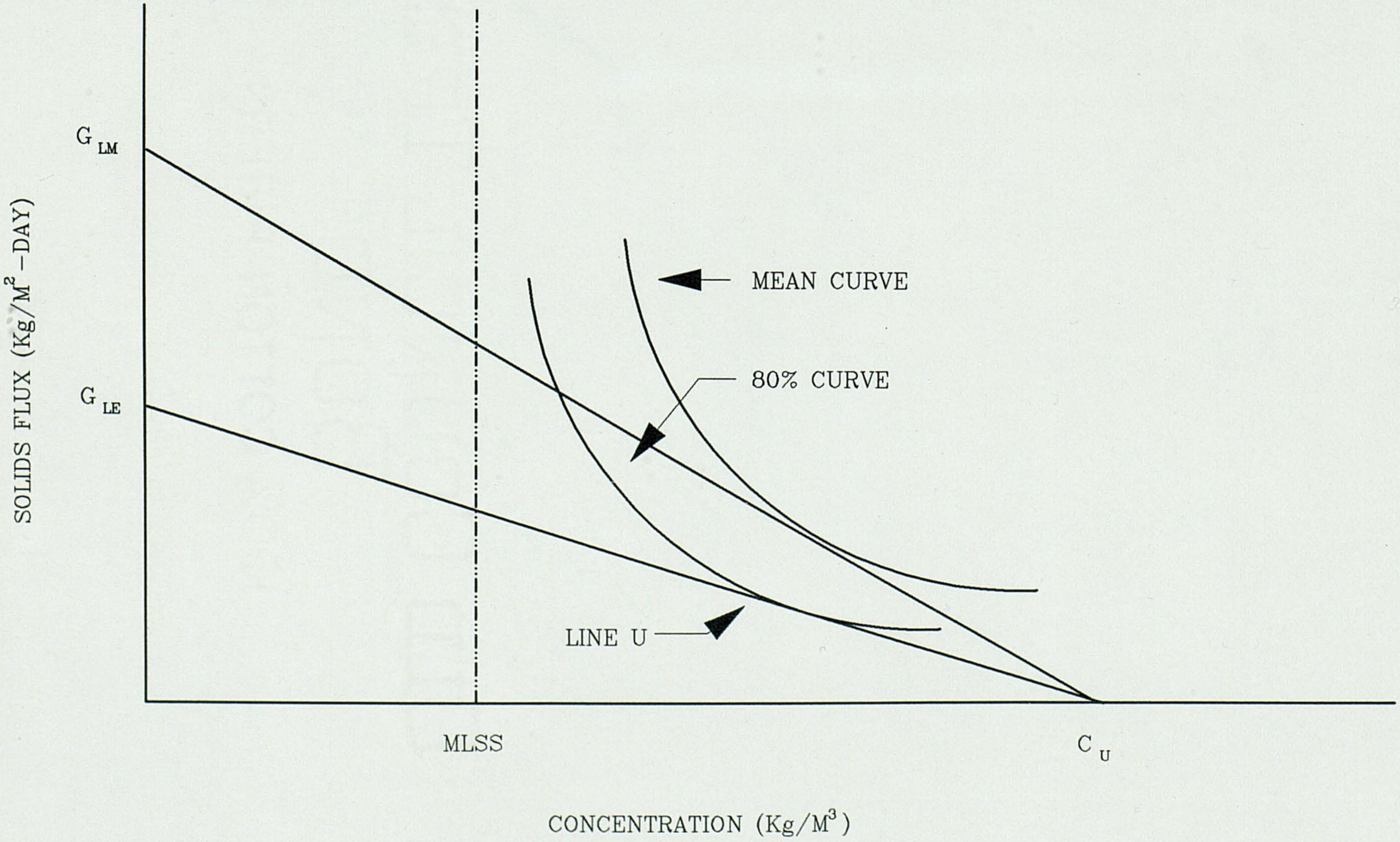

Figure 35. Approach 1 for Safety Factors

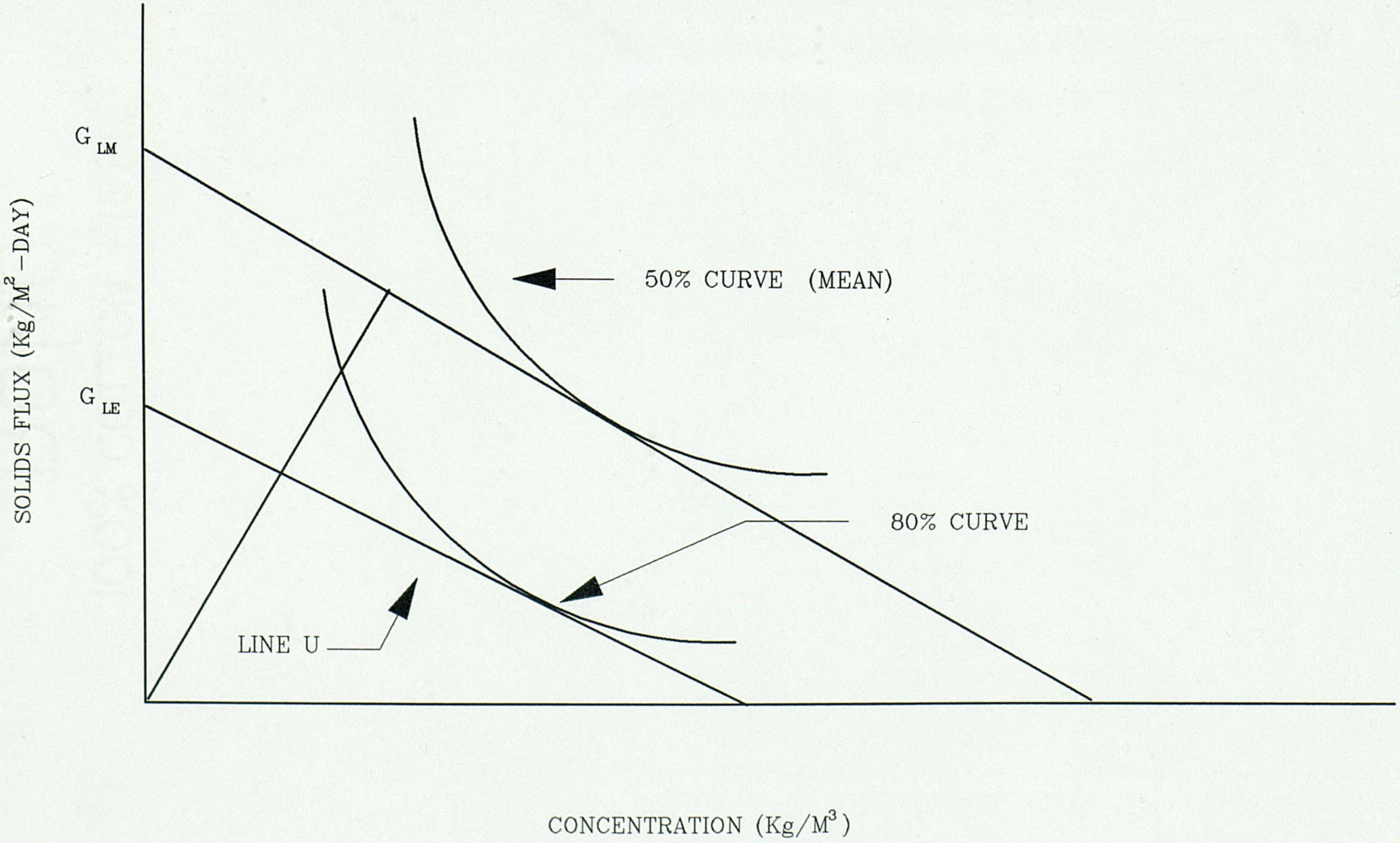

Figure 36. Approach 2 for Determining Safety Factors

Application

The scale factor is a multiplier which is used to scale the maximum solids loading predicted by the batch flux curve to the maximum solids loading observed during the continuous experiment. The safety factor is a multiplier which is used to quantify the variablity of the batch settling flux curves. The clarifier design area (A_F) can be determined directly from the predicted batch loading from,

$$A_F = Q_o(\mathrm{MLSS})/G_{Lb}(\mathrm{SF})(\mathrm{Safety\ Factor}) \quad (\mathrm{m}^2) \qquad (22)$$

where Q_o is the influent flow rate ($\mathrm{m}^3/\mathrm{day}$). An example clarifier design is given in Appendix D.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The scale factors determined in this study are specific to the 20.3 cm diameter prototype clarifiers used for the continuous experiments. The focus of this research was to develop a procedure for determining scale factors between batch and continuous (full scale) experiments for use in clarifier design.

Several problems were encountered during the continuous experiments. The distance between clarifier sample ports often made sampling the thick blanket difficult, especially at low flow rates, since the blankets took up to 4 hours to propagate to the sampling port; and, during this time, pieces of the blanket floated to the clarifier surface due to the formation of gas bubbles in the clarifier bottom. The stirring rake did not reach the edges of the clarifier and, at times, it appeared that some of the sludge was accumulating along the bottom edges of the clarifier while the newly settled sludge was being channelled directly into the underflow line. The underflow line was located on the side of the clarifier and 10.16 cm above the base, this location may have contributed to channelling and gas formation. All of these problems combined to make sampling the thick blanket difficult. Since this work was not performed on a full scale clarifier, the problems which may occur in a full scale facility can only be speculated, and most likely will be site specific.

This research has determined the specific information which is required using a full scale clarifier in order to determine scale factors:

	Measurements	
Parameter	Flow Rates	Concentrations
underflow	x	x
overflow *	x	
influent *	x	
mixed liquor		x
thick blanket *		x

* Indicates optional measurement

In addition, it is necessary to control the underflow velocity so that an overloaded condition can be induced. Minimum underflow pumping constraints may limit the ability to reach solids overload. A sludge judge is needed to measure the height of the thick blanket in order to verify blanket propagation.

The overall objective of this research was to develop a procedure for determining scale factors. The procedure recommended considers the difficulties associated with obtaining accurate measurements of flow rates and concentrations at full scale activated sludge wastewater treatment plants. The selected procedure requires measurements of only two full scale parameters, underflow velocity and concentration.

Scale Factor Procedure Summary

1. Perform batch settling tests and develop a batch flux curve from the Vesilind equation (Flux = $V_0C\exp(-KC)$) using non-linear least squares.
2. Use the batch curve, select a combination of overflow rate and mixed liquor concentration and then estimate the recycle rate which will overload the clarifier. Determine four recycle rates which will incrementally take the clarifier from an underloaded to an overloaded state considering any minimum pumping constraints.
3. Perform the continuous experiment as outlined below:
   a. Start with the current recycle rate (system underloaded) and check the clarifier thick blanket every 15 minutes for one hour to verify that the blanket is stable.

   b. Determine the recycle flow, record the time, and sample the underflow and mixed liquor for suspended solids analysis. Also, measure and record the thick blanket height (if present). As a supplement (optional), obtain measurements of overflow rates and a sample of the thick blanket (if present) for suspended solids analysis.

c. Decrease the recycle rate to the next increment determined from (2) above.

d. Every 15 minutes for 1 hour, measure and record the blanket height, recycle flow rate and time. After 1 hour, if the blanket has propagated, continue with (e) below; if not, return to (c) above.

e. When a blanket propagation has occurred, sample the underflow and record the recycle flow and time. Also, sample and record all the parameters possible, as in (b).

f. Increase the recycle rate back to the normal operating rate and allow the blanket to stabilize.

g. Repeat a-f by decreasing the recycle rate directly to a value between the recycle increments which caused overload.

4. Determine the scale factor by using technique 3 (Figure 33) which uses the batch and continuous limiting flux values and the recycle rate associated with full scale overload,

$$SF = G_{Lf}/G_{Lb}. \tag{23}$$

5. Incorporate the safety factor which accounts for batch curve variability if a large batch curve data base exists.

The scale factor can be incorporated into the state point design procedure for determining clarifier surface area. Any single batch flux curve can be used for design purposes.

Clarifier Surface Area Design Procedure

1. Assume values for the following parameters:
    - Influent flow rate, Q_i (m^3/day)
    - Recycle ratio, R (unitless)
    - Mixed liquor concentration, MLSS (Kg/m^3)
    - Vesilind settling parameters, V_0 and K
2. Establish the system constraints:
    - Maximum overflow rate, v_{MAX} (m/day)
    - Maximum underflow rate, u_{MAX} (m/day)
    - Minimum underflow rate, u_{MIN} (m/day)
    - Minimum underflow concentration, C_u (Kg/m^3)
3. Determine the underflow concentration (C_u) from the batch data for the minimum underflow rate using the equation from Riddell et al. (1983).

$$C_u = \frac{(1+R)MLSS}{2R} + \left[\left(\frac{1+R}{R}\right)^2 \frac{MLSS^2}{4} - \frac{(1+R)MLSS}{R\ K}\right]^{0.5} \qquad (24)$$

4. Calculate the limiting flux, G_{Lb} (Kg/m^2-day) for the batch data,

$$G_{Lb} = V_o\ K\ C_u^2\ \exp(-KC_u). \qquad (25)$$

5. Apply the scale and safety factors,

$$G_{Lf} = G_{Lb}\ (SF)\ (\text{safety factor}). \qquad (26)$$

6. Calculate the limiting flux established by the maximum overflow rate constraint,

$$G_{Lv} = MLSS\ (v + u) \tag{27}$$

7. Choose the smallest limiting flux between G_{Lf} and G_{Lb}.

8. Calculate the clarifier surface area, A (m^2),

$$A = Q_i(MLSS)/G_L \tag{28}$$

Calculation of the design area should include the safety factor for batch curve variability (number 5 above), given that an adequate batch curve data base exists.

Recommendations

Scale Factor

Further research is needed to determine scale factors using full-scale clarifiers. The procedure developed herein for determining scale factors can be used as a guide for future studies. To facilitate flow control and data collection, pilot scale clarifiers were used in this study. Future experimentation should be performed using full-scale clarifiers at as many full-scale facilities as possible in order to develop a substantial data base. The research herein shows that the scale factor depends upon blanket concentration; however, the data base represents only five days of experiments on a prototype clarifier.

Obtaining representative clarifier blanket samples from the prototype units was difficult for several reasons. The sample ports were located on the walls of the clarifiers and along one side; also, the sludge rake was ineffective in preventing sludge from accumulating along the walls. As a result, gas formation in the accumulating sludge caused pieces of the blanket to rise to the surface. It is recommended that techniques be explored for sampling the thick blanket of full-scale clarifiers (i.e., composite sample from various locations in the clarifier).

Safety Factor

This research explored the techniques for determining safety factors to account for batch flux curve variability. A specific safety factor was not determined since the data base was limited to five batch flux curves. It is recommended that the data base be developed over a period of more than one year to account for seasonal as well as diurnal variation. From this large data base, it is recommended that a plot of safety factor vs. exceedence probability be developed in order to determine a safety factor based on a desired level of design risk.

APPENDICES

APPENDIX A

DATA TABLES

TABLE 13

BATCH SETTLING DATA

Date	Concentration (Kg/M^3)	Settling Velocity (M/DAY)	Flux (Kg/M^2 –Day)
6/18/89	1.78	192.0	341.8
	2.69	131.2	352.9
	3.51	57.3	201.1
	5.13	14.0	71.8
	5.34	14.4	76.9
	5.56	7.8	43.4
	5.79	17.8	103.1
	6.68	24.5	163.7
	8.02	4.8	38.5
	9.23	2.7	24.9
6/27/89	2.02	171.2	345.8
	2.47	131.1	323.8
	3.06	126.0	385.6
	5.56	18.6	103.4
	5.76	15.0	86.4
	6.35	7.9	50.2
	7.96	5.0	39.8
	13.47	0.5	6.7
7/ 5/89	2.96	89.7	265.5
	3.54	65.2	230.8
	5.20	40.3	209.6
	5.31	26.2	139.1
	5.37	33.3	178.8
	7.65	11.4	87.2
	9.56	5.4	51.6
7/12/89	1.96	150.6	295.2
	2.04	111.5	227.5
	2.75	144.7	397.9
	3.26	100.4	327.3
	4.09	77.7	317.8
	4.85	50.0	242.5
	5.35	19.8	105.9
	5.59	19.5	109.0
	6.12	33.1	202.6
	7.84	13.0	101.9
7/19/89	3.18	85.9	273.2
	3.26	89.3	291.1
	4.48	39.6	177.4
	5.00	26.7	133.5
	5.68	20.5	116.4
	6.10	11.8	72.0
	6.34	23.4	148.4
	6.54	10.4	68.0
	7.69	10.0	76.9
	9.20	5.8	53.4

TABLE 14. CONTINUOUS CLARIFIER DATA FOR CLARIFIER A

Date	Time	Average Flows Feed (M/DAY)	Average Flows Over (M/DAY)	Average Flows Under (M/DAY)	Feed Conc. (Kg/M^3)	Feed D. O. (mg/L)	Feed Temp (°C)	pH Feed	pH Over	pH Under
6/20	9:40–12:40	61.7	31.1	30.6	3.5	N/A	N/A	N/A	N/A	N/A
	12:40–14:15	54.6	30.2	24.4	3.5	N/A	N/A	N/A	N/A	N/A
	14:15–15:40	44.4	30.2	14.2	3.5	N/A	N/A	N/A	N/A	N/A
6/29	10:30–14:45	76.5	36.5	40.0	3.2	7.41	27	6.72	6.79	6.52
	14:45–16:15	70.3	35.6	34.7	3.2	7.30	27	6.78	6.80	6.52
	16:15–18:15	69.6	36.5	33.1	3.2	7.45	26	6.79	6.88	6.52
7/07	8:50–12:50	47.1	23.6	23.5	3.2	7.26	26	6.97	7.01	6.72
	12:50–14:14	43.1	24.5	18.6	3.2	6.65	28	6.84	7.03	6.71
	14:15–15:15	40.8	23.9	16.9	3.2	6.90	28	7.00	7.04	6.68
	15:15–16:30	37.3	24.0	13.3	3.2	6.60	27	6.96	6.96	6.61
	16:30–17:30	33.8	23.6	10.2	3.2	5.60	29	6.62	7.05	6.70
7/14	9:15–13:15	58.6	29.3	29.3	3.3	7.51	27	6.90	6.94	6.73
	13:15–14:15	52.8	28.8	24.0	3.3	7.30	28	6.94	6.94	6.12
	14:15–15:30	50.6	28.8	21.8	3.3	7.20	29	6.89	6.87	6.55
	15:30–18:30	46.3	30.7	15.6	3.3	6.97	28	6.80	6.78	6.57
7/21	7:45–12:00	30.2	15.1	15.1	3.2	8.09	26	6.74	6.77	6.52
	12:00–13:15	23.5	14.8	8.7	3.2	8.10	27	7.15	7.19	6.77
	13:15–15:45	20.6	14.8	5.8	3.2	8.13	27	6.53	6.64	6.57
	15:45–17:00	30.0	14.9	15.1	3.2	7.60	26	6.83	6.98	6.76
	17:00–18:30	20.9	14.9	6.0	3.2	8.30	26	6.73	6.65	6.27

TABLE 15. CONTINUOUS CLARIFIER DATA FOR CLARIFIER B

Date	Time	Average Flows			Feed			pH		
		Feed	Over	Under	Conc.	D. O.	Temp	Feed	Over	Under
		(M/DAY)			(Kg/M^3)	(mg/L)	($^\circ$C)			
6/20	10:00–13:00	61.3	30.7	30.6	3.5	N/A	N/A	N/A	N/A	N/A
	13:00–14:15	48.8	30.6	18.2	3.5	N/A	N/A	N/A	N/A	N/A
	14:15–15:40	42.2	20.2	22.0	3.5	N/A	N/A	N/A	N/A	N/A
6/29	8:45–12:45	43.6	25.4	18.2	3.2	7.30	26	6.46	6.66	6.43
	12:45–13:45	40.5	24.0	16.5	3.2	7.60	28	6.65	6.74	6.50
	13:45–16:00	40.9	24.4	16.5	3.2	7.92	26	6.71	6.82	6.41
7/07	8:25–12:45	22.6	11.5	11.1	3.2	7.43	26	6.79	6.91	6.60
	12:45–14:15	19.1	11.1	8.0	3.2	7.30	27	6.98	7.10	6.75
	14:15–15:15	16.9	11.6	5.3	3.2	7.30	26	6.98	6.95	6.63
	15:15–16:30	14.9	11.1	3.8	3.2	7.40	26	6.99	7.04	6.60
	16:30–17:30	14.0	11.6	2.4	3.2	7.30	26	7.06	7.15	6.72
7/14	8:30–13:00	38.6	20.8	17.8	3.3	7.37	26	6.89	6.93	6.58
	13:00–14:15	35.5	21.7	13.8	3.3	7.20	27	6.96	6.96	6.62
	14:15–15:30	32.9	21.8	11.1	3.3	7.20	27	6.92	6.92	6.57
	15:30–19:30	29.3	22.2	7.1	3.3	7.20	27	6.88	6.78	6.52
7/21	7:45–12:00	28.9	14.7	14.2	3.2	8.25	25	6.77	6.75	6.50
	12:00–15:30	23.5	14.6	8.9	3.2	8.35	26	6.76	6.80	6.63
	15:30–17:15	20.9	14.7	6.2	3.2	8.00	26	6.90	7.00	6.75
	17:15–18:45	28.0	13.8	14.2	3.2	8.70	26	6.75	6.71	6.30
	18:45–20:30	21.3	15.1	6.2	3.2	8.80	25	6.92	6.87	6.62

TABLE 16. CLARIFIER PROFILE DATA CLARIFIER A

Date	Time	Sample Port 1	Sample Port 2	Sample Port 3	Sample Port 4	Samole Port 5
		Concentrations (Kg/M^3)				
6/20	12:40	6.50	3.70	1.35	1.40	1.30
	14:15	6.95	4.50	1.10	—	1.10
	15:40	9.25	7.30	2.60	—	0.90
6/29	14:45	6.24	2.38	1.47	—	1.32
	16:15	6.40	1.44	1.33	—	1.39
	18:15	7.17	2.45	1.40	—	1.36
7/07	12:50	6.40	1.10	0.70	—	0.65
	14:15	6.99	2.89	0.62	—	0.63
	15:15		No Samples Taken -- No Visual Change			
	16:30	12.25	7.50	4.92	—	0.44
	18:30	14.10	13.14	3.70	—	0.43
7/14	13:15	7.44	3.02	0.96	—	0.95
	14:15	7.60	3.76	0.84	—	0.84
	15:30	8.14	5.94	0.79	—	0.80
	18:30	9.67	8.63	4.23	—	0.79
7/21	12:00	5.76	0.54	0.38	—	0.33
	13:15	8.90	1.15	0.30	—	0.26
	15:45	11.06	7.81	0.29	—	0.26
	17:00	7.35	0.46	0.46	—	0.41
	18:30	11.87	6.41	0.29	—	0.29

TABLE 17. CLARIFIER PROFILE DATA CLARIFIER B

Date	Time	Sample Port 1	Sample Port 2	Sample Port 3	Sample Port 4	Samole Port 5
		Concentrations (Kg/M^3)				
6/20	13:00	6.25	3.30	1.40	1.30	1.20
	14:15	8.80	5.90	1.50	—	0.90
	15:40		No Samples Taken -- No Visual Change			
	17:00	12.15	9.00	—	—	0.80
6/29	12:45	6.15	0.59	0.60	—	0.60
	13:45	6.50	14.24	0.55	—	0.57
	16:00	5.54	20.10	11.38	0.51	0.57
7/07	12:45	6.16	0.72	0.28	—	0.28
	14:15	10.85	0.28	0.26	—	0.26
	15:15		No Samples Taken -- No Visual Change			
	16:30		No Samples Taken -- No Visual Change			
	17:30	15.48	6.10	0.18	—	0.21
7/14	13:00	6.22	3.00	0.67	—	0.60
	14:15	8.11	5.38	0.63	—	0.54
	15:30	10.23	7.67	0.52	—	0.52
	19:30	12.28	13.32	5.12	—	0.44
7/21	12:00	6.27	0.62	0.41	—	0.36
	15:30	10.40	0.64	0.35	—	0.34
	17:15	11.76	5.20	0.29	—	0.33
	18:45	6.70	0.47	0.48	—	0.46
	20:30	10.20	4.67	0.32	—	0.32

TABLE 18

CONTINUOUS FLOWS AND CONCENTRATIONS WHICH PRODUCED BLANKET PROPAGATION

Date	Clarifer	Flow Rates Feed (m/day)	Overflow (m/day)	Underflow (m/day)	Concentrations Feed (kg/m^3)	Underflow (kg/m^3)	Blanket (kg/m^3)
6/20	A	44.4	30.2	14.2	3.50	9.25	6.50
	B	48.8	30.6	18.2	3.50	8.80	5.90
7/ 7	A	37.3	24.0	13.3	3.20	12.25	7.50
	B	14.0	11.6	2.4	3.20	15.50	6.10
7/14	A	46.2	30.7	15.5	3.30	9.67	4.20
	B	29.3	22.2	7.1	3.30	12.28	5.10
7/21	A	20.6	14.8	5.8	3.30	11.06	7.80
	B	20.9	14.7	6.2	3.30	11.76	5.20
	A	20.9	14.9	6.0	3.30	11.87	6.40
	B	21.3	15.1	6.2	3.30	10.20	4.70

TABLE 19

SVI DATA (mg/l)

Date	SVI	DVSI	SSVI
6/18/89	82	85.4	—
6/27/89	78	76	68
7/ 5/89	92	82	84
7/ 7/89	91	83	80
7/12/89	89	92	91
7/14/89	83	85	—
7/19/89	85	85	65
7/21/89	78	80	—

APPENDIX B

RELATIONSHIP BETWEEN SCALE FACTOR AND CLARIFIER AREA

Relationship Between Scale Factor and Clarifier Area (Fig. 37)

Define terms:

A = clarifier surface area (m^2)

A_b = clarifier area determined from batch limiting flux

A_f = clarifier area determined from continuous limiting flux

C_o = clarifier influent solids concentration (Kg/m^3)

F_o = plant influent flow rate (m^3/day)

G_{Lb} = limiting flux from batch curve (Kg/m^2-day)

G_{Lf} = limiting flux from continuous data (Kg/m^2-day)

G_{ob} = flux corresponding with blanket concentration on batch flux curve (Kg/m^2-day)

G_{of} = flux corresponding with blanket concentration on continuous flux curve (Kg/m^2-day)

In general, for linear equations,

$$y = mx + b \tag{29}$$

then,

$$G_o = -(R/A)C_o + G_L \tag{30}$$

or,

$$G_{of} = -(R/A_f)C_o + G_{Lf} \tag{31}$$

and,

$$G_{ob} = -(R/A_b)C_o + G_{Lb} \tag{32}$$

By definition,

$$A_f = F_oC_o/G_{of} \tag{33}$$

and,

$$A_b = F_oC_o/G_{ob} \tag{34}$$

Substituting equations (31) & (32) into (33) & (34), respectively, gives,

$$A_f = (F_oC_o) \div (G_{Lf} - (RC_o/A_f)) \tag{35}$$

and,

$$A_b = (F_oC_o) \div (G_{Lb} - (RC_o/A_b)) \tag{36}$$

Rearranging,

$$G_{Lf}A_f - RC_o - F_oC_o = 0 \tag{37}$$

$$G_{Lb}A_b - RC_o - F_oC_o = 0 \tag{38}$$

Solving for A in each,

$$A_f = C_o(F_o + R) \;/\; G_{Lf} \tag{39}$$

$$A_b = C_o(F_o + R) \;/\; G_{Lb} \tag{40}$$

Dividing equation (39) by (40) yields,

$$A_f/A_b = G_{Lb}/G_{Lf} \tag{41}$$

Therefore, the scale factor is inversely related to clarifier area.

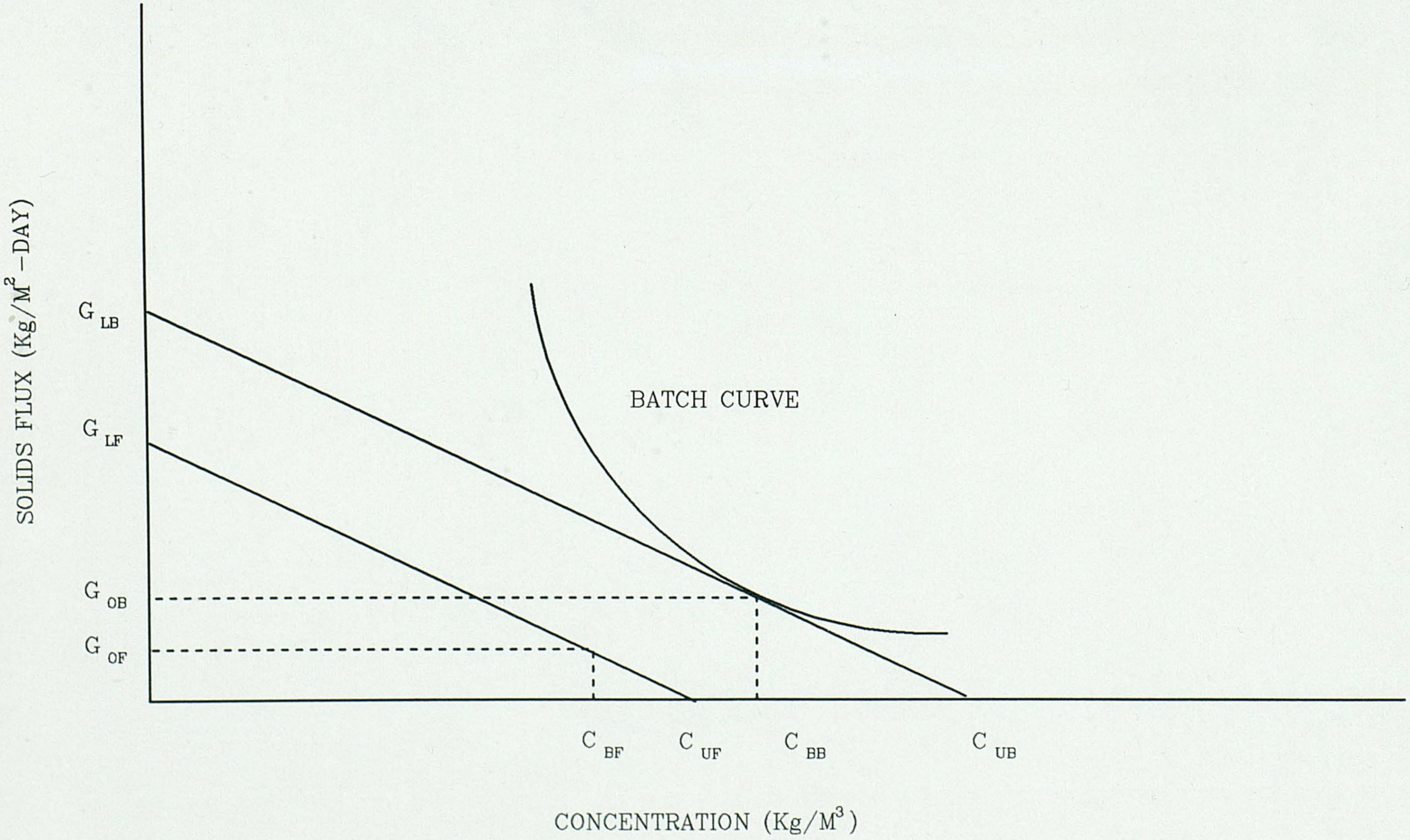

Figure 37. Mathematics of Technique 3

APPENDIX C

APPROACHES FOR DETERMINING SAFETY FACTORS

Approach 1 for Determining Limiting Flux Values (Fig. 35)

1. Define parameters for 80% exceedence curve.

   $V_0 = 827$ m/day

   $K = 0.698$ m^3/Kg

2. Select the mixed liquor (MLSS) and underflow (C_u) concentrations.

   MLSS = 3.33 Kg/m^3

   $C_u = 10.0$ Kg/m^3

3. Calculate the underflow rate (u) which yields a line (line U) that begins at C_u and becomes tangent to the exceedence curve at C_B. This is accomplished by iterating C_B until the following equation is satisfied:

$$C_u = \frac{V_0 C_B \exp(-KC_B)}{(-KV_0 C_B \exp(-KC_B)) + (V_0 \exp(-KC_B))} + C_b \qquad (42)$$

   $C_B = 8.27$ Kg/m^3

$$u = -1 \times (-K\ V_0\ C_B\ \exp(-KC_B) + (V_0\ \exp(-KC_B)) \qquad (43)$$

   $u = 827(.698)\exp(-.698 \times 8.27) / (10.0 - 8.27)$

   $u = 12.3$ m/day

4. The overflow rate is calculated to determine if it is acceptable (24 to 41 m/day is generally accepted). From the mass balance around the clarifier:

$$(v + u)\mathrm{MLSS} = u(C_u) \qquad (44)$$

$$v = (u(C_u)/\mathrm{MLSS}) - u \qquad (45)$$

   $v = ((12.3 \times 10.0) / 3.33) - 12.3$

   $v = 24.6$ m/day

5. Calculate the limiting flux (G_{Le}).

$$G_{Le} = V_0 \; K \; C_B^{\;2} \; \exp(-K \; C_B) \qquad (46)$$

G_{Le} = 827 (.698) (8.27^2) exp(-.698 x 8.27)

G_{Le} = 123 Kg/m^2-day

6. If the overflow rate from (4) is acceptable, repeat steps 3-4 for the mean flux curve values of V_o and K.

V_0 = 514.6 m/day

K = 0.551 m^3/Kg

The results are:

C_B = 7.62 Kg/m^3

u = 24.7 m/day

v = 24.5 m/day

G_{Lm} = 247 Kg/m^2-day

7. Calculate the safety factor.

$$\text{Safety factor} = G_{Le}/G_{Lm} \qquad (47)$$

Safety factor = (123 Kg/m^2-day) / (247 Kg/m^2-day)

Safety factor = 0.50

Approach 2 for Determining Limiting Flux Values (Fig. 36)

1. Define parameters for mean (50%) exceedence curve.

$V_0 = 514.6$ m/day

$K = 0.551$ m^3/Kg

MLSS = 3.33 Kg/m^3

$C_u = 10.0$ Kg/m^3

$G_{Lm} = 247$ Kg/m^2-day (from Approach 1)

2. Determine underflow velocity, u.

$$u = G_{Lm}/C_u \tag{48}$$

$u = 247/10.0$ m/day

$u = 24.7$ m/day

3. Determine the value of C_B (by iteration) which places the underflow velocity line (line U) tangent to the 80% exceedence curve.

$V_0 = 827$ m/day

$K = 0.698$ m^3/Kg

$$u = -((-KV_0C_B\exp(-KC_B)) + (V_0\exp(-KC_B))) \tag{49}$$

$u = 24.7$ m/day

$C_B = 6.96$ Kg/m^3

4. Calculate the underflow concentration.

$$C_u = \frac{V_0C_B\exp(-KC_B)}{u} + C_B \tag{50}$$

$C_u = 8.77$ Kg/m^3

5. Calculate the limiting flux (G_{Le}).

$$G_{Le} = V_0 \ K \ C_B^{\ 2} \ \exp(-K \ C_B) \qquad (51)$$

$$G_{Le} = 827 \ (.698) \ (6.96^2) \ \exp(-.698 \times 6.96)$$

$$G_{Le} = 217 \ \text{Kg/m}^2\text{-day}$$

6. Calculate the safety factor.

$$\text{Safety factor} = G_{Le}/G_{Lm} \qquad (52)$$

Safety factor = 217/247

Safety factor = 0.88

Note: The ratio of C_u (80%) / C_u (mean) can also be used to calculate the safety factor.

C_u (80%) / C_u (mean) = 8.77/10.0 = 0.88

APPENDIX D

PROCEDURE EXAMPLE FOR DETERMINING CLARIFIER AREA

Calculation of Clarifier Area

Known: $V_0 = 295$ m/day
$K = 0.509\ m^3/Kg$
SF = 0.84
Safety factor = 0.50

Assume: MLSS = 3.33 Kg/m^3
$Q_i = 37{,}850\ m^3/day$
R = 0.5

Constraints: $v_{MAX} = 32.6$ m/day
$u_{MAX} = 24.5$ m/day
$u_{MIN} = 16.3$ m/day
$C_{uMIN} = 7.0$ m/day

1. Calculate C_u from batch data.

$$C_u = \frac{(1+0.5)\ 3.33}{2\ (0.5)} + \left[\frac{((1+0.5)/0.5)^2\ 3.33^2}{4} - \frac{(1+0.5/0.5)\ 3.33}{0.509}\right]^{0.5}$$

$C_u = 7.22\ Kg/m^3$

2. Calculate the limiting flux, G_{Lb}.

$G_{Lb} = V_0\ K\ C_u^2\ \exp(-K\ C_u)$

$G_{Lb} = 295\ (0.509)\ (7.22)^2\ \exp(-0.509\ (7.22))$

$G_{Lb} = 198\ Kg/m^2$-day

3. Apply the scale factor, SF, and Safety factor.

$G_{Lf} = 198\ (0.84)\ (0.5)$

$G_{Lf} = 83\ Kg/m^2$-day

4. Calculate the limiting flux established by the maximum overflow velocity, v.

$G_{Lv} = MLSS\ (v + u_{MIN})$

$G_{Lv} = 3.33\ (32.6 + 16.3)$

$G_{Lv} = 163\ Kg/m^2$-day

5. Choose the smallest G_L.

   $G_L = 83$ Kg/m^2-day

6. Determine clarifier area.

   $A = Q_i$ MLSS/G_L

   $A = 37{,}850\ (3.33)/83$

   $A = 1520$ m^2

   Four 22 m diameter clarifiers are required.

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